Leibniz-Institut für Katalyse e.V. an der Universität Rostock

Asymmetric Catalysis in Organic Carbonates

Dissertation

zur Erlangung des akademischen Grades eines
Doktor rerum naturalium (Dr. rer. nat.)

vorgelegt der
Mathematisch-Naturwissenschaftlichen Fakultät der Universität Rostock
von

Benjamin Schäffner

Geboren 30. Juni 1981
in Halberstadt

Rostock, 28. November 2008
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University of Rostock

Abstract

Asymmetric Catalysis in Organic Carbonates

By Benjamin Schäffner

Leibniz Institute of Catalysis at the University of Rostock

This thesis presents the use of organic carbonates (especially propylene carbonate) as alternative solvents for asymmetric catalysis. In the last decades the usefulness of these solvents for homogeneous and heterogeneous catalysis has been presented in several publications. In this thesis homogeneous palladium-, rhodium- and iridium-catalyzed reactions were investigated in organic carbonates. A major part was the use of the rhodium-catalyzed hydrogenation to obtain chiral products with high stereoselectivities. Moreover, it could be shown, that organic carbonates can be used to afford an efficient catalyst recycling as well as to obtain pure products via product distillation out of the reaction media. Furthermore this thesis includes results on the use of organic carbonates as solvents for palladium catalyzed copper-free Sonogashira reaction as well as for asymmetric allylic substitutions.

Die in dieser Doktorarbeit präsentierten Ergebnisse basieren auf der Verwendung von organischen Carbonaten (insbesondere Propylencarbonat) als Lösungsmittel in der asymmetrischen Katalyse. Im letzten Jahrzehnt wurde diese Lösungsmittelklasse als alternative Lösungsmittel in der Katalyse zunehmend attraktiv und in diversen Publikationen vorgestellt. Diese Dissertation beschreibt die Verwendung organischer Carbonate als Lösungsmittel bei homogenen Palladium-, Rhodium- und Iridium-katalysierten Reaktionen. Im Mittelpunkt steht dabei die Verwendung der asymmetrischen, Rhodium-katalysierten Hydrierung. Des Weiteren wird in dieser Dissertation ein effizientes Katalysatorrecycling sowie die destillative Produktabtrennung aus Propylencarbonat vorgestellt. Abschließend werden Palladium-katalysierte Reaktionen wie die kupferfreie Sonogashira-Reaktion und die asymmetrische allylische Substitution in organischen Carbonaten untersucht.

„Das Ende eines Dinges ist besser denn sein Anfang. Ein geduldiger Geist ist besser denn ein hoher Geist.“

Die Bibel: Prediger, 7, 8.

„Denn wo viel Weisheit ist, da ist viel Grämens;
und wer viel lernt, der muss viel leiden.“

Die Bibel: Prediger, 1, 18.

Table of Contents

List of Abbreviations

AAA	Asymmetric Allylic Alkylation
Ac	Acetate
approx.	approximately
AN	Acetonitrile
Ar	Aryl
β	Hydrogen Bond Acceptor
BINOL	2,2'-bis(diphenylphosphanyl)-1,1'-binaphthol
BINAP	2,2'-bis(diphenylphosphanyl)-1,1'-binaphthyl
bmim	1-Butyl-3-methyl-1,3-imidazolium ion
bm_2im	1-Butyl-2,3-dimethyl-1,3-imidazolium ion
Bn	Benzyl
b.p.	Boiling point
Boc	*tert*-Butyloxycarbonyl
^{t}Bu	*tert*-Butyl
Cat.	Catalyst
Cat*AS*ium M	2,3-bis[2,5-Dimethylphospholanyl]maleic acid anhydride
COD	1,5-Cyclooctadiene
conv.	Conversion
cP	Centipoise (value of viscosity)
cy	Cyclohexyl
dba	Dibenzylidene acetone
DEC	Diethyl carbonate
DMC	Dimethyl carbonate
DMF	Dimethylformamide
DMSO	Dimethylsulfoxide
DuPHOS	1,2-bis[2,5-Dimethylphospholanyl]benzene
ε_r	Relative permittivity ("dielectric constant")
E_T^N	Polarity (30 °C)
EC	Ethylene carbonate
ee	enantiomeric excess
eq	Equivalent
Et	Ethyl

e.g.	exempli gratia
et al.	et alii, et aliae or et alia
f.p.	Flash point
GC	Gas chromatography
GyC	Glycerol carbonate
IL	Ionic Liquid
L	Ligand
LD_{50}	*Dosis Letalis* (Value of Toxicity)
μ	Dipole moment in Coulombmeter (Cm)
Me	Methyl
mill	million
MTBE	Methyl-tertiary-butyl ether
NBD	Norbornadiene
Nu	Nucleophile
OTf	Triflate (trifluoromethanesulfonate)
p	para
p	pressure
PC	Propylene carbonate
Ph	Phenyl
ppm	Parts per million
*i*Pr	*iso*-Propyl
R	Organic group
r.t.	Room temperature
sc	supercritical
T	Temperature
THF	Tetrahydrofurane
TMS	Temperature-Dependent Multicomponent-Solvent (System)
VOC	Volatile Organic Compound
wt.	weight

1 Preface

Chemistry as a central science describes processes at a molecular level. Investigations in this field are necessary to encounter the problems of the 21st century. One approach to achieve improvements for a more sustainable future is to include ideas of Green Chemistry into research and development. Within the manifold of molecular transformations to new compounds, catalytic reactions offer an efficient strategy and represent a key technology for the advance of 'Green Chemistry'. Thus, catalysis is essential in modern synthesis. This is especially true with regard to waste prevention, energy saving and atom efficiency. About 80% of all chemical processes in industry are catalyzed. Especially homogeneous transition metal catalysis offers a great potential for an increased use in industry and academia. These catalysts consist of a transition metal atom, which is capable to form or cleave bonds with reactants, and one or more ligands around the metal. The ligands define the electronic and steric surrounding at the central atom and thus the catalytic activity and selectivity. Phosphorus, nitrogen, (sulphur) and oxygen are appropriate donor atoms in ligands due to their free electron pairs to allow quick bond formation and cleavage. More than 2000 ligands have been synthesized to solve numerous synthetic problems.

In order to reduce the use of toxic, volatile and flammable compounds the choice of solvent is of special interest in chemistry. History has revealed that not every new solvent was an advantage and could also include new risks. One of the most popular examples was the use of the carcinogenic benzene in the production of dyes and coatings. According to this the public's consciousness for Green Chemistry has increased in the last decades of the 20th century to conserve a liveable world for the following generations. Thus, industry and science are searching for less toxic processes and compounds to minimize the risks for employees, society and nature.

This work presents new methodologies and techniques for the use of organic carbonates as alternative, so-called "green" solvents in asymmetric catalysis to minimize the use of hazardous solvents. They should be capable to substitute currently applied solvents to follow the twelve rules of Green Chemistry.

2 Introduction

2.1 Process of Solvent Innovation in History

The use of solvents is an essential part in the history of chemistry and alchemy.[1] Throughout the different ages a solvent and a solute may be defined as two compounds if mixed together to give a single, homogeneous liquid phase.[2] Water was considered to be the "purest" of all solvents and the Greek philosophers thought, that every solvent is related to water and it could ransom matter to reveal *Materia Prima*.[a] Later on, the Greek principles were picked up by Paracelsus (1493-1541, Figure 1) and his successors on their search for a "universal solvent" – the *alkahest* – as medicine against liver deseases.[b,3]

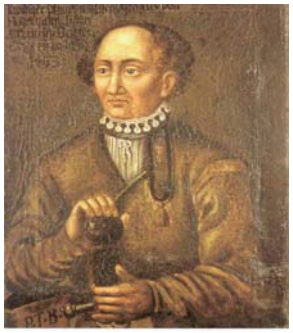


Figure 1: Paracelsus

Figure 2: J. B. van Helmont

Age of Alchemists

Paracelsus gave only little valuable information about his solvent which should dissolve every matter. Van Helmont (1579-1644, Figure 2), one of Paracelsus successors, completed the idea to a whole theory to reveal *Materia Prima*.[4,5] His theory was that dissolution in alkahest would reduce matter to elemental water.[6] However, opponents of this theory like the German alchemist Johann Kunckel (1630-1703) gave the eligible remark "If the alkahest dissolves everything, it should dissolve the vessel which contains it".[7] Despite the failures of preparing the alkahest the theory lived on till the middle of the 18th century. In modern time historians and chemists believe that alkahest was not a single substance because van Helmont's alkahest dissolved a broad variety of materials (charcoal, stones, plants, metals etc.).[8]

Although the search of the alchemists was not successful, it afforded new laboratory techniques and knowledge in the field of solvation-chemistry.

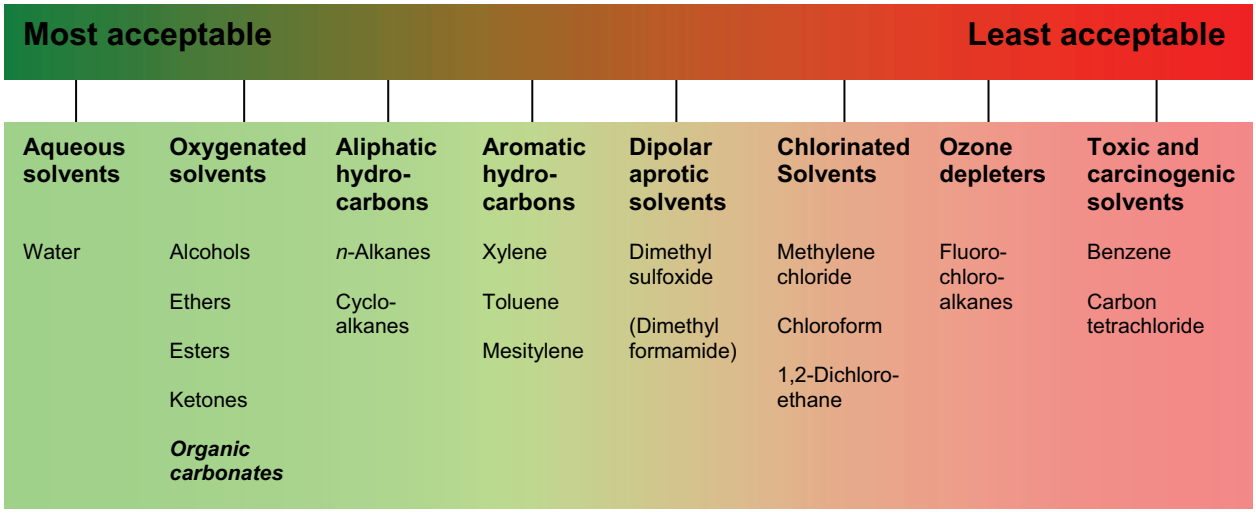
[a] *Materia Prima* was the alchemist's term for the pure spirit of every kind of matter and is normally hidden. Through transformation processes the alchemists hoped to reveal this spirit and used it for transmutation of metals to gold or the preparation of the Sorcerer's Stone.

[b] The meaning of the name *Alkahest*, given by Paracelsus, is not known. Some of his successors (Glauber, Starkey) had their own interpretations about the name e.g. *Al-gehest*, which means all spirits or *alkali est*.

The Success of molecular Solvents

With the beginning of the 19th century the three researchers Raoult (1830-1901), van't Hoff (1852-1911) and Arrhenius (1859-1927) defined the modern solution theory and formed the fundament for further investigations on solutions.[9,10] Benzene as a prominent example for these new molecular solvents became more and more important in the 19th century. Mitscherlich and Liebig described it in 1835. At the same time chlorinated solvents like methylene chloride and chloroform were developed. The main difference between these solvents and former used mixtures and solutions (*e.g.* salt solutions in water, aqueous alcoholic mixtures, mercury) was their ability to dissolute a major part of organic compounds like the newly developed synthetic dyes. Unfortunately, until the Fifties of the 20th century the risks of these solvents for health and nature were not investigated.

Today about 60 mill tons of organic solvents are used each year. Most solvent applications like cleaning, degreasing and the use in electronics or coatings are "non-chemical" applications. The most popular organic solvents can be easily evaporated to remove them from products and are so called volatile organic compounds (VOC). However, VOCs can destroy the ozone layer as well as implicate the greenhouse effect. In 1987 the Montreal conference adopted the Montreal protocol (Geneva 1991, Kyoto 1997) to reduce the use of special VOCs like fluorochloro alkanes, bromofluorocarbons and CCl_4.[11,12] With the sensitization of the society for delayed diseases like cancer, solvent classes were separated into more and less acceptable groups (Scheme 1).[2]



Scheme 1: Acceptability of molecular solvents.

To encounter the risks of high-flammability (f.p. < 21 °C), toxicity (LD_{50} < 200 mg / kg and carcinogenic and mutagenic substances) and eco-toxicity, several solvents were replaced by less dangerous derivatives. For instance, today most applications were accomplished in

toluene instead of the carcinogenic benzene or in MTBE instead of highly flammable diethyl ether. In industry oxygenated solvents are more acceptable than hydrocarbons or chlorinated solvents because they are believed to biodegrade more easily. Thus, sales of less acceptable solvents dropped significantly in the last years.[a,13] Nevertheless, the case of the highly volatile methylene chloride which is replaced by the less volatile but toxic 1,2-dichloroethane shows that there is still a need for new innovations.

2.2 Green Chemistry

"Green chemistry efficiently utilises (preferably renewable) raw materials, eliminates waste and avoids the use of toxic and/or hazardous reagents and solvents in the manufacture and application of chemical products." [14]

2.2.1 Twelve Principles of Green Chemistry

At the end of the 1990s chemists started to introduce sustainable aspects into their work. Modern analytical techniques allowed following the way of a chemical from production to its disposal.[15] The methodology of the chemical life-cycle was soon adopted by the industry to prevent further pollution of the environment and to fulfil new regulations To prioritize the further work and the aims of Green Chemistry, 12 basic rules were drafted.[16] Three major objectives can be pointed out from these principles:

- Reduction of waste and used energy
- Use of renewables as often as possible
- Reduced used of toxic reactants and solvents

Several incorporation fields have been pointed out to be key areas for application of the 12 principles: polymers,[17] catalysis, solvents, renewables,[18] analytical methods[19] and new synthetic pathways.[20] The fields of catalysis and solvents are described in more detail in the next two chapters. Although all fields of chemistry are influenced by the twelve principles it is of great importance to include education. Therefore it is necessary to allocate literature and education material to educators and to the next generation scientists. At least it is important to note that scientists have to be open for the ideas of Green Chemistry. It is up to researchers to

[a] In detail the sales of hydrocarbons and chlorinated solvent dropped by 17% in the years of 1996-2001 in Western Europe.

use the 12 principles of Green Chemistry in their every-day research in order to reduce risks for health and environment.

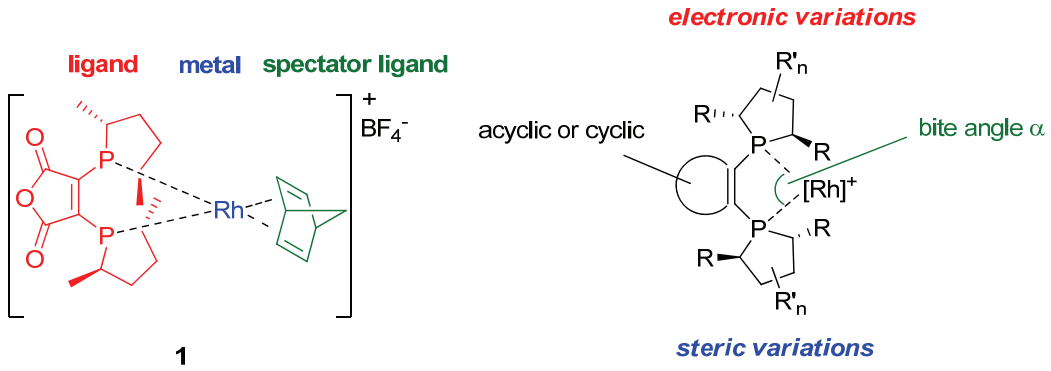
2.2.2 Catalysis as method to more sustainable Chemistry

General

A catalyst is a compound which increases the speed of a reaction until its equilibrium is achieved.[21] It forms intermediates with substrates in order to obtain new C-C or C-X (X = H, O, N, S, P, etc.) bonds, to cleave existing bonds or to transfer chirality. A formal catalytic cycle consists of three elementary steps: formation of the catalyst-substrate complex via addition of the substrate, formation of the product and elimination of the product with regeneration of the catalytically active species. Catalysis can be divided into homogeneous and heterogeneous catalysis, and biocatalysis. The field of homogeneous catalysis includes transition metal catalysis as well as acid-base catalysis and organocatalysis. The results of this dissertation are based on asymmetric homogeneous transition metal catalysis. In contrast to heterogeneous catalysts, homogeneous catalysts are completely soluble in the reaction media and are highly active compounds which can be used in low concentrations. Due to the fact, that they are completely soluble it is not necessary to consider mass transport effects. Furthermore, the use of chiral catalysts is one possibility to introduce chirality into pro-chiral compounds. In general, one drawback of homogeneous metal catalysts is the difficult catalyst separation from the product. In cases where the substrate / catalyst ratio is not high enough so that the catalyst concentration is very low (e.g. less than 10 ppm for pharmaceutical applications, and below 1 ppm for toxic metals like osmium), it is necessary to purify the product. This is also necessary if the catalysts are rather expensive. An overview about the known catalyst recycling methods in homogeneous catalysis is given by Behr.[21] Late transition metal atoms e.g. rhodium, ruthenium, iridium, palladium and platinum are widely used as metal centres in catalysts.

Furthermore a catalyst consists of at least one ligand. The most common ligands are neutral molecules with donor atoms such as phosphorus, nitrogen and oxygen. One example, a [Rh(Cat*A*Sium M)(NBD)]BF_4 (**1**) complex is shown in Scheme 2. Ligands offer numerous possibilities for fine-tuning; different variations at a basic model of a ligand lead to ligand families (Scheme 3).[22] At least, catalysts often contain spectator ligands which act as “placeholder” in the pre-catalyst. These spectator ligands can be charged (anions like

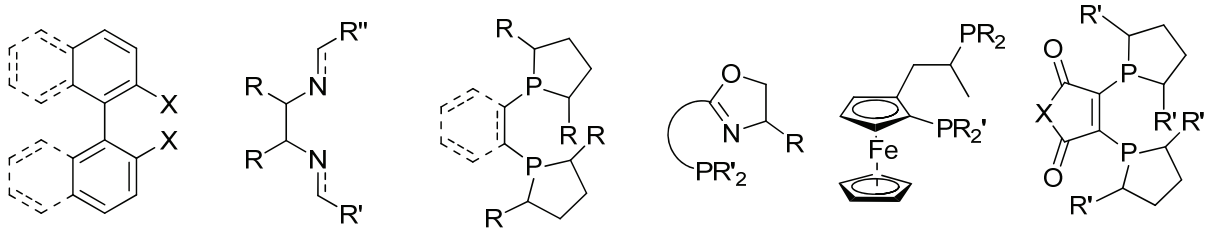
halogens, cyanide, trifluoro acetates, etc.) or neutral (diolefins such as NBD in Scheme 2 (left) or cycloocta-2,5-diene).



Scheme 2: A typicial rhodium pre-catalyst (left) and possible ligand modifications (right).

Spectator-ligands in the active catalyst are replaced by a solvent or the substrate molecule in an equilibrium which can be shifted from the pre-catalyst to the solvate complex by changing the conditions (e.g. temperature, hydrogen pressure). The variations in the "primary" ligand (e.g. bis-phosphine Scheme 2 right) affect the electronic and steric surrounding at the metal centre. All variation possibilities of the bidentate Cat*AS*ium ligands – as one of the privileged ligand families – are summarized in Scheme 2 right. The overall effect of these variations is not only limited to the reactivity of a catalyst. Moreover, enantioselectivity strongly depends on the right ligand. The sensitivity of the interplay between chiral catalyst and prochiral substrate was pointed out by Knowles in 1983. "Since achieving 95% *ee* only involves differences of about 2 kcal, which is not more than the barrier encountered in a simple rotation of ethane, it is unlikely that before the fact one can predict what kind of ligand structure will be effective."[23] The use of phosphorus as donor atom in chiral ligands offers several advantages. Phosphorus easily binds to late transition metals and can be analyzed by ^{31}P-NMR experiments (^{31}P is the most frequented isotope of P). Well established syntheses for all kinds of chiral phosphorus ligands exist.[24] To encounter the problem of unknown selectivity of each single ligand, ligand families became very popular. Within these families, the backbone structure remains constant and only slight changes were introduced at the substituents. Some of the most privileged ligand families for asymmetric catalysis are presented in Scheme 3.[25] However their advantages, homogeneous transition metal catalyzed reactions are a minority in industrial scale.[27b] Still, in the last years the use of high-throughput screening (HTS) became very popular. Due to the modified automatization it allows to test hundreds of ligands in short time, which is an efficient way to examine the most active and selective catalyst for a reaction before scaling up it. Furthermore, monodentate

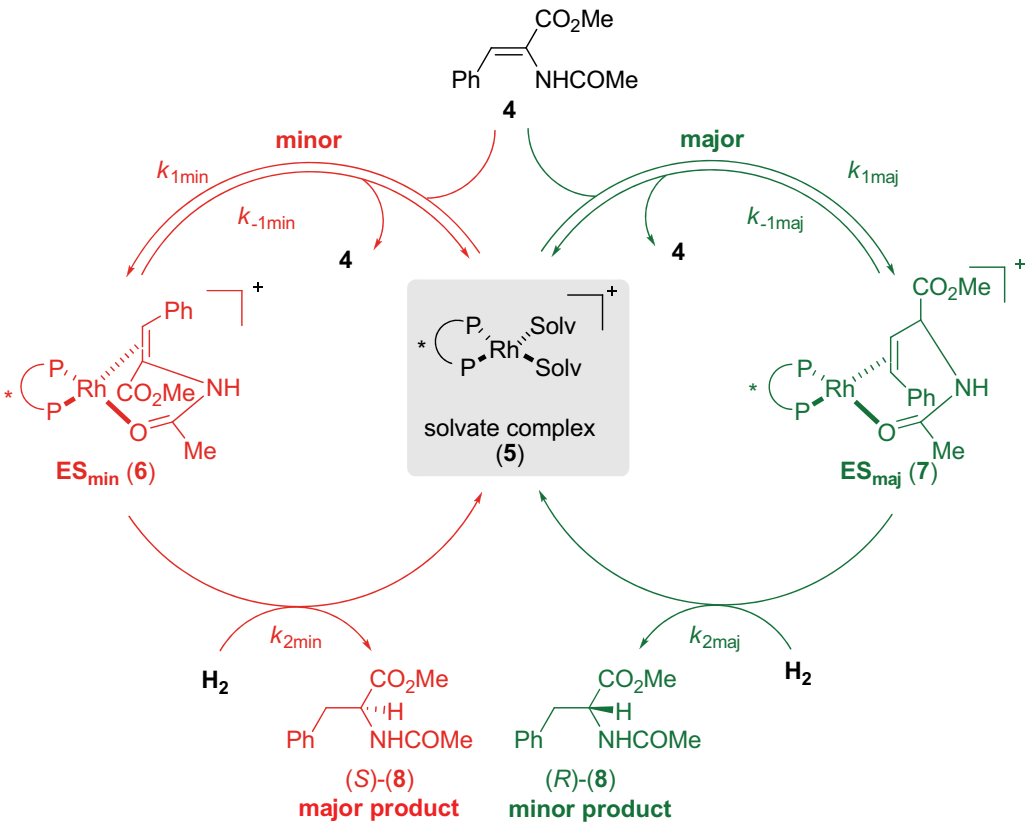
ligands can be used in mixtures, which can have an impact on the reactivity as well as on the stereoselectivity.[26]



Scheme 3: Privileged ligand families in asymmetric catalysis.

Asymmetric Hydrogenation

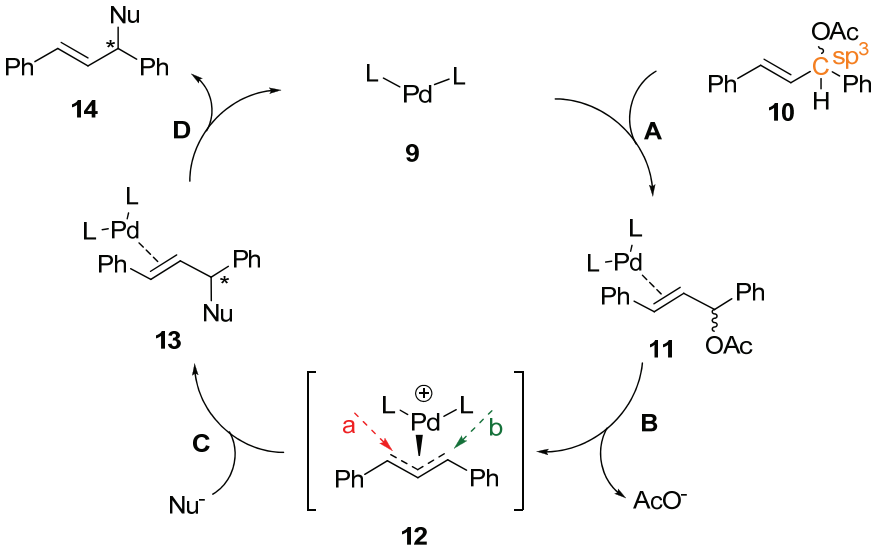
Asymmetric hydrogenation has reached a high level of application in industry and science.[27] Molecular hydrogen can be converted with 100% atom efficiency to reduce olefinic bonds as well as double bonds of ketones and imines. Today it is one key technology to introduce chirality into molecules. Especially suitable are catalysts using metals like Rh, Ru and Ir. First results were published in 1966 by Wilkinson using $[Rh(PPh_3)_3Cl]$.[28] The interplay between two different chiral ligands was investigated by Noyori in the 1980s. One breakthrough was his $[RuCl_2(BINAP)(DPEN)]$ system, which could reduce ketones selectively to alcohols with 99% *ee* in a substrate to catalyst ratio of 1.000.000 : 1.[29] The mechanism for the asymmetric hydrogenation using bisphosphanes as ligands shown in Scheme 4 is based on the pioneering work of Halpern and co-workers (Scheme 4),[30] in which two diastereomers are formed (**7** and **6**). If the major diastereomer was converted to the lead product-enatiomer, the reaction is said to follow the lock-and-key principle as it is know from enzyme kinetics. In case of the hydrogenation of methyl (*Z*)-α-acetamidocinnamate - AMe (**4**) and other well known benchmark substrates, however, the Major – Minor concept is valid in case of a more reactive minor enantiomer than the major one and thus defining the stereochemical outcome. Heller and co-workers discovered that both mechanisms can co-exist in the same reaction in dependence on the applied hydrogen pressure.[31] The main complex in both mechanisms is displayed by the solvate complex, which are highly active but not stable. Thus, Rh-precursors contain one or two diolefines instead of other ligands or solvent molecules. Widely used are norbornadiene (NBD) and cycloocta-2,5-diene (COD) which show an different reaction behaviour under hydrogenation conditions.[32]



Scheme 4: Hydrogenation mechanism of AMe by Halpern and Heller.

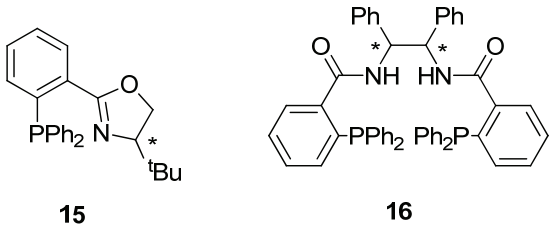
Asymmetric Allylic Substitution

Transition metal catalyzed C-C couplings have been intensively investigated since the 1950s. There are numerous reactions to form new carbon-carbon bonds using aromatic halides and olefinic systems.[33] In the field of asymmetric C-C bond formations the Pd-catalyzed asymmetric allylic alkylation (AAA) achieved great popularity. The allylic alkylation was primarily used by Trost and co-workers in 1973.[34] Since then many improvements have been reported including an enantioselective version.[35] With the AAA it is possible to convert compounds from racemic mixtures into enantiopure products through a *meso*-intermediate or through a dynamic asymmetric kinetic transformation (DYKAT).[36] In contrast to other metal-catalyzed reactions this reaction occurs at a sp^3 instead of a sp^2 carbon atom (compare **10** and **4**). The catalytic cycle of the AAA is shown in Scheme 5. 1-Acetoxy-1,3-diphenyl propene (**10**) forms with Pd(0) source **9** to form the π-complex **11** through an addition (**A**). After cleavage of the carbon-oxygen bond and removal of the OAc-group (step **B**) there are two possible ways (a or b at **12**) for the nucleophilic attack on the *meso* π-allyl intermediate **12** to give the chiral adduct **13**. Enantioselective discrimination takes place during the attack of the nucleophile at the *meso* complex (step **C**). Decomplexation leads to the regenerated Pd(0)-catalyst and the product **14** (step **D**).



Scheme 5: Mechanism of the Pd-catalyzed AAA by Trost and co-wokers.

It is noteworthy, that the above described mechanism is generally practical on all known AAA substrates but the two possible attack pathways of the nucleophile at **12** are rather unique for this substrate. Thus, results with this substrate can not applied to other substrates without further investigations.[37] The above described PHOX **15** and Salen type (Trost ligand **16**) ligand families are especially suitable for the AAA. Depending on the used substrates stereoselectivities > 99% *ee* were achieved.[25k, 36]



Scheme 6: Trost and PHOX ligands for the AAA.

2.2.3 Alternative Solvents

Water and supercritical carbon dioxide

The use of problematic organic solvents in industrial facilities is not mainly an issue during the reaction than during the process of solvent recovery. Volatile Organic Compounds (VOCs) are often used in two steps which can lead to solvent losses. To reduce these losses, an internal solvent recycling would be more sophisticated. The most traditional version is the usage of phase transfer reactions with an organic solvent in combination with water. However, water can be contaminated with organic compounds or metal catalysts which lead to an expensive clean-up process. Despite of this disadvantage, phase transfer reactions with

water are well established for hydroformylations (Rhône-Poulenc Process).[38] Next to water, $scCO_2$ is widely used for biphasic reactions. In contrast to scH_2O which is only stable under harsh conditions (374 °C, 221 bar) $scCO_2$ can be obtained at 31 °C and 74 bar pressure.[39] This issue is of great importance for reactions with sensitive compounds.[40] Interesting approaches using $scCO_2$ for homogeneous catalysis were given by the groups of Leitner, Jessop and Cole-Hamilton.[41] Next to supercritical solvents other alternative solvents can be used at ambient conditions for biphasic reactions.

Ionic Liquids (ILs)

ILs own perfect properties to be used in biphasic reactions with homogeneous catalysts. They are defined as organic salts with melting points below 100 °C. ILs can be easily synthesized and own high polarities. Due to their high variety of cations and anions ILs offer nearly unlimited modification possibilities.[42] However, many ILs exhibit a high viscosity which is two magnitudes greater than in "traditionally" organic solvents (often above 70 cP).[43] It has to be reduced to 40 – 50 cP before ILs can be used as solvent. A famous method to reduce the viscosity is the anion-exchange.[44] ILs are able to form biphasic systems with organic solvents and have been successfully used in catalysis.[45] Despite their advantages, there are still some drawbacks for the use of ILs: Firstly, only few data about the toxicity for most of the used ILs are known[46] and secondly ILs are not available in large scale[47] and in comparison to other solvents they are still expensive.[21,42]

Fluorinated Solvents

Fluorinated solvents are highly fluorinated alkanes, ethers and amines. They own high densities and low polarities.[48] They are non-toxic, inflammable and chemically inert. However, the latter point leads to the lack of biodegradability, which is a big disadvantage. Due to their low van der Waals interactions it possible to solve gases like oxygen or carbon dioxide within them. To obtain catalysis in fluorinated solvents it is necessary to include perfluorinated moieties at the ligands (fluorous ponytails) to increase the solubility of a catalyst in the solvent. One exception is represented by fluorinated alcohols. They are highly polar, combined with low hydrogen bond acceptor properties (in contrast to normal alcohols). Catalysts can be readily used in fluorinated alcohols without further modifications.[49] Like ILs, fluorinated solvents are rather expensive.

Polyether

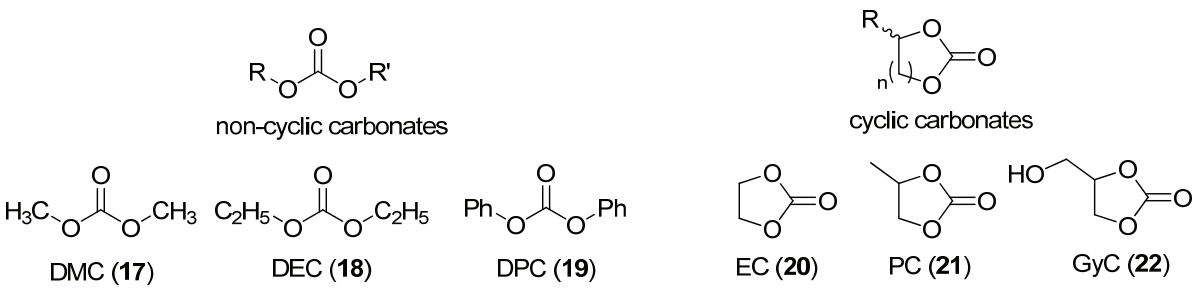
Polyethers like polyethylene glycol (PEG) or polypropylene glycol (PPG) are stable liquid polymers which can be used as solvent if there molecular weight is below 600 – 800 (higher

weights are waxen or solid). They are non-volatile, nearly inflammable and biodegradable. Furthermore, they can be used in mixtures with other solvents like water but they are immiscible with hydrocarbons. They were successfully used by Jessop *et al.* and others for homogeneous catalysis.[50]

2.3 Organic Carbonates

2.3.1 Physical and Chemical Properties

Organic carbonates are diesters of carbonic acid. In contrast to carbonic acid, the esters are stable and can be used as intermediates for synthesis or as polar, aprotic solvent for industrial and academic applications. Organic carbonates belong to oxygenated solvents (Scheme 1) and can be divided in cyclic and non-cyclic carbonates (Scheme 7). Dimethyl carbonate (**17**) is a low boiling solvent and can be used as methylating reagent or as alternative for phosgene.[51]

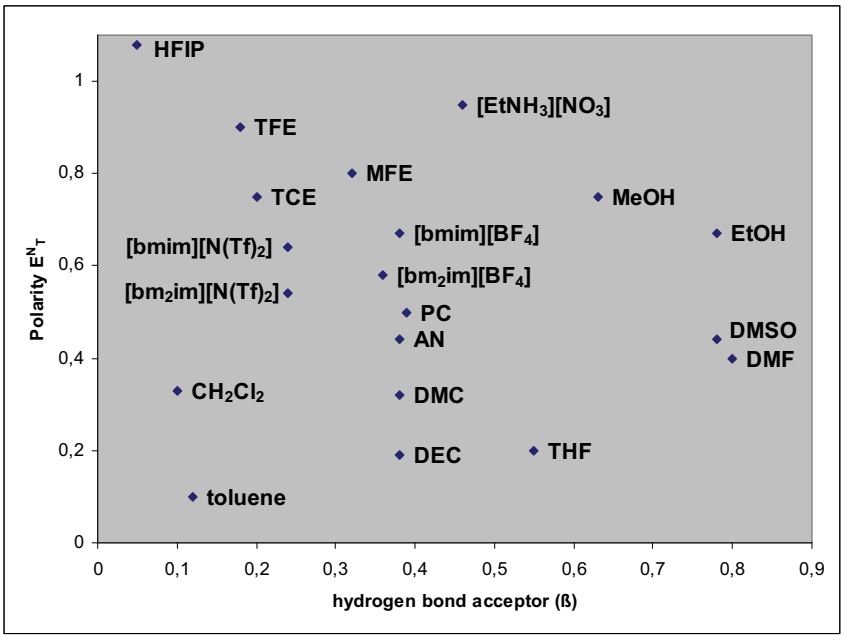


Scheme 7: Organic carbonates for synthesis and as solvents.

On the other side, cyclic carbonates, especially propylene carbonate (PC) own perfect properties to act as green solvents. It is inflammable (flash point: 132 °C), non-toxic (LD_{50} (oral) mouse: 20700 mg / kg), UV-stable, biodegradable, odourless and has a low vapour pressure.[52] Furthermore PC (**21**) shows a broad range in which it is present as liquid (-49 °C – 242 °C), it is moderately viscous (51 cP) and thus can be used as polar solvent for synthesis and catalysis. In contrast to PC ethylene carbonate (EC) is solid at ambient temperature (m.p. 36 °C) and glycerol carbonate is a highly viscous liquid (77 cP) which can be used as protic carbonate solvent or for synthesis. This work discuss only short chain non-cyclic and cyclic carbonates with n = 1. Longer non-cyclic carbonates are used for cosmetic and pharmaceutical applications.[53]

With view to their polarity, organic carbonates belong to the class of aprotic highly dipolar solvents (AHD) like DMSO or DMF.[54] Thus, they are able to form biphasic mixtures with hydrocarbons and other unpolar solvents as well as with water (e.g. propylene carbonate is only partly miscible with water, the miscibility gap is between 30 mol% and 90 mol% of

water).[55] One possibility to compare several different solvents is the determination of the polarity by using solvatochromic dyes.[56] The solvent properties of organic carbonates are rather unique and only met by few other solvents (Scheme 8). Interestingly, the polarity and the hydrogen bond acceptor properties (basicity β) of PC (0.39) match perfectly with those of acetonitrile (AN) (0.38).[57] However, with same basicities the non-cyclic carbonates like DMC and DEC own lower polarities which are more close to methylene chloride and THF.[58]



Scheme 8: Polarities and basicities of selected solvents.

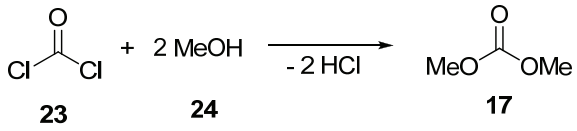
Other properties of organic carbonates are their high dipole moment and the high dielectric constant. Thus, PC has a dipole moment of $\mu = 16.5\ 10^{30}$ Cm and an outstanding dielectric constant of $\varepsilon_r = 64.92$ (for comparison: ε_r (H_2O) = 78.36; ε_r (DMSO) = 46.45). This makes PC especially suitable for non-aqueous, electrochemical applications. In contrast to other presented alternative, so called "green" solvents, organic carbonates are available in large scale (production of approx. 0.8 – 1.0 Mt per year) at low costs. DMC could yield a market volume of 2000 Mt/year if it would be added to gasoline in large scale.[59] The annual DMC production can be estimated to be 0.1 – 0.5 Mt and production of PC yields approx. 0.4 Mt per year.[a]

2.3.2 Synthesis

The synthesis of non-cyclic carbonates is mainly applied by using the highly toxic phosgene (**23**). Especially older plants are using this ecologically-unfriendly method to form DMC in a

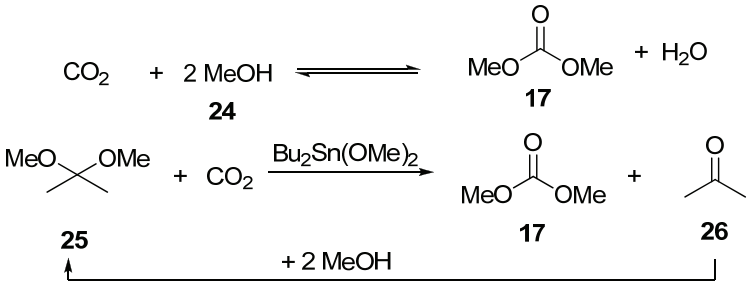
[a] Special thanks to Mr. T. J. Clark from Huntsman who supported us with important information about organic carbonates.

reaction with 2 eq. methanol (**24**) (Scheme 9).[51] Another major drawback in this reaction is the large formation of corrosive HCl, which has to be recycled or trapped as salt.



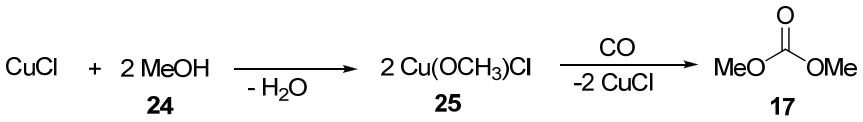
Scheme 9: Synthesis of dimethyl carbonate using phosgene.

However, a direct carbonate formation with alcohols and CO_2 is difficult due to the fact that the reaction's equilibrium is shifted to the side of the starting materials. To overcome this drawback, acetals e.g. **25** in $scCO_2$ can be used in the synthesis of DMC and achieved 88% yield in presence of tin catalysts (Scheme 10). Formed acetone (**26**) can be recycled with 2 eq. methanol to **25**.[60]



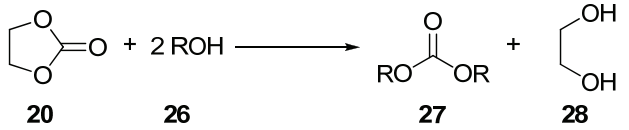
Scheme 10: Reaction to DMC with acetals in $scCO_2$.

An additionally applied method is the selective oxidation of methanol in presence of copper(I)chloride and carbon monoxide (Scheme 11).[61] In contrast to the other used metals mercury and palladium, copper is directly re-oxidized during the reactions.



Scheme 11: Oxidative carbonylation of methanol in presence of copper(I)chloride.

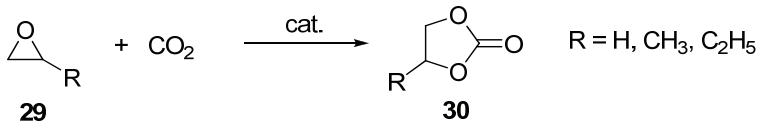
Other possibilities to non-cyclic carbonates are transesterificiations from EC (**20**) with aliphatic or aromatic alcohols **26** (Scheme 12).



Scheme 12: Transesterification of ethylene carbonate.

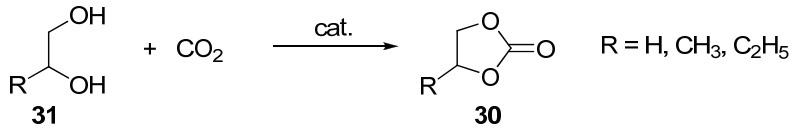
The transesterification is especially used for the synthesis of more specialized carbonates **27** and is also one possibility to obtain polycarbonates via a non-phosgene route.[62] At least, reactions of alcohols with urea can give organic carbonates as well as polyurethanes.[63]

The main route to cyclic carbonates **30** is the addition of CO_2 to the epoxide **29** in presence of a catalyst (Scheme 13). Propylene carbonate can be synthesized directly out of propylene oxide which can be formed in an efficient reaction of propylene and hydrogen peroxide (HPPO process).[64] Several homogeneous and heterogeneous catalysts have been applied in the synthesis of PC (MgO, KI/K_2CO_3, Mg[smectite], KOH/molecular sieves 4Å, etc.).[65]



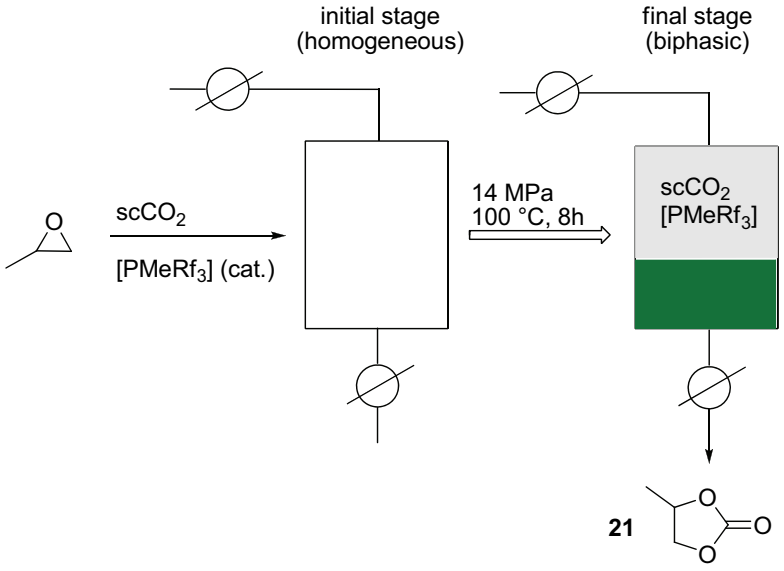
Scheme 13: Selected synthetic pathways to organic carbonates.

Another route, starting directly from the 1,2- diol **31** suffers from the low activity of the diol and produces the corresponding carbonate **30** only in low yield (Scheme 14).[66]



Scheme 14: Synthesis of Cyclic carbonates out of diols.

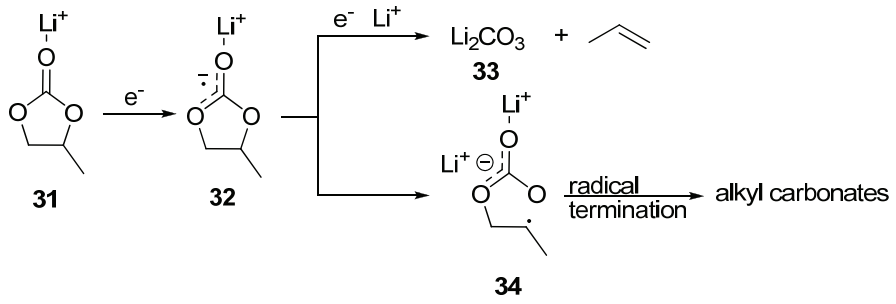
One sophisticated approach is the direct use of $scCO_2$ in the synthesis of PC. If perfluorinated organocatalysts are used, pure PC (**21**) can be obtained in a biphasic reaction with nearly quantitative yield (Scheme 15).[67]



Scheme 15: Synthesis of propylene carbonate under biphasic conditions using $scCO_2$.

2.3.3 Application in Industry and Academia

Organic carbonates have been used since the 1950s in bulk industry and for pharmaceutical and cosmetic applications.[68] Cyclic carbonates (especially PC) are suitable to physically absorb CO_2 and H_2S from natural gas streams at higher pressures without removing hydrocarbons. This ability was used in the FLUOR Process. This process is still used today, in particular for offshore drilling platforms.[69] Since the 1980s it is allowed to add PC to cosmetic products as solvent and surfactant.[70] DMC is discussed as fuel additive in exchange for MTBE or ETBE in diesel and gasoline.[63] Of special interest is the use of cyclic carbonates in Li-batteries.[71] EC and PC own high electronic constants and are able to solve Li-salts. However, in cycling experiments it turned out that EC is superior to PC due to its better cycling abilities and lower Li losses. One advantage of both carbonates is the reaction with the Li electrode. On the surface of electrodes **31** easily forms solid electrolyte interphases (SEI). This layer containing Li carbonate (**33**) has a permeability for Li ions while further reactions of the metal electrode with the electrolyte solution are inhibited and is formed in a single electron reaction from **32** (Scheme 16).[72] Through a radical side reaction **34** and alkyl carbonates were observed. To reduce the viscosity of cyclic carbonates, DMC, DEC or 1,2-dimethoxyethane are added to the electrolyte solutions. Newer approaches are using polymer electrolytes in order to reduce the formation of lithium dentrites in the electrolyte solution, which can lead to explosions under discharging conditions. The polymer electrolytes are also including organic carbonates in the liquid areas of their structures (except for the dry polyethylenoxide electrolyte).[71,72]



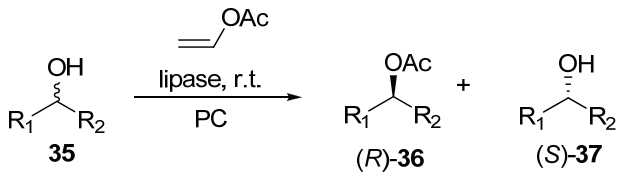
Scheme 16: Reaction of propylene carbonate at lithium surfaces.

A relatively new application on industrial scale is the use of PC in the production of coated copper wire in exchange for cresol by BASF. It turned out, that the use of PC is possible at the same costs and has an environmental impact.[73] The eco-efficiency analysis could help to reduce approx. 5200 t (Germany, 2002) of toxic solvents which are waste in the production of lacquered copper wires.[74] Other applications using organic cyclic carbonates are associated to the synthesis of polyurethanes and their modification during coating processes.[75] Cleaning

agents containing organic carbonates are known to be environmentally and physically safe, pH neutral, non-volatile and inflammable. They can be diluted in water and are able to remove oils, greases, organic adhesives etc.[76] Furthermore, aliphatic carbonates with ether moieties are often used as hydraulic fluids and as lubricants.[77] Due to its broad liquid range and the modest viscosity PC is a perfect carbonate representative for the use in synthesis and catalysis. Initially it was used for analytic measurements of iron complexes.[78] The principles were later expanded on the polarographic determination of tallium(III), cadmium(II), indium(III) and antimony (III) salts using gas-stirred solvent extractions.[79] In contrast to other solvents, Ross *et al.* found strong evidences that an ionic mechanism is involved in the reaction of *N*-bromosuccinimide with toluene, fluorine and acenaphthene in PC.[80]

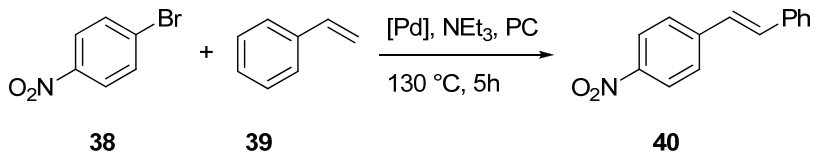
2.3.4 Carbonates as Solvents in Catalysis

Xia and co-workers could show for the first time that it is possible to accomplish lipase-catalyzed kinetic resolutions of **35** in PC (Scheme 12).[81] They obtained (*R*)**-36** and (*S*)**-37** in enantioselectivities of up to 99% and could recycle their enzymes 4 times without losing selectivity.



Scheme 17: Lipase-catalyzed kinetic resolution in propylene carbonate using vinyl acetate.

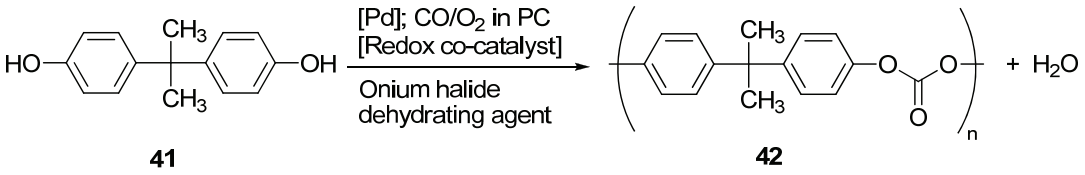
Heterogeneous catalysis and the use of nanoclusters were also accomplished in PC. It is possible to stabilize transition metal systems as weak coordination solvent. Reetz *et al*. used PC to stabilize Pd-clusters and to perform Heck reactions in this solution.[82] Reactions of the palladium nanoclusters in PC with nitrophenyl bromide (**38**) and styrene (**39**) achieved the Heck-product **40** with 96% yield in presence of NEt_3 (Scheme 18).



Scheme 18: Heck-reaction with propylene carbonate stabilized Pd-nanoclusters.

Similar results for Pd-colloids were obtained by Behr and Schmidke in a selective hydrogenation of diolefins to olefins, where Pd-colloids were stabilized by PC.[83] Furthermore, Poizot and co-workers were successful in the electrochemical homocoupling of

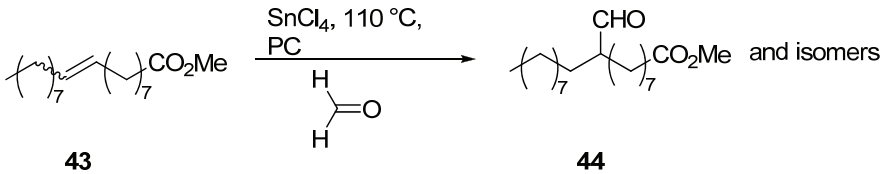
aryl iodides at silver electrodes.[84] Of great importance in this reaction is the large dielectric constant of PC (ε_r = 65.1). Other reactions like the PtL_2Cl_2-catalyzed electrochemical hydroformylations performed by the group of Mortreux in the 1980s.[85] The heterogeneous Pt-catalyzed hydrogenation of ethyl pyruvate achieved 45% *ee* if a chiral cinchonidine was used.[86] Homogeneous catalysis in organic carbonates especially uses Pd, Ru, Rh and Ir catalysts. A sophisticated, phosgene-free process is the Pd-catalyzed oxidative carbonylation of bisphenol A (**41**) to obtain polycarbonate **42** (Scheme 19).[87] As ligands for the homogeneous Pd-catalysts 2,2'-bipyridines or 2,2'-bithienyl structures were used. The use of methylene chloride, a traditional solvent for this reaction, was avoided in order to increase the environmental impact of this reaction.



41 42

Scheme 19: Palladium-catalyzed oxidative carbonylation in the synthesis of polycarbonates.

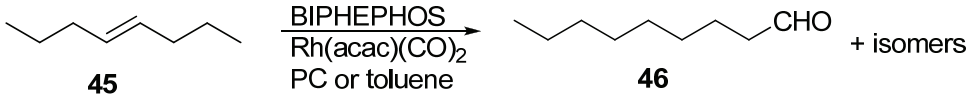
As mentioned above, all cyclic carbonates own high polarities, which is important to form biphasic mixtures with unpolar compounds like hydrocarbons or fatty acids and aldehydes. Behr *et al*. used PC as solvent in the reaction of formaldehyde with unsaturated fatty acid esters **43** in presence of $SnCl_4$ and other Lewis acids as catalyst (Scheme 20).[88] The use of PC reduced the sublimation of *para*-formaldehyde significantly and increased yield from 52% with 1,4-dioxane to 74% with PC. As products **44**, isomers and several by-products were obtained.



43 44

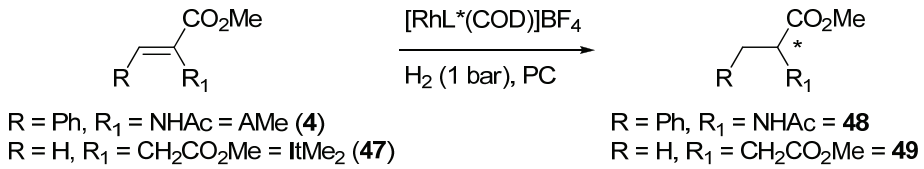
Scheme 20: Tin-catalyzed reaction of formaldehyde with fatty acids.

Remarkable results were obtained by Behr and co-workers in the Rh-catalyzed isomerising hydroformylation of *trans*-4-octene (**45**) in propylene carbonate (Scheme 21).[89] **45** was converted with 94% with 95% selectivity for *n*-nonanal (**46**). In contrast to these results the selectivity dropped significantly if toluene was used as solvent. This difference was explained with the different solubility of **45** in the two solvents. The same working group published in 2002 the Pt-catalyzed hydrosilylation of unsaturated fatty acid esters in PC.[90]



Scheme 21: Rhodium-catalyzed isomerizing hydroformylation of *trans*-4-octene.

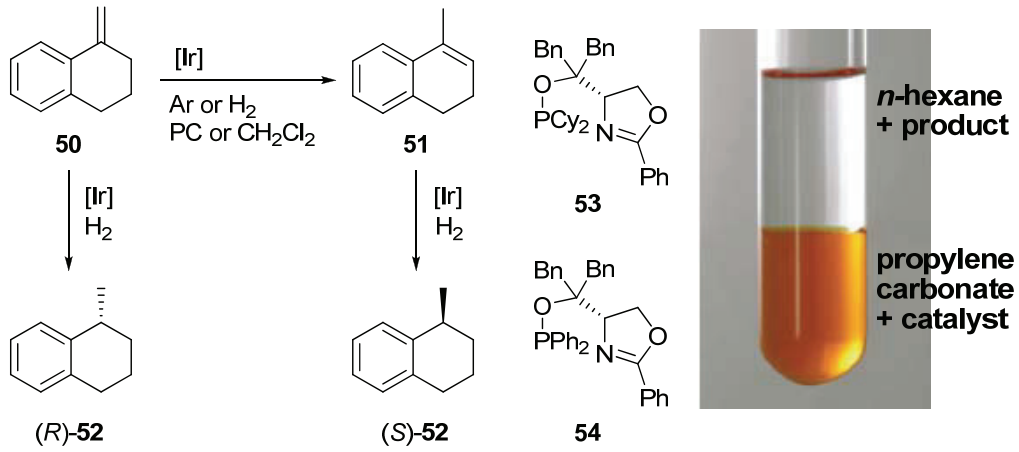
However, the homogeneous catalyzed hydrogenations were rarely investigated. Preliminary kinetic investigations were accomplished by Preetz *et al.* in comparison to standard organic solvents like tetrahydrofuran, methylene chloride and methanol.[32] The application of PC in asymmetric hydrogenations was given by Börner and co-workers. The rhodium-catalyzed hydrogenation of benchmark substrates proceeded fast with high enantioselectivities (Scheme 22).[91]



Scheme 22: Asymmetric hydrogenation of benchmark substrates in propylene carbonate.

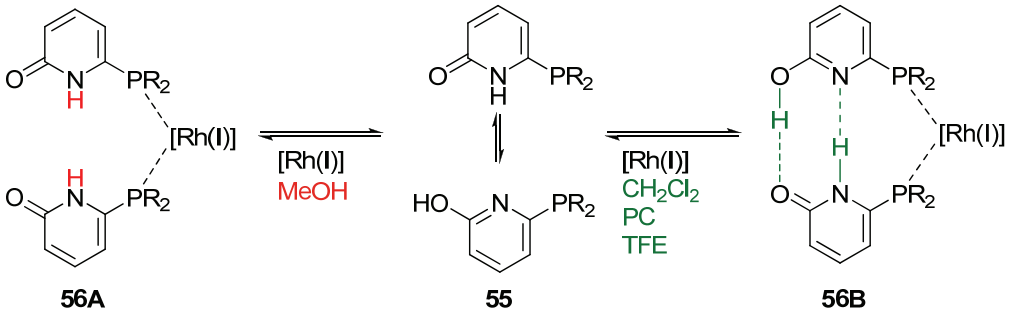
Furthermore, the advantage of a biphasic workup was shown in an isomerisation / hydrogenation network approach. Methylene-1,2,3,4-tetrahydronaphthalene (**50**) isomerizes quickly to **51** in standard hydrogenation solvents like methylene chloride (Scheme 23). Nevertheless, the isomerisation was slowed down in PC and resulted in higher enantioselectivities due to the favoured formation of (*R*)-**52** instead of (*S*)-**52**. In contrast to methylene chloride where the highest *ee* was 26% of (*S*)-**52** with ligand **53** and 17% of (*R*)-**52** with ligand **54** the enantioselectivity changed in PC to 8% (*R*)-**52** with **53** and 82% (*S*)-**52** with **54**. Best results were obtained at hydrogen pressures of 50 and 100 bar. Finally, recycling experiments, using *n*-hexane for extraction of the product showed could be accomplished for 6 cycles without losing reactivity or stereoselectivity.

Subsequently, it was necessary to estimate the overall hydrogenation ability of apolar highly dipolar (AHD) solvents. DMSO and DMF were chosen as other representatives of this solvent class for comparison.[92] Schäffner *et al.* could show that only dimethyl formamide (DMF) can compete with PC and butylene carbonate (BC). For this experiment, well known benchmark substrates were used as shown in Scheme 22. Interestingly, in some cases an improvement in enantioselectivity could be achieved if BC was used instead of PC.



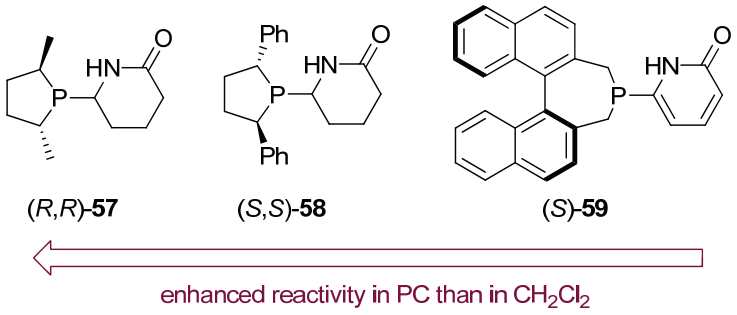
Scheme 23: Hydrogenation of unpolar substrates and workup in propylene carbonate.

Next to the use of solvatochromic dyes, the use of self-assembling ligands (**55**) is a good method to investigate the character of a solvent. The formation of *pseudo*-bidentate ligand (**56B**), as shown in Scheme 24, is only possible in aprotic solvents with low hydrogen acceptor properties (β) (Scheme 8).[93] Unfortunately, the high selectivity of self-assembling ligands was combined with low catalytic activities if they are used with benchmark substrates like **4** and **47** (Scheme 22). High reactivities but low *ee*'s were only achieved with **56A** in the protic solvent methanol. Nevertheless, it could be shown by the group of Börner, that hydrogenations in propylene carbonate combine the high enantioselectivity of aprotic solvents with the increased reactivity of the rhodium complex in methanol.[94]



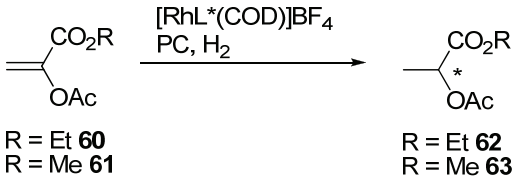
Scheme 24: Mechanism of self-assembling within rhodium-catalyzed hydrogenations.

Especially with small phospholane ligands like the 2,5-dimethyl **57** and the 2,5-diphenyl derivatives **58** high conversion rates were achieved (Scheme 25). The phosphepine **59** showed no enhanced activity in PC. Nevertheless, the ligand was also very active in methylene chloride. At least a rhodium-catalyzed hydrogenation of unsaturated lactate acid precursors **60** and **61** achieved excellent enantioselectivities (higher 99%) in propylene carbonate (Scheme 26).[58] Most suitable were the above describe ligands of the Cat*AS*ium and DuPHOS families. They achieved enantioselectivities higher than 99% within short reaction times.



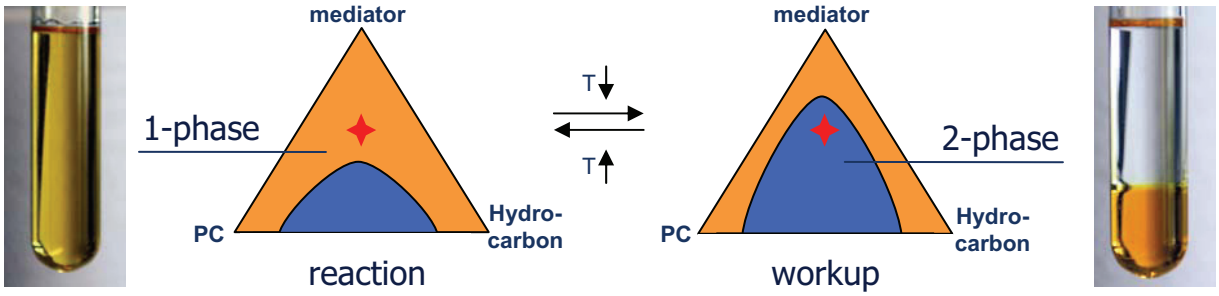
Scheme 25: Reactivity of self-assembling ligands in rhodium-catalyzed hydrogenations.

The obtained products own adequate boiling points (176 – 181 °C) to distillate them directly out of the reaction mixture (b.p.(PC) = 242 °C) without further workup. Under industrial-valuable conditions (90 °C and 8 – 10 mbar vacuum) the pure product **62** or **63** were obtained in distillations using a slit tube column in 77% for **62** and 86% for **63**. It was the first direct distillation out of PC.



Scheme 26: Rhodium-catalyzed hydrogenation of lactate precursors in propylene carbonate.

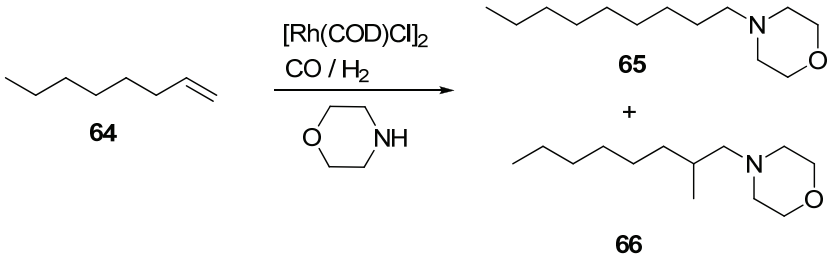
Another method for product-separation was developed by Behr *et al.* with the temperature-dependent-multicomponent-solvent (TMS) systems.[95] It is based on the miscibility gap between two solvents at ambient temperature. By adding a third compound (mediator or solubilizer) to the mixture the gap is repressed at elevated temperature (Scheme 27).



Scheme 27: TMS system at elevated and ambient temperature.

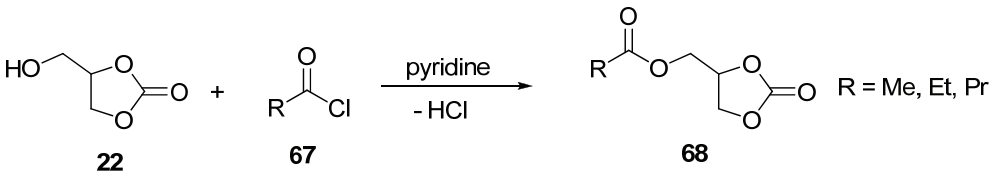
The red star symbolizes the operation point of the ternary mixture. At r.t. the mixture is biphasic (grey area) but becomes homogeneous (green area) if the temperature is elevated. Various compounds can be applied as mediator if their polarity is between the two solvents. Most convenient is the use of the starting material as solubilizer. Since its concentration is reduced during the reaction, the homogeneous mixture may become biphasic by the time all

starting material has been converted. Other usable mediators are THF, anisole, dioxane, toluene, *N*-methyl-2- pyrrolidone or *N*-octyl-2-pyrrolidone. The principle of TMS systems (*p*-xylene, PC, dodecane) was used in the reaction shown in Scheme 28. The best results were obtained at an operating point of 22.5 wt.% PC, 19.5 wt.% dodecane and 58 wt.% *p*-xylene.[96] Very low catalyst leaking was observed in case of the Rh-catalyzed hydroaminomethylation (Scheme 17).[97] A perfect ternary mixture for this reaction was PC / *n*-hexane / dioxane = 1 / 0.55 / 1.3. In this case **64** was converted to **65** and **66** with a selectivity of 96% and with a ratio of **65** / **66** of 1.4 / 1.



Scheme 28: Rh-catalyzed hydroaminomethylation of 1-octene.

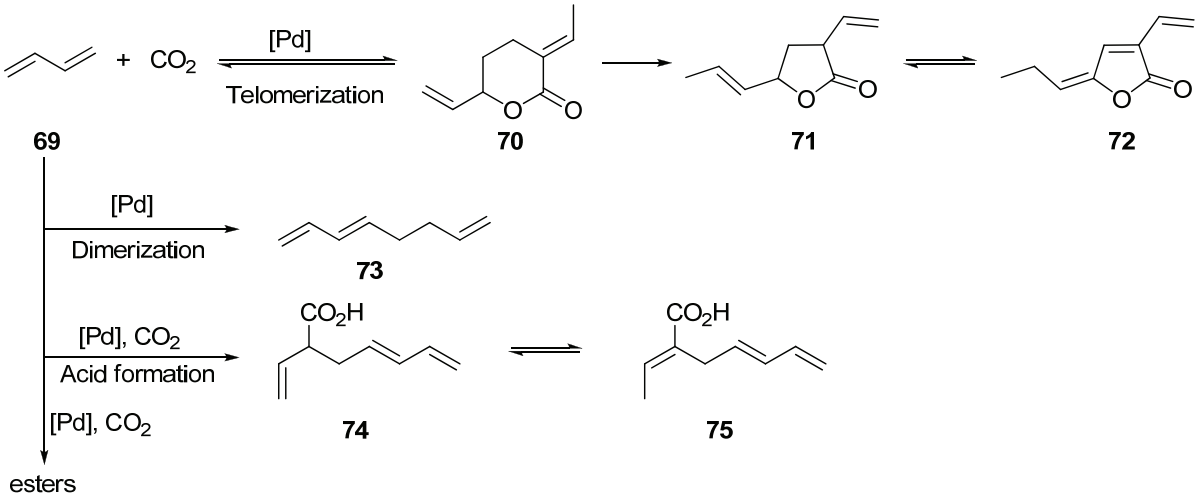
High boiling carbonates **68** are useful solvents under fine vacuum conditions at enhanced temperature. They are available by reacting glycerol carbonate (**22**) with carboxylic acid chlorides **67** (Scheme 29).[98] Like glycerol the carbonates **68** are very viscous at r.t.



Scheme 29: Synthesis of high boiling carbonates from glycerol carbonate.

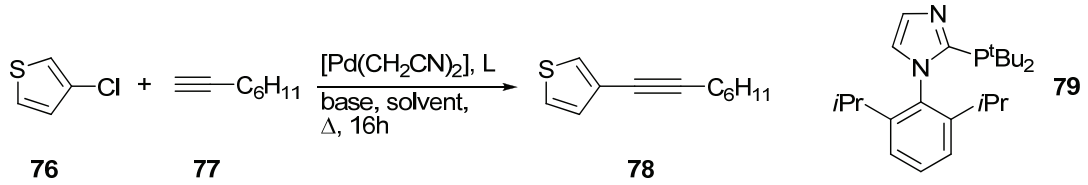
They were applied in the telomerization of butadiene with carbon dioxide to form δ-lactones which are valuable intermediates for a large variety of reactions (Scheme 30).[97,99] The reaction control is difficult due to several side-reactions: dimerization to octa-1,3,7-triene (**73**), acid formations (**74** and **75**) and the formation of several esters. In presence of palladium catalysts bearing nitrile groups, the reaction can be shifted to the desired δ-lactones **70**, **71** and **72**.[100] In organic cyclic carbonates like ethylene, propylene and butylene carbonate the δ-lactones were achieved in good yields and selectivities (in BC with selectivities up to 70%). However, the boiling points of these carbonates are too low for using them in a continuous procedure. Thus, glycerol carbonate esters **68** became attractive. Unfortunately, glycerol carbonate butyrate (**68** with R = Pr) achieved only a conversion of 46% and yielded the δ-

lactones in 23% with a selectivity of 49%. Yet, the use of high boiling carbonates could be attractive in a semi-technical scale, where δ-lactones can be removed by distillation.



Scheme 30: Telomerization of butadiene with carbon dioxide in organic carbonates.

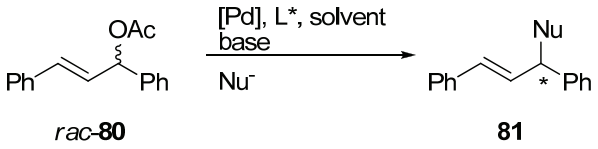
Since it is known that the chemico-physical properties of propylene carbonate are similar to those of acetonitrile (AN), this toxic solvent has been successfully substituted in the copper-free Sonogashira reaction (Scheme 31).[101] Ligand **79**, which was originally synthesized for Pd-catalyzed hydroxylation reactions[102] achieved the unpolar coupling product **78** in PC with yields up to 76%. The subsequently workup could succeed with two methods: subsequent extraction with hydrocarbons or the use of a TMS system.



Scheme 31: Copper-free Sonogashira reaction using propylene carbonate.

Moreover, asymmetric palladium-catalyzed reactions like the asymmetric allylic alkylation (Chapter 2.2.2) can be accomplished in organic carbonates. Next to propylene and butylene carbonate, aliphatic carbonates like diethyl carbonate (Scheme 7, **17**) can be used for palladium-catalyzed reactions. Due to their lower polarities, dialkyl carbonates are not suitable for rhodium-catalyzed reactions like hydrogenations (many catalysts are only partly soluble in non-cyclic carbonates). Schäffner *et al.* used several chiral ligands which gave the chiral product **81** in a reaction of *rac*-**80** with a nucleophile with enantioselectivities up to 93%.[103] Although it is possible to use enantiopure propylene carbonate instead of racemic for the reaction, no influence on enantioselectivity was observed. While a similar hydrogenation

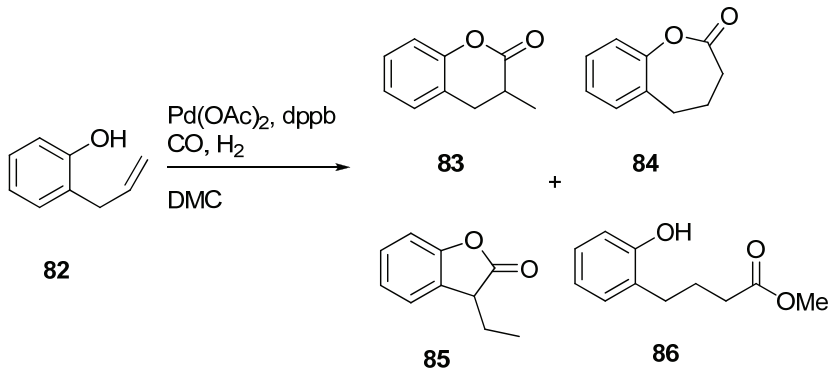
approach to the results of Leitner and co-workers with enantiopure PC was not successful. Thus, it can be supposed that in contrast to chiral ILs chiral organic carbonates are not interacting strong enough with the catalyst to have influence on the enantioselectivity.[104]



rac-**80** **81**

Scheme 31: Asymmetric allylic alkylations in various organic carbonates.

As another non-cyclic representative, dimethyl carbonate (DMC) is also a usable solvent for catalysis. Bernini *et al.* observed high conversion rates for the Re-catalyzed oxidation with hydrogen peroxide.[105] A similar approach with RuO_4 and $NaIO_4$ as oxidant was given by Dragojlovic and co-workers.[106] Vasapollo *et al.* demonstrated a Pd-catalyzed cyclocarbonylation approach in DMC (Scheme 32). Allylphenols like **82** were converted to a mixture of lactones (**83**, **84**, **85**).[107] Under normal conditions (100 °C, 24h) the oxepinone **84** is preferred in this reaction. At longer reaction times or higher temperatures (120 °C, 48h) reaction of **82** in DMC gives **86**.



82 **83** **84** **85** **86**

Scheme 32: Pd-catalyzed cyclocarbonylation using DMC as solvent.

Finally, in the Ru-catalyzed ring closure metathesis (RCM) and cross metathesis similar results were obtained in methylene chloride and in DMC.[108] A recycling-process using the separation via nanofiltration was given by Rabiller-Baudry *et al.*.[109] An enlarged Hoveyda II type catalyst was recycled four times for reuse in RCM of diallyltosylamide.

2.4 Conclusions

Organic Carbonates have become a part of modern chemistry and play an important role on the way to more sustainable methods and synthesis. Despite their known low toxicity the syntheses of carbonates using phosgene and propylene oxide are still major drawbacks and in strong contrast to the rules of Green Chemistry. However, with their "green" properties and known toxicological data, organic carbonates can match with other alternative solvents like ionic liquids, polyethers and fluorinated solvents. Low boiling non-cyclic carbonates are useful intermediates in syntheses and solvents for Pd- and Ru-catalyzed reactions like metathesis and cyclocarbonylations. On the other hand, the high-boiling cyclic carbonates are used in electrochemistry as well as specialized solvents for catalysis. The results of Behr and co-workers nicely show the usefulness of this solvent class. However, expanding the scope of reactions in which organic carbonates may be used would help to determine chances and limitations of these "green" solvents. Furthermore, only little attention was paid to the highly important homogeneous hydrogenation with transition metal catalysts. The results presented by Preetz *et al.* clearly indicated the value of cyclic carbonates in this reaction. With their polar character it should be possible to retain the catalyst in the organic carbonate phase while removing the product. Further studies in this field can be based on the experience of other liquid-liquid separation methods (e.g. ionic liquids / $scCO_2$). New investigations are necessary to overcome current separation limitations by using high-boiling cyclic carbonates. An exchange of a volatile organic solvent by organic carbonates is only useful if there is a subsequent separation method for the product after the reaction. Such a method could decrease catalyst and solvent losses which is especially necessary for pharmaceutical and cosmetic applications. In conclusion, organic carbonates are another alternative solvent class, which can have an ecological and economic impact on several reactions.

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3 Objectives of this Work

Although, some catalytic applications were successfully developed in organic carbonates, there is still a high demand for the evaluation of their chances and limitations in catalysis and synthesis. To guarantee further systematic work on this field it is necessary to introduce the full set of physical properties. Based on former results we turned our attention on the determination of vapour pressures of aliphatic dialkyl carbonates. In *J. Chem. Thermodynamics* a full set of data was presented for dialkyl non-cyclic carbonates. (Publication 6.1, **2008**). In *Fluid Phase Equilibria* the same experiments were accomplished for ethylene, propylene, butylene and glycerol carbonates. A major point is the use of the transpiration method for measurement of the vapour pressures to complete the data down to ambient temperature. This is of special interest for environmental chemistry due to the fact that former results were obtained at elevated temperature or at the boiling point (Publication 6.2, **2008**). Subsequently, the standard molar enthalpies of formation were determined using combustion calorimetry. Additional results of *ab initio* calculations of molar enthalpies of formation were applied with the G3MP2 method for the cyclic alkylene carbonates and are presented in *J. Chem. Thermodynamics* (Publication 6.3, **2008**). Since organic carbonates belong to the group of aprotic highly dipolar solvents it is necessary to compare their behavior in catalysis with other solvents of this class. Dimethyl sulfoxide and dimethyl formamide were chosen for a study in Rh-catalyzed hydrogenations with standard benchmark substrates of the group of α-amino acid precursors. Furthermore, acetonitrile which is not a member of the aprotic highly dipolar solvent class was chosen for this study because it owns similar polarity and basicity to propylene carbonate. The results presented in *Chirality* indicate that only DMF behaves similar to organic carbonates (Publication 6.4, **2009**). The publication in *Angew. Chem.* was addressed to the difficulties in the separation process of products out of organic carbonates. During Ir-catalyzed hydrogenations of 1-methylene-1,2,3,4-tetrahydronaphthalene in PC the isomerization as competitive reaction was suppressed. Additionally, a complete catalyst recycling was presented using hydrocarbons to extract the product (Publication 6.5, **2007**). High reactivities could be achieved in Rh-catalyzed hydrogenations using self-assembling ligands as shown in *Tetrahedron Lett.* The behavior of self-assembling ligands in catalysis strongly depends on the used solvent. In propylene carbonate Rh-catalysts containing self-assembling moieties observed enantioselectivities similar to methylene chloride within the reaction-times of methanol (Publication 6.6, **2008**). We developed the first destillative separation method for products from propylene carbonate. Enol acetates were transferred into the corresponding lactic acid esters in Rh-catalyzed

hydrogenations with >99% *ee*. Subsequent destillative workup gave the pure lactic acid esters in excellent yields without the use of other solvents (Publication 6.7, **2008**, *ChemSusChem*). We developed the use of propylene, butylene and diethyl carbonate in Pd-catalyzed allylic substitution reactions. Furthermore enantiopure propylene carbonate was used to investigate the influence of enantiopure solvents on this reaction (Publication 6.8, **2008**). A new P*-chiral bisdiamidophosphite ligand with a mannite backbone could be also applied in Rh-catalyzed hydrogenations as well as in Pd-catalyzed allylic substitutions in organic carbonates (Publication 6.9, **2008**). At least, the Pd-catalyzed copper-free Sonogashira reaction was successfully applied in propylene carbonate and toluene. Aryl chlorides were converted with alkynes to aryl alkynes. The traditional reaction is carried out in acetonitrile, however it was not successful in this solvent in case of [*N*-(2,6-diisopropylphenyl)-2-imidazolyl]-di-*tert*-butylphosphine as ligand (Publication 6.10, **2009**).

4 Publications

4.1 Vapour pressure and enthalpy of vaporization of aliphatic dialkyl carbonates

Svetlana A. Kozlova, Vladimir N. Emel'yanenko, Miglena Georgieva, Sergey P. Verevkin*, Yury Chernyak, Benjamin Schäffner, Armin Börner, *J. Chem. Thermodynamics* **2008**, *40*, 1136-1140.

Contributions

My contribution as co-author to this paper accounts 10%. I was involved in discussion of the results as well as in planning further experiments and contributed to the draft of the manuscript.

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Vapour pressure and enthalpy of vaporization of aliphatic dialkyl carbonates

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Abstract

Molar enthalpies of vaporization of aliphatic alkyl carbonates: dimethyl carbonate [616-38-6], diethyl carbonate [105-58-8], di-*n*-propyl carbonate [623-96-1], di-*n*-butyl carbonate [542-52-9], and dibenzyl carbonate [3459-92-5] were obtained from the temperature dependence of the vapour pressure measured by the transpiration method. A large number of the primary experimental results on temperature dependences of vapour pressures have been collected from the literature and have been treated uniformly in order to derive vaporization enthalpies of dialkyl carbonates at the reference temperature 298.15 K. An internal consistency check was performed on enthalpy of vaporization values for dialkyl carbonates studied in this work.

Keywords: Vapour pressure; Enthalpy of vaporization; Transpiration method; Carbonates

1. Introduction

Dialkyl carbonates are known as outstanding dipolar aprotic solvents widely utilized in electrochemical applications and extraction processes. Their excellent solvency, high flash and boiling temperatures, low toxicity, and evaporation rates make them attractive choices in many solvent applications. Dialkyl carbonates are biodegradable, noncorrosive, and relatively odourless materials, as well as being readily available from several solvent manufacturers. They are "safe" and environmentally friendly solvent alternatives to traditional products such as methylene chloride, aromatic solvents, and other high volatile and hazardous industrial solvents. In our recent work, we have identified advantages of propylene carbonate in asymmetric hydrogenation [1], and also for palladium-catalyzed substitution reactions [2].

Alkyl carbonates are high boiling liquids. Precise measurement of the vapour pressure of low-volatile compounds at ambient temperature is usually difficult, that is why the most of published data are referred to elevated temperatures close to the boiling point [3]. The transpiration method [4] used in this work provided a capability for the measurement of new vapour pressure data for dialkyl carbonates near ambient temperatures, where the data are especially relevant for the assessment of their fate and behaviour in the environment.

2. Experimental section

2.1. Materials

The liquid samples of dialkyl carbonates of 0.99 mass-fraction purity were obtained from Aldrich and Fluka and further purified by repetitive distillation in vacuum.

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Gas chromatography (GC) showed no traceable amounts of impurities in dialkyl carbonate samples after they were purified. The products were analyzed with a Hewlett-Packard gas chromatograph 5890 Series II with a flame ionization detector and Hewlett-Packard 3390A integrator. The dimensions of the capillary column HP-5 (stationary phase cross linked 5% PH ME silicone) were the following: the column length, inside diameter, and film thickness were 25 m, 0.32 mm, and 0.25 μm, respectively. The flow rate of a carrier gas (nitrogen) was 12.1 $cm^3 \cdot s^{-1}$. The starting point for the GC temperature programme was $T = 323$ K with a heating rate of 0.167 $K \cdot s^{-1}$ up until reaching 523 K temperature.

2.2. Vapour pressure measurements of alkyl carbonates

Vapour pressures of dialkyl carbonates were determined using the method of transpiration [4] in a saturated nitrogen stream. About 0.5 g of the sample was mixed with glass beads and placed in a thermostatted U-shaped tube having a length of 20 cm and a diameter of 0.5 cm. Glass beads with a diameter of the glass spheres of 1 mm provide a surface area large enough for rapid (vapour + liquid) equilibration. At constant temperature (±0.1 K), a nitrogen stream was passed through the U-tube and the transported amount of gaseous material was collected in a cooling trap. The flow rate of the nitrogen stream was measured using a soap bubble flow meter and was optimized in order to reach the saturation equilibrium of the transporting gas at each temperature under study. The amount of condensed substance was determined by GC analysis using an external standard (hydrocarbon n-C_nH_{2n+2}). The saturation vapour pressure p_i^{sat} at each temperature T_i was calculated from the amount of the product collected within a definite period of time. Assuming that Dalton's law of partial pressures applied to the nitrogen stream saturated with the substance i of interest is valid, values of p_i^{sat} were calculated with equation:

$$p_i^{sat} = m_i \cdot R \cdot T_a / V \cdot M_i; \quad V = V_{N_2} + V_i; \quad (V_{N_2} \gg V_i), \qquad (1)$$

where $R = 8.314472\ J \cdot K^{-1} \cdot mol^{-1}$; m_i is the mass of the transported compound, M_i is the molar mass of the compound, and V_i; its volume contribution to the gaseous phase. The V_{N_2} is the volume of the carrier gas and T_a is the temperature of the soap bubble meter. The volume of the carrier gas V_{N_2} was determined from the flow rate and the time measurement.

3. Results and discussion

3.1. Vapour pressure and vaporization enthalpies

Vapour pressures of alkyl carbonates measured in this work and enthalpies of vaporization (table 1) were treated with equations (2) and (3), respectively

TABLE 1
Experimental vapour pressures and enthalpy of vaporization of dialkyl carbonates measured by the transpiration method

T^a/K	m^b/ mg	$V_{N_2}{}^c$/ dm^3	N_2 flow/ ($dm^3 \cdot h^{-1}$)	p^d/Pa	($p_{exp} - p_{calc}$)/ Pa	$\Delta_l^g H_m$/ ($kJ \cdot mol^{-1}$)
Dimethyl carbonate; $\Delta_l^g H_m\ (298.15K) = (38.02 \pm 0.19)/(kJ \cdot mol^{-1})$						
$ln(p/Pa) = \frac{255.1}{R} - \frac{53945.8}{(R \cdot T/K)} - \frac{53.4}{R} ln\left(\frac{T/K}{298.15}\right)$						
274.2	34.62	0.514	2.06	1918.4	6.6	39.31
275.0	35.81	0.514	2.06	1981.3	−35.1	39.26
276.0	38.87	0.514	2.06	2143.5	4.4	39.21
276.9	41.42	0.514	2.06	2277.1	15.8	39.16
277.9	44.50	0.514	2.06	2433.8	29.9	39.11
280.7	52.48	0.514	2.06	2844.4	−9.3	38.96
283.2	28.74	0.244	0.98	3273.5	−32.5	38.82
285.8	33.93	0.244	0.98	3846.4	17.4	38.69
288.2	39.14	0.244	0.98	4424.4	40.1	38.56
290.8	43.67	0.242	0.97	4978.5	−83.1	38.42
293.1	50.14	0.242	0.97	5709.8	−23.1	38.30
295.7	59.28	0.242	0.97	6716.6	118.3	38.16
298.3	66.91	0.242	0.97	7570.4	18.3	38.02
300.7	75.64	0.242	0.97	8550.7	17.5	37.89
303.2	84.79	0.242	0.97	9675.8	9.0	37.75
304.1	87.56	0.242	0.97	9982.9	−97.0	37.71
Diethyl carbonate; $\Delta_l^g H_m\ (298.15K) = (44.35 \pm 0.22)/(kJ \cdot mol^{-1})$						
$ln(p/Pa) = \frac{276.3}{R} - \frac{64238.2}{(R \cdot T/K)} - \frac{66.7}{R} ln\left(\frac{T/K}{298.15}\right)$						
273.1	7.953	0.592	2.37	287.6	6.7	46.03
273.3	18.514	1.374	5.50	288.3	3.2	46.01
274.0	8.420	0.592	2.37	304.3	2.9	45.96
274.0	19.863	1.374	5.50	307.7	7.5	45.97
275.0	21.299	1.374	5.50	328.9	5.8	45.90
276.2	22.864	1.374	5.50	352.5	0.0	45.82
276.5	10.240	0.604	2.37	361.9	1.7	45.80
277.1	24.512	1.374	5.50	377.1	1.0	45.76
278.1	11.499	0.592	2.37	412.2	8.3	45.69
278.2	13.506	0.706	2.81	406.5	−0.3	45.69
282.4	17.560	0.660	2.64	558.3	13.0	45.41
283.1	16.215	0.592	2.37	579.3	5.4	45.36
283.3	18.922	0.706	2.81	558.7	−21.1	45.35
285.0	17.716	0.592	2.37	632.1	−20.4	45.23
286.8	24.696	0.664	2.66	776.9	41.5	45.11
288.2	24.013	0.629	2.22	790.7	−12.7	45.02
288.3	23.394	0.592	2.37	825.8	15.5	45.01
288.4	26.338	0.702	2.81	784.1	−29.9	45.01
291.8	32.551	0.669	2.66	1016.6	4.1	44.78
293.0	28.610	0.557	2.22	1051.2	−40.8	44.70
293.1	31.329	0.628	2.49	1041.6	−57.2	44.69
293.1	27.954	0.555	2.22	1033.0	−65.8	44.69
293.1	27.954	0.555	2.22	1037.9	−60.9	44.69
293.2	37.542	0.725	2.81	1078.0	−27.7	44.69
293.3	12.194	0.241	0.96	1064.2	−52.0	44.68
296.8	46.132	0.664	2.66	1447.4	67.1	44.44
298.0	44.372	0.624	2.49	1485.1	1.0	44.36
298.1	45.614	0.633	2.53	1516.3	23.3	44.36
298.1	17.453	0.251	1.00	1454.8	−42.7	44.35
298.2	18.168	0.249	0.96	1535.6	33.5	44.35
301.8	22.700	0.248	0.99	1907.1	48.8	44.11
303.0	24.276	0.251	1.00	2010.2	18.0	44.03
303.1	27.341	0.284	1.02	2021.1	17.3	44.02
303.1	24.670	0.251	1.01	2056.5	52.7	44.02
303.3	22.812	0.241	0.96	1988.0	−39.0	44.01
306.8	29.196	0.248	0.99	2453.2	−19.2	43.78
307.8	32.479	0.251	1.00	2688.5	67.1	43.71
308.2	30.486	0.242	0.96	2635.6	−37.1	43.68
308.2	32.644	0.256	1.02	2688.9	16.2	43.68

(*continued on next page*)

TABLE 1 (*continued*)

T^a/K	m^b/ mg	$V_{N_2}{}^c$/ dm^3	N_2 flow/ ($dm^3 \cdot h^{-1}$)	p^d/Pa	($p_{exp} - p_{calc}$)/ Pa	$\Delta_l^g H_m$/ ($kJ \cdot mol^{-1}$)
308.2	32.003	0.251	1.01	2668.6	−11.5	43.68
310.9	37.405	0.253	0.99	3073.9	−24.5	43.50
313.3	41.378	0.238	0.95	3654.4	130.4	43.34
315.0	45.629	0.241	0.96	3963.3	108.5	43.23
315.2	48.077	0.256	1.02	3948.5	53.1	43.22
Dipropyl carbonate; $\Delta_l^g H_m\ (298.15K) = (53.22 \pm 0.29)/(kJ \cdot mol^{-1})$ $ln(p/Pa) = \frac{307.8}{R} - \frac{78529.7}{(R \cdot T/K)} - \frac{84.9}{R} ln\left(\frac{T/K}{298.15}\right)$						
273.9	2.45	1.465	5.86	29.55	−0.47	55.28
274.6	2.52	1.461	5.85	28.97	−2.82	55.22
275.7	2.87	1.465	5.86	34.25	−0.75	55.13
276.3	3.09	1.465	5.86	36.88	0.00	55.08
278.3	3.21	1.237	4.95	44.84	1.03	54.91
280.0	4.48	1.465	5.86	52.91	2.32	54.76
281.7	5.05	1.495	5.98	58.59	0.29	54.62
283.2	5.83	1.465	5.86	68.51	2.28	54.49
283.4	5.01	1.237	4.95	69.71	2.67	54.47
285.3	6.98	1.465	5.86	81.82	3.63	54.31
288.2	3.04	0.524	2.10	99.15	0.36	54.06
290.1	1.75	0.270	1.08	109.59	−4.90	53.90
293.3	4.81	0.549	2.20	149.04	3.57	53.63
295.3	2.68	0.270	1.08	165.68	−3.12	53.46
298.3	3.46	0.279	1.11	210.59	0.55	53.21
300.7	4.01	0.270	1.08	248.38	−0.81	53.00
303.3	4.95	0.279	1.11	300.39	1.63	52.78
305.7	5.70	0.270	1.08	353.37	0.15	52.58
308.3	6.95	0.279	1.11	421.35	2.36	52.36
312.0	8.57	0.270	1.08	530.76	−2.72	52.05
313.1	9.26	0.279	1.11	559.40	−14.85	51.95
314.1	10.19	0.283	1.13	608.20	−3.68	51.86
315.5	11.16	0.283	1.13	666.11	0.01	51.75
318.2	13.08	0.279	1.11	789.77	2.54	51.52
Dibutyl carbonate; $\Delta_l^g H_m(298.15K) = (62.88 \pm 0.38)/(kJ \cdot mol^{-1})$ $ln(p/Pa) = \frac{338.6}{R} - \frac{93140.6}{(R \cdot T/K)} - \frac{101.5}{R} ln\left(\frac{T/K}{298.15}\right)$						
287.1	0.84	1.398	2.40	8.56	−0.23	64.00
290.1	1.13	1.414	2.42	11.34	−0.20	63.70
292.9	1.31	1.230	2.11	15.11	0.21	63.41
296.8	1.24	0.840	2.02	20.96	0.14	63.02
299.8	2.31	1.222	2.10	26.73	−0.16	62.71
300.6	2.48	1.190	2.04	29.18	0.38	62.63
302.1	2.77	1.165	2.00	33.70	1.17	62.48
303.1	1.86	0.747	1.28	34.93	−0.55	62.37
305.0	2.06	0.722	1.24	40.28	−0.94	62.19
306.1	2.37	0.743	1.27	44.75	−0.15	62.08
307.1	2.73	0.754	1.29	50.97	2.01	61.97
308.6	2.94	0.740	1.27	56.08	1.38	61.82
311.0	2.35	0.515	1.24	64.37	−1.94	61.57
313.2	3.05	0.539	1.29	79.57	1.39	61.35
315.2	2.85	0.431	1.29	93.08	2.12	61.14
317.6	3.10	0.415	1.24	105.09	−3.06	60.90
320.7	3.11	0.321	1.28	136.24	1.46	60.59
323.3	3.40	0.313	1.25	153.08	−8.79	60.33
324.9	4.14	0.316	1.27	184.26	3.12	60.16
326.2	4.62	0.322	1.29	201.71	4.05	60.03
329.1	5.16	0.309	1.24	235.94	−3.85	59.74
Dibenzyl carbonate; $\Delta_l^g H_m(298.15\,K) = (96.74 \pm 0.66)/(kJ \cdot mol^{-1})$ $ln(p/Pa) = \frac{390.3}{R} - \frac{130969.7}{R \cdot T/K} - \frac{114.8}{R} ln\left(\frac{T/K}{298.15}\right)$						
341.7	0.64	17.95	8.97	0.36	0.01	91.75
344.8	0.42	8.82	8.97	0.49	0.02	91.39
345.0	0.43	9.03	9.04	0.49	0.01	91.37
346.7	0.73	12.87	8.87	0.58	0.02	91.17
349.1	0.60	9.03	9.04	0.68	−0.02	90.90

TABLE 1 (*continued*)

T^a/K	m^b/ mg	$V_{N_2}{}^c$/ dm^3	N_2 flow/ ($dm^3 \cdot h^{-1}$)	p^d/Pa	($p_{exp} - p_{calc}$)/ Pa	$\Delta_l^g H_m$/ ($kJ \cdot mol^{-1}$)
349.2	0.40	5.96	8.94	0.69	−0.02	90.89
351.2	0.67	8.20	8.95	0.83	−0.01	90.66
353.8	0.41	4.06	9.03	1.03	−0.02	90.36
354.2	0.72	7.02	9.16	1.04	−0.05	90.31
356.4	0.66	5.19	7.24	1.29	−0.03	90.06
359.2	0.62	3.76	9.03	1.68	0.01	89.74
359.3	0.64	3.73	8.96	1.73	0.05	89.73
361.5	0.80	4.22	7.24	1.91	−0.11	89.48
362.7	0.64	2.98	8.94	2.20	−0.03	89.34
364.3	0.94	3.73	8.96	2.57	0.03	89.15
367.5	0.79	2.48	4.25	3.27	−0.01	88.79
369.6	0.86	2.19	4.37	4.00	0.13	88.55
369.6	0.83	2.12	4.25	3.99	0.13	88.55
371.6	0.82	1.82	4.37	4.58	0.07	88.32
373.6	0.75	1.46	4.37	5.22	−0.04	88.09

[a] Saturation temperature.
[b] Mass of transferred sample condensed at $T = 243$ K.
[c] Volume of nitrogen used to transfer mass m of sample.
[d] Vapour pressure at temperature T, calculated from m and the residual vapour pressure at the cooling temperature $T = 243$ K.

$$R \cdot \ln p_i^{sat} = a + \frac{b}{T} + \Delta_l^g C_p \cdot \ln\left(\frac{T}{T_0}\right), \quad (2)$$

$$\Delta_l^g H_m(T) = -b + \Delta_l^g C_p \cdot T, \quad (3)$$

where p_i^{sat} is vapour pressure; a and b are adjustable parameters (table 1); T_0 is an arbitrarily chosen reference temperature (T_0 is 298.15 K in this work); and $\Delta_l^g C_p$ is the difference of the molar heat capacities of the gaseous and the liquid phase. Values of $\Delta_l^g C_p$ (see table 2) were either calculated from experimental isobaric molar heat capacities C_p^l of alkyl carbonates [5,6] or predicted using the group contribution method of Chickos and Acree [7]. The parameterization of the latter method was extended using experimental results from Steele *et al.* [5] and Becker *et al.* [6]. Enthalpy of vaporization values determined by the transpiration method were usually accurate to $\pm(0.3$ to $0.5)\ kJ \cdot mol^{-1}$. This uncertainty of the enthalpy of vaporization was equal to the average deviation of experimental $\ln(p_i^{sat})$ from the linear correlation given by equation (2). The uncertainty of the GC analysis of transported mass of the material, $\delta m_i = (1$ to $3)\%$, was the main contributor to the total experimental error of vapour pressure data, $\delta p_i = (1$ to $3)\%$, measured by the transpiration method.

The vapour pressures of dialkyl carbonates (see table 2) were studied earlier [8–11], but no enthalpies of vaporization were derived from those literature data in the original works with the exception of Steele *et al.* [5]. Equations (2) and (3) were applied in this work to each available experimental data set in order to develop enthalpy of vaporization values and to provide a consistent comparison between the literature results and the present work (table 2).

TABLE 2
Compilation of data on enthalpies of vaporization at $T = 298.15$ K for dialkyl carbonates

Compounds	Technique[a]	T/K	$\Delta_l^g H_m$ (T_{av})/(kJ · mol^{-1})	$\Delta_l^g H_m$ (298.15 K)[b]/(kJ · mol^{-1})	Reference
Dimethyl carbonate	S	283.3 to 382.1	36.53 ± 0.19	38.14 ± 0.19	[8]
	E	310.6 to 397.5	35.51 ± 0.12	38.30 ± 0.12	[5]
	E	326.1 to 411.3	35.17 ± 0.04	38.29 ± 0.04	[9]
	T	274.2 to 304.1	38.56 ± 0.19	**38.02 ± 0.19**	This work
Diethyl carbonate		263.0 to 398.9	41.96 ± 0.20	43.43 ± 0.20	[10]
	K	308.3 to 368.4	40.92 ± 0.21	43.58 ± 0.21	[11]
	C	298.15		43.60 ± 0.15	[12]
	E	352.5 to 415.7	38.35 ± 0.07	44.19 ± 0.07	[9]
	T	273.1 to 315.2	44.76 ± 0.22	**44.35 ± 0.22**	This work
Dipropyl carbonate	T	273.9 to 318.2	53.42 ± 0.29	**53.22 ± 0.29**	This work
Dibutyl carbonate	T	287.1 to 329.1	62.08 ± 0.38	**62.88 ± 0.38**	This work
Dibenzyl carbonate	T	341.7 to 373.6	89.61 ± 0.66	**96.74 ± 0.66**	This work

[a] Techniques: E = ebulliometry; T = transpiration; S = static; K = Knudsen effusion; C = calorimetry.
[b] Literature vapour pressure were treated with equations (2) and (3) to determine the enthalpy of vaporization at $T = 298.15$ K consistent with values presented in table 1.

There was an excellent agreement between all reported data for dimethyl carbonate including this work (figure 1). Due to high consistency of the literature data on vapour pressure of dimethyl carbonate [5,8,9], the main purpose of our measurements was rather to validate the applicability and confirm high accuracy of the transpiration method for the experimental study of the dialkyl carbonates family. Results of our measurements for diethyl carbonate were in close agreement with vapour pressure data from several literature sources [9–12] with the exception of data from Stull [10] (figure 2). Measurements on dipropyl-, dibutyl-, and dibenzyl carbonate were performed for the first time.

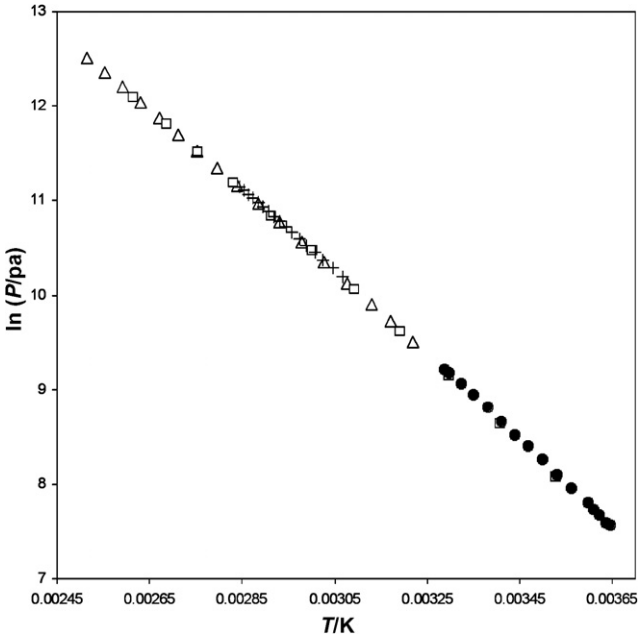

FIGURE 1. Plot of experimental vapour pressures as ln(P/Pa) against reciprocal temperature for dimethyl carbonate: ● – this work; △ – [5]; □ – [8]; + – [9].

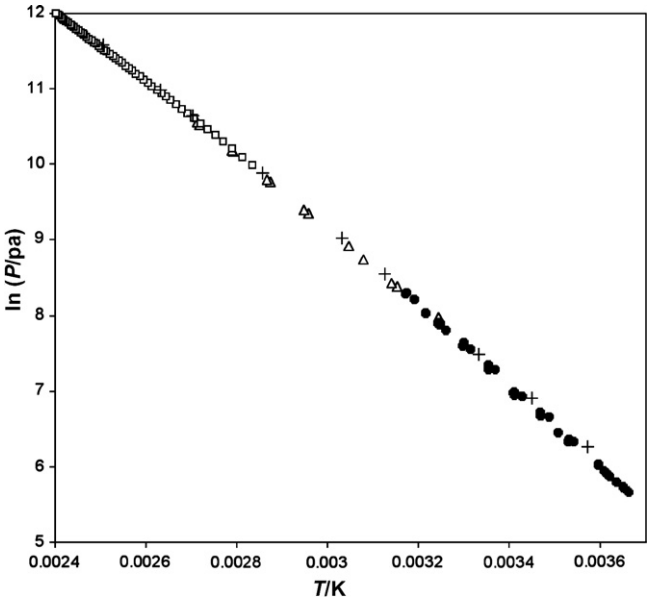

FIGURE 2. Plot of experimental vapour pressures as ln(P/Pa) against reciprocal temperature for diethyl-carbonate: ● – this work; △ – [11]; □ – [9]; + – [10].

3.2. Comparison of $\Delta_l^g H_m$ for dialkyl carbonates and n-alkyl acetate families

Vaporization enthalpies measured in this work were checked for internal consistency using well-established values of $\Delta_l^g H_m$ for the *n*-alkyl acetate family [13]. In fact, the chemical structure of dialkyl carbonates, R–O–C(=O)–O–R, is parent to the structure of the *n*-alkyl acetates because of the common functionality –C(=O)–O–R. Thus, vaporization enthalpies from both families were expected to be linearly dependent. Such a check for data consistency using family comparisons was successfully applied in the past for the benzyl derivatives [14]. The correlation

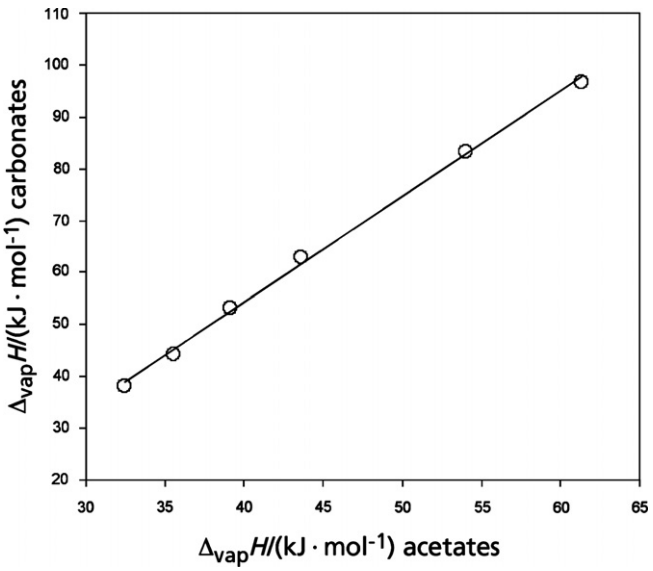

FIGURE 3. Plot of enthalpy of vaporization of dialkyl carbonates against the enthalpy of vaporization of the *n*-alkyl acetates [13] (alkyl = Me, Et, Pr, Bu, Ph, benzyl).

between $\Delta_l^g H_m$ for dialkyl carbonates and *n*-alkyl acetates shown in figure 3 is, indeed, linear with a correlation coefficient $r = 0.998$, which confirms the consistency of enthalpy of vaporization values for dialkyl carbonates reported in this work.

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4.2 Vapour pressure and enthalpy of vaporization of cyclic alkylene carbonates

Sergey P. Verevkin*, Alexey Toktonov, Yury Chernyak, Benjamin Schäffner, Armin Börner, *Fluid Phase Equilibria* **2008**, *268*, 1-6.

Contributions

My contribution as co-author to this paper accounts 10%. I was involved in discussion of the results as well as in planning further experiments and contributed to the draft of the manuscript.

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Vapour pressure and enthalpy of vaporization of cyclic alkylene carbonates

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ABSTRACT

Molar enthalpies of vaporization of cyclic alkyl carbonates: ethylene carbonate, propylene carbonate, butylene carbonate, and glycerine carbonate were obtained from the temperature dependence of the vapour pressure measured by the transpiration method. A large number of the primary experimental results on temperature dependences of vapour pressures have been collected from the literature and have been treated uniformly in order to derive vaporization enthalpies of alkylene carbonates at the reference temperature 298.15 K. This collection together with the new experimental results has been used for the selection of the reliable data sets for each compound under study. Experimental vapour pressure data from various literature sources were reviewed and regressed together with data developed in this work. The resulting correlations for vapour pressure of cyclic alkylene carbonates are recommended for use over a temperature range from ambient to the normal boiling point. Consequently, these correlations were used to derive recommended molar enthalpy of vaporization values at 298.15 K.

1. Introduction

The use of carbon dioxide in organic synthesis, as a safe and inexpensive C1-building block, is a great challenge of "green chemistry". One of the promising reactions involving CO_2 is a chemical fixation of carbon dioxide as cyclic carbonates with further synthesis of polycarbonate systems [1]. Physicochemical properties of cyclic alkylene carbonates such as outstanding solvency and reactivity, high biodegradability, low toxicity, and high boiling temperature favour a number of their industrial applications. The carbonates are widely used as solvents in agriculture and textile industries. They find utilization as agents for gas treating applications; additives to fuels, lubes, and hydraulic fluids; components of polyurethanes (reactive diluents and plasticizers); electrolyte components in lithium-ion rechargeable batteries, building blocks in the manufacturing of polycarbonates and polyester elastomers. Our recent research has revealed specific features of propylene carbonate towards asymmetric hydrogenation with self-assembling catalysts [2] and for palladium-catalyzed substitution reactions [3].

Knowledge of the vapour pressures and vaporization enthalpies of pure alkylene carbonates (see Fig. 1) is critical for modelling of phase equilibria and separation processes. Most of the data reported in the literature are at high temperatures up to the normal boiling temperature [4]. In the present work we used the transpiration method to extend the range of vapour pressure data down to ambient temperature, which is particularly of interest to environmental chemistry.

2. Experimental

2.1. Materials and purity of the sample

Samples of alkylene carbonates of commercial purity were obtained from Huntsman Corporation and were further purified by fractional distillation at reduced pressures. The purity analyses were performed using a gas chromatograph (GC) with a flame ionization detector. A HP-5 capillary column (stationary phase crosslinked 5% PH ME silicone) was used in all our experiments. The column was 30 m long, 0.32 mm inside diameter, and had a film thickness of 0.25 μm. The flow rate of the carrier gas (nitrogen) was maintained at 7.2 $dm^3\,h^{-1}$. The starting temperature for the GC was $T = 323$ K for the first 180 s followed by heating to $T = 523$ K at the rate of 10 $K\,min^{-1}$. No impurities

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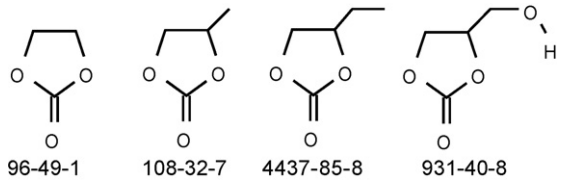

Fig. 1. Structures of alkylene carbonates studied in this work: ethylene carbonate [96-49-1], propylene carbonate [108-32-7], butylene carbonate [4437-85-8], and glycerine carbonate [931-40-8].

greater than 0.02 mass% were detected in all samples used in this work.

2.2. Measurements of the vapour pressures using the transpiration method

Vapour pressures were developed by the method of transpiration in a saturated nitrogen stream [5,6]. Enthalpies of vaporization were obtained from vapour pressure data using the Clausius–Clapeyron equation. Approximately 0.5 g of the sample was mixed with glass beads and placed in a thermostated 20 cm long U-shaped tube of 0.5 cm diameter. Glass beads of 1 mm diameter provided sufficient surface area for the vapour–liquid equilibration between the carrier gas and the investigated material. A nitrogen stream of constant temperature (±0.1 K) passed through the U-tube with the flow rate optimized to achieve a complete saturation with the material at each temperature under study. The cold trap was used for the collection of transported material during the experiment. To determine the amount of the condensed product, it was dissolved in a solvent (methanol or acetonitrile) and then analysed using a GC with autosampler. The estimated uncertainties of the sample mass were within (1–3)% in all our experiments. The saturated vapour pressure of the material, p_i^{sat}, at each temperature, T_i, was determined from the mass of gas-transported product, m_i, collected in a known period of time. Assuming the validity of the Dalton's law for the gas mixture stream, the values of p_i^{sat} were calculated from the following equations:

$$p_i^{sat} = \frac{m_i R T_a}{V M_i}; \quad (1)$$

$$V = V_{N2} + V_i \qquad (V_{N2} \gg V_i) \quad (2)$$

where $R = 8.314472\ J\ K^{-1}\ mol^{-1}$; M_i is the molar mass of the compound, and V_i is its volume contribution to the gaseous phase. V_{N2} is the volume of the transporting gas determined from the flow rate and time measurements, and T_a is the temperature of the soap bubble meter.

The saturated vapour pressure of the material was correlated with the temperature-dependent equation [6]:

$$R \ln p_i^{sat} = a + \frac{b}{T} + \Delta_l^g C_p \ln\left(\frac{T}{T_0}\right) \quad (3)$$

where a and b are adjustable parameters and $\Delta_l^g C_p$ is the difference between the molar heat capacity of the gaseous and the liquid phase. T_0 is an arbitrarily chosen reference temperature ($T_0 = 298.15$ K in this work).

The expression for the vaporization enthalpy, $\Delta_l^g H_m$, derived from Eq. (3) is

$$\Delta_l^g H_m(T) = -b + \Delta_l^g C_p T. \quad (4)$$

Values of $\Delta_l^g C_p$ were calculated according to the procedure of Chickos and Acree [15]. Experimental vapour pressure data, and parameters a and b for the Eq. (3) are given in Table 1. Detailed error analyses of the vapour pressure measurement using the transpiration method were performed in our earlier work for n-alkanols [6]. It was established that the total uncertainty of the data for this experimental technique was within the range from 1% to 3% with the main source of errors attributed to the reproducibility of GC measurements. In order to assess the uncertainty of the vaporization enthalpy, the vapour pressure data were approximated with the linear equation $\ln(p_i^{sat}) = f(T^{-1})$ using the method of least squares. The uncertainty of the enthalpy of vaporization was assumed to be equal to the average deviation of experimental $\ln(p_i^{sat})$ values from this linear correlation. Uncertainties of $\Delta_l^g C_p$ values calculated according to the procedure of Chickos and Acree [15] are ill-defined and they were not taken into account.

3. Results and discussion

The vapour pressures, p_i^{sat}, and vaporization enthalpies, $\Delta_l^g H_m$, of alkylene carbonates developed in this work are summarized in Table 1. The comparison of our and literature data of the enthalpy of vaporization [4,7–13] is given in Table 2. For the consistency of the $\Delta_l^g H_m$ comparison, all enthalpy of vaporization values were developed from the originally reported vapour pressures [4,7–13] using Eqs. (3) and (4).

3.1. Ethylene carbonate

All liquid vapour pressure data reported in the literate were collected and were in good agreement with themselves and our data as shown in Fig. 2. However, enthalpies of vaporization values at 298.15 K reported in this work were about 2–3 kJ mol^{-1} lower than the literature values. Such a difference, in our opinion, was due to an extrapolation error of literature data from high temperatures down to ambient ones, while data measured by the transpiration method were at low temperature and did not require extrapolation.

The melting temperature of ethylene carbonate is 309.5 K, so this compound is a solid at the reference temperature of 298.15 K. There were only three literatures experimental data points on vapour pressure available in the low temperature range [7]. These data were measured using the Knudsen effusion technique and were in fair agreement with results of our measurements as shown in Fig. 2. The values for sublimation enthalpy, $\Delta_{cr}^g H_m(298.15\ K) = (74.1 \pm 0.6)\ kJ\ mol^{-1}$, and vaporization enthalpy, $\Delta_l^g H_m$ $(298.15\ K) = (60.8 \pm 0.1)\ kJ\ mol^{-1}$, were determined from our measurements below the melting point (280.6–302.4 K) and above it (310.3–369.5 K), correspondingly. The consistency of our experimental data was tested by comparison of our experimental enthalpy of fusion at 298.15 K defined as

$$\Delta_{cr}^l H_m(298.15\ K) = \Delta_{cr}^g H_m - \Delta_l^g H_m = 74.1 - 60.8 = (13.3 \pm 0.7)\ kJ\ mol^{-1} \quad (5)$$

with the literature value $\Delta_{cr}^l H_m(T_{fus})$ determined in a calorimetric experiment [14] and adjusted to the reference temperature 298.15 K. A value for enthalpy of fusion, $\Delta_{cr}^l H_m(T_{fus}) = 13.3\ kJ\ mol^{-1}$, was reported in [14] at the melting temperature, $T = 309.49$ K. The following equation [16] was applied to experimental $\Delta_{cr}^l H_m(T_{fus})$ to account for the temperature correction of $\Delta_{cr}^l H_m$ to 298.15 K

$$\Delta_{cr}^l H_m(T_{fus}\,(K)) - \Delta_{cr}^l H_m(298.15\ K)\,(J\ mol^{-1}) = \left\{(0.75 + 0.15 C_p^{cr})[T_{fus}\,(K) - 298.15]\right\} - \left\{(10.58 + 0.26 C_p^{l})[T_{fus}\,(K) - 298.15]\right\} \quad (6)$$

Table 1
Experimental vapour pressures, p, and molar enthalpies of vaporization, $\Delta_l^g H_m(298.15\,K)$, of alkylene carbonates measured by transpiration method

T[a] (K)	m[b] (mg)	$V_{(N2)}$[c] (dm^3)	Gas-flow (dm^3/h)	p[d] (Pa)	$p_{exp} - p_{calc}$ (Pa)	$\Delta_{cr}^g H_m$ or $\Delta_l^g H_m$ (kJ mol^{-1})
Ethylene carbonate; $\Delta_{cr}^g H_m(298.15\,K) = (74.08 \pm 0.63)\,kJ\,mol^{-1}$, $\ln(p/Pa) = \frac{278.64}{R} - \frac{79556.09}{R\cdot(T,K)} - \frac{18.4}{R}\ln\left(\frac{T,K}{298.15}\right)$						
280.6	2.51	113.2	9.57	0.62	−0.01	74.41
286.2	2.93	69.1	9.60	1.19	0.01	74.30
291.3	2.74	38.2	9.60	2.00	−0.03	74.21
295.5	3.18	27.4	9.60	3.25	0.10	74.13
299.4	3.44	20.3	9.60	4.72	0.06	74.06
303.2	3.09	12.8	9.57	6.75	−0.02	73.99
304.4	3.38	12.0	9.60	7.85	0.24	73.97
306.4	3.63	11.2	9.57	9.07	−0.13	73.93
308.4	3.70	9.6	9.57	10.77	−0.34	73.89
Ethylene carbonate; $\Delta_l^g H_m(298.15\,K) = (60.81 \pm 0.12)\,kJ\,mol^{-1}$, $\ln(p/Pa) = \frac{264.13}{R} - \frac{74971.42}{R\cdot(T,K)} - \frac{47.5}{R}\ln\left(\frac{T,K}{298.15}\right)$						
310.3	7.53	17.53	9.56	12.00	0.10	60.23
314.4	7.37	12.75	9.56	16.15	0.02	60.04
314.5	3.11	5.39	7.19	16.14	−0.11	60.04
317.3	3.77	5.27	7.19	20.00	0.11	59.90
320.3	4.82	5.39	7.19	24.99	0.39	59.76
320.4	6.73	7.59	9.30	24.75	−0.03	59.75
324.4	6.47	5.51	7.19	32.81	0.15	59.56
323.5	1.04	0.958	2.87	30.50	−0.21	59.61
327.4	6.77	4.80	7.21	39.39	−0.59	59.42
331.3	7.70	4.20	7.21	51.19	−0.49	59.24
328.6	1.11	0.718	2.87	43.12	−0.17	59.37
335.4	8.84	3.61	7.21	68.48	1.29	59.04
333.6	10.08	4.72	5.67	59.62	−0.31	59.13
342.3	6.07	1.65	3.29	103.13	0.29	58.71
341.4	9.02	2.58	6.18	97.80	0.40	58.76
338.7	10.40	3.50	5.67	83.12	0.56	58.89
345.2	9.39	2.16	6.18	121.26	−1.03	58.58
349.0	13.02	2.36	5.67	153.99	1.31	58.40
343.8	9.25	2.36	5.67	109.42	−3.11	58.64
347.6	6.77	1.37	3.29	137.93	−2.85	58.46
354.0	11.71	1.61	5.67	203.68	0.91	58.16
352.4	7.34	1.10	3.29	186.92	1.56	58.23
357.5	7.28	0.822	3.29	247.33	1.33	57.99
363.2	9.02	0.767	3.29	328.31	−5.60	57.72
364.1	18.87	1.51	5.67	348.61	−1.46	57.68
360.6	9.17	0.877	3.29	292.05	1.18	57.85
358.9	13.40	1.42	5.67	264.20	−1.24	57.93
366.7	11.12	0.767	3.29	404.73	4.07	57.56
369.5	13.82	0.822	3.29	469.45	7.24	57.42
Propylene carbonate; $\Delta_l^g H_m(298.15\,K) = (61.48 \pm 0.31)\,kJ\,mol^{-1}$, $\ln(p/Pa) = \frac{277.7}{R} - \frac{77611.3}{R\cdot(T,K)} - \frac{54.1}{R}\ln\left(\frac{T,K}{298.15}\right)$						
298.4	5.26	14.93	9.00	8.50	0.29	61.47
303.3	5.55	10.72	9.00	12.47	0.22	61.21
308.2	5.07	6.75	9.00	18.10	0.11	60.94
311.3	3.89	4.20	9.00	22.30	−0.49	60.77
313.2	6.49	6.18	5.19	25.29	−1.00	60.67
318.2	6.76	4.37	5.19	37.23	−0.64	60.40
321.2	7.28	3.89	5.19	45.03	−1.84	60.24
322.7	3.73	1.73	5.19	51.93	−0.11	60.16
324.2	7.41	3.03	5.19	58.93	1.19	60.07
326.6	7.81	2.77	5.19	67.88	−0.12	59.94
329.6	7.47	2.16	5.19	83.07	−0.04	59.78
332.7	6.23	1.47	5.19	101.9	0.11	59.61
335.7	6.68	1.25	5.19	128.1	4.65	59.45
337.7	7.41	1.30	5.19	137.5	−2.55	59.34
338.8	7.68	1.21	5.19	152.5	2.54	59.28
340.8	8.04	1.12	5.19	172.1	2.44	59.18
341.8	12.21	1.64	5.19	178.7	−1.60	59.12
344.9	10.96	1.21	5.19	217.8	0.38	58.95
Butylene carbonate; $\Delta_l^g H_m(298.15\,K) = (63.19 \pm 0.31)\,kJ\,mol^{-1}$, $\ln(p/Pa) = \frac{285.6}{R} - \frac{81554.2}{R\cdot(T,K)} - \frac{61.6}{R}\ln\left(\frac{T,K}{298.15}\right)$						
288.6	2.46	28.17	9.014	1.86	0.03	63.78
293.5	3.96	29.60	9.014	2.84	−0.01	63.48
298.5	3.05	14.27	9.014	4.53	0.13	63.17
303.4	2.57	8.37	4.974	6.49	−0.14	62.87
307.3	2.55	6.22	4.974	8.70	−0.40	62.63
310.3	2.74	4.97	4.974	11.64	0.11	62.44
313.3	4.00	5.88	5.687	14.39	−0.14	62.26
316.3	4.11	4.74	5.687	18.37	0.14	62.07
319.3	4.09	3.79	5.687	22.81	0.07	61.89
322.5	3.85	2.90	4.974	28.05	−0.61	61.69
327.4	4.01	2.07	4.974	40.92	0.52	61.39

Table 1 (*Continued*)

T[a] (K)	m[b] (mg)	$V_{(N2)}$[c] (dm³)	Gas-flow (dm³/h)	p[d] (Pa)	$p_{exp} - p_{calc}$ (Pa)	$\Delta^g_{cr}H_m$ or $\Delta^g_l H_m$ (kJ mol^{-1})
330.3	3.98	1.74	4.974	48.39	−0.84	61.21
333.6	6.04	1.99	5.687	64.15	2.79	61.01
338.7	6.17	1.52	5.687	86.00	0.62	60.69
343.8	7.80	1.42	5.687	115.9	−1.6	60.38
Glycerine carbonate; $\Delta^g_l H_m(298.15\,K) = (85.42 \pm 0.37)$kJ mol^{-1}, $\ln(p/Pa) = \frac{315.1}{R} - \frac{105182.6}{R(T,K)} - \frac{66.3}{R}\ln\left(\frac{T,K}{298.15}\right)$						
330.2	3.13	221.7	9.09	0.29	0.00	83.29
333.2	3.25	174.4	9.37	0.39	0.01	83.09
338.3	3.24	109.8	9.09	0.62	0.01	82.76
343.2	2.25	51.67	9.09	0.91	−0.01	82.43
348.4	2.40	34.62	9.09	1.44	0.03	82.09
351.2	2.25	27.12	9.09	1.73	−0.03	81.90
355.5	3.80	31.71	9.35	2.50	0.02	81.62
360.6	2.56	14.73	9.35	3.62	−0.03	81.28
363.7	2.04	9.81	9.80	4.33	−0.27	81.07
366.4	2.36	9.09	9.09	5.42	−0.20	80.89
369.4	2.37	7.27	9.09	6.81	−0.16	80.69
371.8	3.49	9.32	9.48	7.82	−0.43	80.54
373.2	2.25	5.30	9.09	8.86	−0.23	80.44
377.2	2.13	3.79	9.09	11.71	−0.25	80.18
359.8[e]	22.3	125.1	10.37	3.68	0.23	81.33
384.5[e]	7.7	7.93	6.70	20.19	0.77	79.69
387.3[e]	11.8	10.26	6.41	23.92	0.67	79.51
388.0[e]	9.0	7.57	5.94	24.71	0.40	79.46
392.7[e]	12.3	7.66	5.78	33.39	0.76	79.15
398.5[e]	12.4	5.49	5.78	46.94	0.54	78.77

[a] Saturation temperature.
[b] Mass of transferred sample condensed at T = 243 K.
[c] Volume of nitrogen used to transfer m of the sample.
[d] Vapour pressure at temperature T, calculated from the m and the residual vapour pressure at T = 243 K.
[e] The amount of condensed product was determined by weighing (±0.0001 g).

Values of the experimental isobaric molar heat capacity of liquid ethylene carbonate, $C^l_p = 136.2\,J\,mol^{-1}\,K^{-1}$ and the isobaric molar heat capacities of the solid ethylene carbonate, $C^{cr}_p = 117.4\,J\,mol^{-1}\,K^{-1}$, were reported in [14].

The resulting standard enthalpy of fusion, $\Delta^l_{cr}H_m(298.15\,K)$, calculated by Eq. (6) was 13.0 kJ mol^{-1}. This value of $\Delta^l_{cr}H_m(298.15\,K)$ was in excellent agreement with our experimental value (13.3 ± 0.7) kJ mol^{-1} provided by Eq. (5), which confirms the consistency of our vapour pressure data. It should be mentioned that enthalpy of fusion, $\Delta^l_{cr}H^\circ_m(T_{fus})$, reported in ref. [14] is in good agreement with another values available from the literatures [17,18].

3.2. Propylene carbonate

Vapour pressures of propylene carbonate were measured earlier using the static method [8,12,13], ebulliometry [4,8,10–11], and the Knudsen effusion method [7]. Most data from all these literature

Table 2
Compilation of data on enthalpies of vaporization, $\Delta^g_l H_m$, of alkylene carbonates

	Technique[a]	Temperature range (K)	$\Delta^g_l H_m(T)$ (kJ mol^{-1})	$\Delta^g_l H_m$ (298.15 K)[b] (kJ mol^{-1})	Ref.
Ethylene carbonate (cr)	K	273.9–296.6	68.7 ± 1.9[c]	68.5 ± 1.9[c]	7
	T	280.6–302.4	74.2 ± 0.6[c]	**74.1 ± 0.6**[c]	This work
Ethylene carbonate (l)	E	423	56.5	62.4	9
	E	382.1–436.8	58.1 ± 0.3	63.4 ± 0.3	10
	E	451.6–505.5	55.5 ± 0.1	64.0 ± 0.1	4
	E	368.4–449.9	58.4 ± 0.2	63.5 ± 0.2	11
	T	310.3–369.5	58.9 ± 0.1	**60.8 ± 0.1**	This work
Propylene carbonate (l)	K	328.2–369.6	33.8 ± 2.3	36.6 ± 2.3	7
	S + E	363.2–508.2	55.5 ± 0.5	62.6 ± 0.5	8
	E	412.8–466.2	53.6 ± 0.1	61.3 ± 0.1	10
	E	459.9–513.2	51.1 ± 0.1	61.3 ± 0.1	4
	E	368.6–462.1	55.7 ± 0.2	61.8 ± 0.2	11
	L	668.6–762.6	48.7 ± 0.6	71.2 ± 0.6	12
	S	298.2–473.2	58.8 ± 0.8	62.9 ± 0.8	13
	S	318.2–473.2	55.8 ± 0.2	60.6 ± 0.2[d]	13
	T	298.4–344.9	60.2 ± 0.3	**61.5 ± 0.3**	This work
Butylene carbonate (l)	E	397.3–522.7	54.2 ± 0.1	63.8 ± 0.1	4
		288.6–343.8	62.2 ± 0.3	**63.2 ± 0.3**	This work
Glycerine carbonate (l)	E	429.9–455.6	78.1 ± 0.4	87.8 ± 0.4	4
		330.2–398.5	81.2 ± 0.4	**85.4 ± 0.4**	This work

[a] Techniques: E, ebulliometry; S, static manometer; T, transpiration; L, low residence time flow method; K, Knudsen effusion.
[b] Literature vapour pressure data were treated with Eqs. (3) and (4) to determine the enthalpy of vaporization at 298.15 K consistent with values presented in Table 1.
[c] Enthalpy of sublimation $\Delta^g_{cr}H_m$.
[d] First four experimental points from the publications were omitted due to their inconsistency.

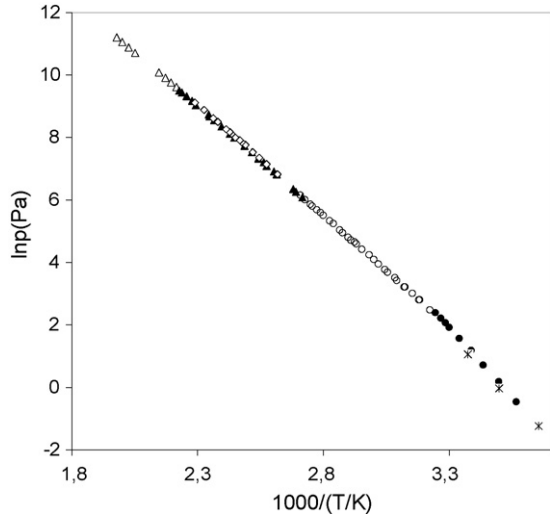

Fig. 2. Experimental vapour pressure of the solid and liquid ethylene carbonate (○) this work, liquid range; (●) this work, solid range; (△) [4]; (▲) [11], (□) [10]; (⋊) solid range [7].

sources and from this work agreed well with each other with the exception of several data points measured by the Knudsen effusion [7] and the static [13] methods at low temperatures (Fig. 3). Enthalpy of vaporization values of propylene carbonate determined from each sets of vapour pressure data [4,6,7,10–13] were in excellent agreement as well.

3.3. Butylene carbonate

Vapour pressure data of butylene carbonate measured in this work using the transpiration method was consistent with those from ebulliometry [4]. Comparison of the results is presented in Fig. 4. Enthalpies of vaporization derived from both data sets were in very good agreement.

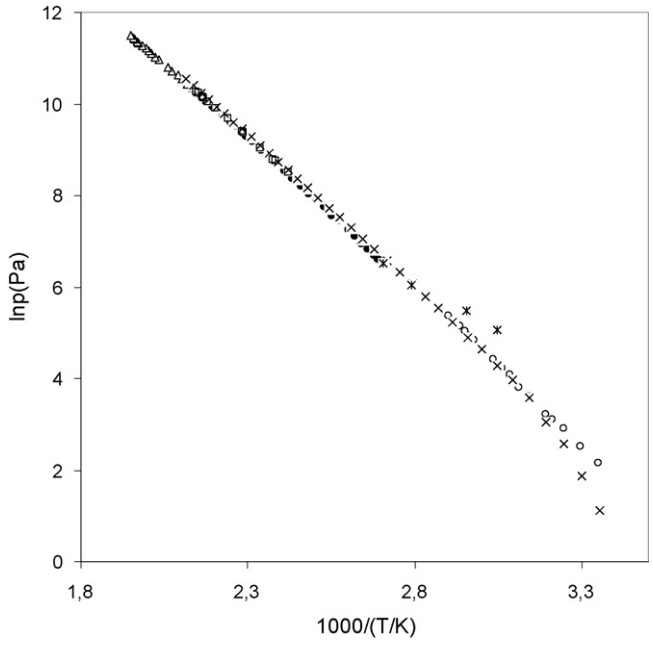

Fig. 3. Experimental vapour pressure of the liquid propylene carbonate, (○) this work, (△) [4]; (⋊) [7]; (+) [8] (●) [11]; (□) [10]; (x) [13].

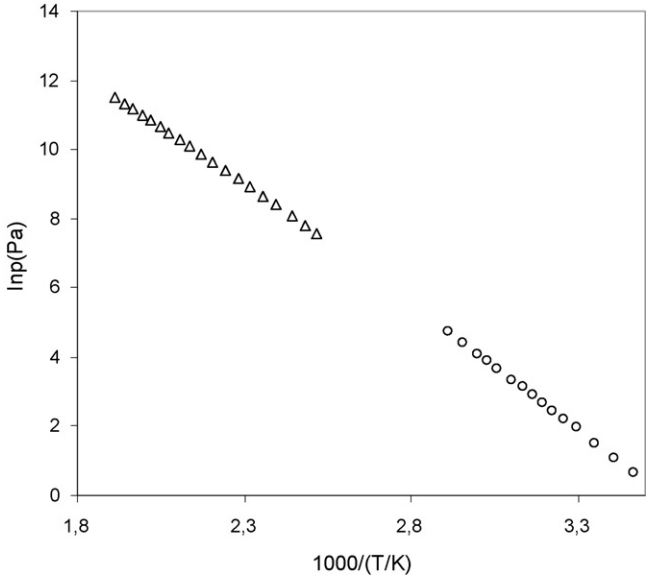

Fig. 4. Experimental vapour pressure of the liquid butylene carbonate, (○) this work; (△) [4].

3.4. Glycerine carbonate

The vapour pressures of glycerine carbonate measured in this work were consistent with data determined by the ebulliometric technique [4] as shown in Fig. 5. Enthalpies of vaporization derived from both data sets were in reasonable agreement, considering the extrapolation errors of high temperature data [4] to ambient temperatures. Compared to other carbonates studied in this work, a broader main peak was observed in our GC experiments with the glycerine carbonate due to its hydroxyl group. To insure accurate determination of the amount of transported compound, *m*, in Eq. (1), an alternative analytical procedure was used in addition to a standard GC technique. It included collection of glycerine carbonate in a special cold trap followed by direct weighting of the condensed product using an analytical balance to the accuracy of (±0.0001 g). Vapour pressure data determined using both analytical techniques was found practically indistinguishable as shown in Fig. 5.

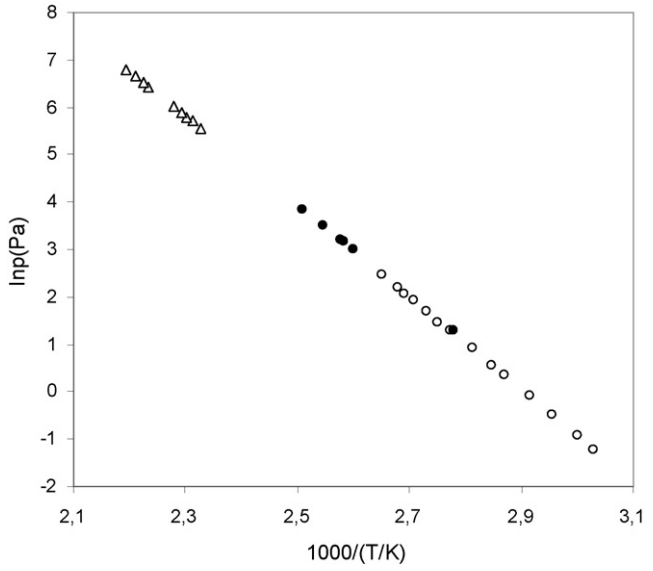

Fig. 5. Experimental vapour pressure of the liquid glycerine carbonate, (○) this work, GC; (●) this work, weighing; (△) [4].

Table 3
Vapor pressure coefficients of the Eq. (3) and recommended enthalpies of vaporization, $\Delta_l^g H_m$(298.15 K), for alkylene carbonates

Alkylene carbonate	Temperature range (K)	a	b	$\Delta_l^g C_p$	$\Delta_l^g H_m$(298.15 K), kJ mol^{-1}
Ethylene carbonate	310.3–505.5	270.020	−76971.19	47.5	62.8 ± 0.1
Propylene carbonate	298.2–513.2	273.410	−76362.22	54.1	60.2 ± 0.1
Butylene carbonate	288.6–522.7	286.380	−81761.66	61.6	63.4 ± 0.2
Glycerin carbonate	330.2–455.6	316.350	−105625.97	66.3	85.9 ± 0.2

3.5. Vapour pressures correlations for alkylene carbonates

Taking the very good agreement between vapour pressure data reported in this work and the literature into account, all experimental data were regressed together to develop correlations accurately describing the vapour pressure of alkylene carbonates over a temperature range from ambient to the normal boiling point. Table 3 summarizes coefficients of the vapour pressure correlation (Eq. (3)) for alkylene carbonates as well as the recommended molar enthalpies of vaporization values at 298.15 K.

List of symbols

C_p^g, C_p^l, C_p^{cr} molar heat capacities of gas, liquid, and crystal at constant pressure
$\Delta_l^g C_p$ difference of the molar heat capacities at constant pressure for the gaseous and liquid phase, respectively
$\Delta_l^g H_m$ molar enthalpy of vaporization
$\Delta_{cr}^g H_m$ molar enthalpy of sublimation
$\Delta_{cr}^l H_m$ molar enthalpy of fusion
p vapour pressure
T_a ambient temperature

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4.3 Cyclic alkylene carbonates. Experiment and first principle calculations for prediction of thermochemical properties

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Contributions

My contribution as co-author to this paper accounts 10%. I was involved in discussion of the results as well as in planning further experiments and contributed to the draft of the manuscript.

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Cyclic alkylene carbonates. Experiment and first principle calculations for prediction of thermochemical properties

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ABSTRACT

The standard molar enthalpies of formation of ethylene carbonate, propylene carbonate, and butylene carbonate were measured using combustion calorimetry. *Ab initio* calculations of molar enthalpies of formation of alkylene carbonates were performed using the G3MP2 method. The calculated values are in excellent agreement with available experimental data. Ring strain corrections were quantified for the refinement of the group-contribution method for prediction of enthalpies of formation and vaporization of alkylene carbonates.

1. Introduction

The alkylene carbonates (or 1,2-glycol carbonates, or cyclic acid esters) have become increasingly attractive not only for their unique physico-chemical properties but also for the relative simplicity of their manufacturing [1]. They are long-term commercially available solvents used in many industrial applications such as cleaning, degreasing, paint stripping, gas treating, and textile dyeing [2]. Cyclic alkylene carbonates, such as ethylene carbonate, propylene carbonate, and their linear analogue, dimethyl carbonate, as well as their mixtures are widely used as solvents of electrolytes in lithium-ion batteries [3]. Our recent research has revealed specific features of propylene carbonate towards asymmetric hydrogenation with self-assembling catalysts [4] and for palladium-catalyzed substitution reactions [5]. Alkylene carbonates are biodegradable and non-toxic, thus they could be considered as possible "green" solvents. There is great interest in the computation of heat balances, equilibrium yields and feasibilities of processes, using the thermodynamic properties of organic compounds. Despite the practical importance of carbonates, relevant thermodynamic information is rather limited [6–10]. The aim of this work was an experimental and computational study of the enthalpies of formation for a series of alkylene carbonates (figure 1). This paper extends our previous experimental research of organic carbonates [11–14].

2. Experimental

2.1. Materials

Samples of alkylene carbonates of commercial purity were obtained from Huntsman Corporation and were further purified by fractional distillation at reduced pressures. The purity analyses were performed using a gas chromatograph (GC) with a flame ionization detector. A HP-5 capillary column (stationary phase cross-linked 5% PH ME silicone) was used in all our experiments. The column was 30 m long, 0.32 mm inside diameter, and had a film thickness of 0.25 μm. The flow rate of the carrier gas (nitrogen) was maintained at 7.2 $dm^3 \cdot h^{-1}$. The starting temperature for the GC was $T = 323$ K for the first 180 s followed by heating to $T = 523$ K at the rate of 10 $K \cdot min^{-1}$. No impurities greater than 0.0002 mass fraction were detected in all samples used in this work.

2.2. Combustion calorimetry

An isoperibol bomb calorimeter was used for measurements of energy of combustion of alkylene carbonates. The detailed

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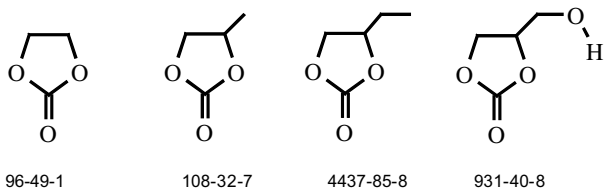

FIGURE 1. Structures of alkylene carbonates studied in this work: ethylene carbonate [CAS-number 96-49-1], propylene carbonate [CAS-number 108-32-7], butylene carbonate [CAS-number 4437-85-8], and glycerine carbonate [CAS-number 931-40-8].

experimental procedure has been described previously [15]. In this study, we used commercially available 1 cm^3 polyethylene bulbs (Fa. NeoLab, Heidelberg, Germany) as sample containers for the liquid carbonates. The combustion products were examined for carbon monoxide (Dräger tube) and unburned carbon, but none was detected. The energy equivalent of the calorimeter ε_{calor} was determined with a standard reference sample of benzoic acid (sample SRM 39i, N.I.S.T.). Correction for nitric acid formation was based on the titration with 0.1 mol · dm^{-3} NaOH (aq). The atomic masses used were those recommended by the IUPAC Commission [16]. The sample masses were reduced to vacuum, taking into consideration the density values given in table 1. Five to six successful combustion experiments (without soot traces) were carried out for each compound. For converting the energy of the actual bomb process to that of the isothermal process, and reducing to standard states, the conventional procedure [17] was applied.

2.3. Computations

Standard *ab initio* molecular orbital calculations were performed with the Gaussian 03 Rev.04 series of programs [18]. Energies were obtained at the G3MP2 level of theory. The G3 theory is a procedure for calculating energies of molecules containing atoms of the first and second rows of the periodic chart based on *ab initio* molecular orbital theory. A modification of the G3 theory that uses reduced orders of Moller–Plesset perturbation theory is the G3MP2 theory [19]. This method saves considerable computational time compared to G3 theory with some losses in accuracy, but it is much more accurate than G2MP2 model predicts. For all the species included in this study, full geometry optimizations were carried out at the HF/6-31G(d) level. The corresponding harmonic vibrational frequencies were evaluated at the same level of theory to confirm that the optimized structures found correspond to potential energy minima and to evaluate the corresponding zero-point vibrational energies, ZPE, and the thermal corrections at $T = 298$ K. The values of ZPE were scaled by the empirical factor 0.8929. All the minima found at the HF/6-31G(d) level were again fully re-optimized at the MP2(FULL)/6-31G(d) level. The G3MP2 theory uses geometries from second-order perturbation theory and scaled zero-point energies from Hartree–Fock theory followed by a series of single-point energy calculations at the MP2(Full), QCISD(T) and MP2/GTMP2Large levels of theory (for details, see reference [19]). The enthalpy value of the compounds studied at $T = 298$ K was evaluated according to standard thermodynamic procedures [20].

3. Results and discussion

3.1. Enthalpies of formation from combustion calorimetry

Results of combustion experiments for alkylene carbonates are summarized in tables 2 to 4. Values of the standard specific energies of combustion $\Delta_c u^\circ$, together with their mean, are also given in table 2. To derive $\Delta_f H^\circ_m$ (l or cr) from $\Delta_c H^\circ_m$, molar enthalpies of formation of H_2O (l): $-(285.830 \pm 0.042)$ kJ · mol^{-1} and CO_2 (g): $-(393.51 \pm 0.13)$ kJ · mol^{-1} were taken, as assigned by *CODATA* [21]. Table 5 lists the derived standard molar enthalpies of combustion, and standard molar enthalpies of formation of alkylene carbonates. The total uncertainties were calculated according to the guidelines presented by Olofsson [22]. The uncertainties assigned to $\Delta_f H^\circ_m$ were twice the overall standard deviation and included the uncertainties of calibration, combustion energies of the auxiliary materials, and the uncertainties of the enthalpies of formation of the reaction products H_2O and CO_2.

The enthalpy of combustion of butylene carbonate is reported for the first time (see table 5). Previous calorimetric determinations of the standard molar enthalpy of formation, $\Delta_f H^\circ_m$ (cr), of ethylene carbonate were reported by Silvestro and Lenchitz [8]: $-(580.9 \pm 1.3)$ kJ · mol^{-1}, Vasil'eva *et al.* [9]: $-(581.6 \pm 0.4)$ kJ · mol^{-1}, and Calhoun [10]: $-(586.3 \pm 3.8)$ kJ · mol^{-1}. All literature and our values were in close agreement (see table 1). However, our experimental results for the heat of combustion of ethylene carbonate (-584.8 ± 0.6) kJ · mol^{-1} were found to be in disagreement with the work of Choi and Joncich [7]: $-(682.8 \pm 2.1)$ kJ · mol^{-1} and Vogdanis *et al.* [6]: $-(590.9)$ kJ · mol^{-1}.

The standard molar enthalpy of formation, $\Delta_f H^\circ_m$(l), of propylene carbonate determined by combustion calorimetry is $-(631.8 \pm 2.1)$ kJ · mol^{-1} and $-(613.4 \pm 1.3)$ kJ · mol^{-1} as reported by Choi and Joncich [7] and Vasil'eva *et al.* [9], respectively. Our value of $\Delta_f H^\circ_m$(l) determined in a combustion experiment was $-(614.1 \pm 0.8)$ kJ · mol^{-1}, which agrees well with the value reported by Vasil'eva *et al.* [9], and resolves the conflict between the literature results for the standard molar enthalpy of propylene carbonate.

3.2. Vapour pressures, sublimation and vaporization enthalpies

Vapour pressures of alkylene carbonates were measured in our previous work [11] using the transpiration method [23–25]. Molar

TABLE 1
Formula, density ρ ($T = 293$ K), massic heat capacity c_p ($T = 298.15$ K), and expansion coefficients $(\delta V/\delta T)_p$ of the materials used in this study

Compounds	Formula	ρ^a/(g · cm^{-3})	$c_p{}^b$/(J · K^{-1} g^{-1})	$10^{-6} \cdot (\delta V/\delta T)_p{}^c$/($dm^3$ · K^{-1})
Ethylene carbonate	$C_3H_4O_3$	1.32	1.33	0.1
Propylene carbonate	$C_4H_6O_3$	1.23 [31]	1.20	1.0
Butylene carbonate	$C_5H_8O_3$	1.14	1.20	1.0
Polyethene[d]	$CH_{1.93}$	0.92	2.53	0.1
Cotton[e]	$CH_{1.774}O_{0.887}$	1.50	1.67	0.1

[a] Measured with a pycnometer.
[b] From reference [11].
[c] Estimated.
[d] From 13 combustion experiments, $\Delta_c u^\circ = -(46361.0 \pm 3.1)$ J · g^{-1}.
[e] From 10 combustion experiments, $\Delta_c u^\circ = -(16945.2 \pm 4.2)$ J · g^{-1}.

TABLE 2
Results for typical combustion experiments at $T = 298.15$ K ($p^\circ = 0.1$ MPa) of the ethylene carbonate[a]

m(substance)/g[b]	1.032182	1.068698	1.030644	1.012889	1.017638	1.008019	1.036652
m'(cotton)/g[b]	0.003649	0.00356	0.004035	0.003655	0.004068	0.003501	0.004235
ΔT_c/K[c]	0.92930	0.96230	0.92873	0.91161	0.91689	0.90804	0.93439
$(\varepsilon_{calor}) \cdot (-\Delta T_c)$/J	−13755.6	−14243.9	−13747.1	−13493.6	−13571.8	−13440.8	−13830.8
$(\varepsilon_{cont}) \cdot (-\Delta T_c)$/J	−15.93	−16.62	−15.96	−15.59	−15.69	−15.52	−16.03
ΔU_{corr}/J[d]	15.52	16.14	15.51	15.2	15.29	15.12	15.6
$-m' \cdot \Delta_c u'$/J	61.83	60.32	68.37	61.93	68.93	59.32	71.76
$\Delta_c u^\circ$(cr)/(J · g^{-1})	−13267.2	−13272.3	−13272.4	−13261.1	−13269.2	−13275.4	−13273.0

[a] For the definition of the symbols, see reference [17], calorimeter: $T_h = 298.15$ K; V(bomb) = 0.2664 dm^3; p^i(gas) = 3.04 MPa; $m^i(H_2O) = 1.00$ g.
[b] Masses obtained from apparent masses.
[c] $\Delta T_c = T^f - T^i + \Delta T_{corr}$; $(\varepsilon_{cont}) \cdot (-\Delta T_c) = (\varepsilon^i_{cont}) \cdot (T^i - 298.15\ \text{K}) + (\varepsilon^f_{cont}) \cdot (298.15\ \text{K} - T^f + \Delta T_{corr.})$.
[d] ΔU_{corr}, the correction to standard states, is the sum of items 81 to 85, 87 to 90, 93, and 94 in reference [17]; ε_{calor}=14802.0 ± 1.0 J · K^{-1}.

TABLE 3
Results for typical combustion experiments at $T = 298.15$ K ($p^\circ = 0.1$ MPa) of the propylene carbonate[a]

m(substance)/g[b]	0.497919	0.491504	0.575586	0.529713	0.53881
m'(cotton)/g[b]	0.003551	0.003376	0.003686	0.003179	0.003722
m''(polythen)/g[b]	0.283244	0.297263	0.291872	0.292214	0.290877
ΔT_c/K[c]	1.49185	1.52777	1.61265	1.55741	1.56596
$(\varepsilon_{calor}) \cdot (-\Delta T_c)$/J	−22083.3	−22615.0	−23871.4	−23053.7	−23180.3
$(\varepsilon_{cont}) \cdot (-\Delta T_c)$/J	−27.5	−28.25	−30.12	−28.8	−28.61
$\Delta U_{decomp}HNO_3$/J	43.00	44.20	45.99	44.20	44.79
ΔU_{corr}/J[d]	9.99	10.13	11.21	10.56	25.36
$-m' \cdot \Delta_c u'$/J	60.17	57.21	62.46	53.87	63.07
$-m'' \cdot \Delta_c u''$/J	13131.48	13781.41	13531.48	13547.33	13485.35
$\Delta_c u^\circ$(liq)/(J · g^{-1})	−17806.4	−17803.1	−17808.5	−17795.6	−17799.0

[a] For the definition of the symbols, see reference [17], calorimeter: $T_h = 298.15$ K; V(bomb) = 0.2664 dm^3; p^i(gas) = 3.04 MPa; $m^i(H_2O) = 1.00$ g.
[b] Masses obtained from apparent masses.
[c] $\Delta T_c = T^f - T^i + \Delta T_{corr}$; $(\varepsilon_{cont}) \cdot (-\Delta T_c) = (\varepsilon^i_{cont}) \cdot (T^i - 298.15\ \text{K}) + (\varepsilon^f_{cont}) \cdot (298.15\ \text{K} - T^f + \Delta T_{corr.})$.
[d] ΔU_{corr}, the correction to standard states, is the sum of items 81 to 85, 87 to 90, 93, and 94 in reference [17], ε_{calor} = 14802.6 ± 1.0 J · K^{-1}.

TABLE 4
Results for typical combustion experiments at $T = 298.15$ K ($p^\circ = 0.1$ MPa) of the butylene carbonate[a]

m(substance)/g[b]	0.393786	0.603616	0.441995	0.367577	0.30439
m'(cotton)/g[b]	0.003535	0.003363	0.003386	0.003395	0.003536
m''(polythen)/g[b]	0.288258	0.302798	0.288243	0.294574	0.29045
ΔT_c/K[c]	1.47442	1.82201	1.5434	1.45614	1.35243
$(\varepsilon_{calor}) \cdot (-\Delta T_c)$/J	−21825.3	−26970.5	−22846.3	−21554.7	−20019.4
$(\varepsilon_{cont}) \cdot (-\Delta T_c)$/J	−27.01	−34.62	−28.43	−26.57	−24.46
$\Delta U_{decomp}HNO_3$/J	44.79	52.56	44.79	42.41	40.02
ΔU_{corr}/J[d]	8.62	11.78	9.27	8.37	7.48
$-m' \cdot \Delta_c u'$/J	59.9	56.99	57.38	57.53	59.92
$-m'' \cdot \Delta_c u''$/J	13363.93	14038.02	13363.23	13656.75	13465.55
$\Delta_c u^\circ$(liq)/(J · g^{-1})	−21268.1	−21281.3	−21267.4	−21264.1	−21258.7

[a] For the definition of the symbols, see reference [17], calorimeter: $T_h = 298.15$ K; V(bomb) = 0.2664 dm^3; p^i(gas) = 3.04 MPa; $m^i(H_2O) = 1.00$ g.
[b] Masses obtained from apparent masses.
[c] $\Delta T_c = T^f - T^i + \Delta T_{corr}$; $(\varepsilon_{cont}) \cdot (-\Delta T_c) = (\varepsilon^i_{cont}) \cdot (T^i - 298.15\ \text{K}) + (\varepsilon^f_{cont}) \cdot (298.15\ \text{K} - T^f + \Delta T_{corr.})$.
[d] ΔU_{corr}, the correction to standard states, is the sum of items 81 to 85, 87 to 90, 93, and 94 in reference [17], ε_{calor} = 14802.6 ± 1.0 J · K^{-1}.

enthalpies of vaporization of the compounds given in table 5 (column 4) were obtained from the temperature dependence of the vapour pressure. The molar enthalpy of sublimation of ethylene carbonate was measured in the same way.

3.3. Calculation of the gaseous enthalpies of formation

Values of vaporization and sublimation enthalpies of alkylene carbonates, derived in our previous work [11] (table 5), can now be used together with the results from our combustion experiments for further calculation of the gaseous standard enthalpies of formation, $\Delta_f H^\circ_m(g)$ at $T = 298.15$ K. The resulting values of $\Delta_f H^\circ_m(g)$ of alkylene carbonates are given in the last column in table 5.

3.4. Quantum chemical calculations for carbonates

Results of *ab initio* molecular orbital methods for calculation of the enthalpy of formation of alkyl carbonates have not been yet reported in the literature. The G3MP2 total energies at $T = 0$ K and enthalpies at $T = 298.15$ K of the molecules studied in this work are given in table 6. We calculated enthalpies of formation of alkylene carbonates using atomization [26] and bond separation reactions [27]. For the latter method, we have chosen the following two reactions:

$$C_nH_{2n}O_3 + (n+3)CH_4 \rightleftharpoons 3CH_3OH + nC_2H_6 \quad (1)$$

$$C_nH_{2n}O_3 + (n+6)CH_4 \rightleftharpoons 3H_2O + (n+3)C_2H_6 \quad (2)$$

TABLE 5
Thermochemical data at $T = 298.15$ K ($p^\circ = 0.1$ MPa) for alkylene carbonates

Compounds	State	$\Delta_c H^\circ_m$/(kJ · mol^{-1})	$\Delta_f H^\circ_m$/(kJ · mol^{-1})	$\Delta^g_l H_m$/(kJ · mol^{-1})[a]	$\Delta_f H^\circ_m$(g)/(kJ · mol^{-1})
Ethylene carbonate	cr	−1167.4 ± 0.4	−584.8 ± 0.6	74.1 ± 0.6[b]	−510.7 ± 0.9
				62.8 ± 0.1	
Propylene carbonate	liq.	−1817.4 ± 0.6	−614.1 ± 0.8	60.2 ± 0.1	−553.9 ± 0.8
Butylene carbonate	liq.	−2470.8 ± 1.0	−640.1 ± 1.2	63.4 ± 0.2	−576.7 ± 1.2
Glycerine carbonate	liq.			85.9 ± 0.2	

[a] From reference [11].
[b] Enthalpy of sublimation.

TABLE 6
G3MP2 total energies at $T = 0$ K and enthalpies at $T = 298.15$ K (in Hartree) of the molecules studied in this work

Compounds	E_0	H_{298}
Ethylene carbonate	−341.955390	−341.949504
Propylene carbonate	−381.198374	−381.191084
Butylene carbonate	−420.432786	−420.424070
Glycerine carbonate	−456.337492	−456.329067

Enthalpies of these reactions calculated by the G3MP2 method and experimental enthalpies of formation $\Delta_f H^\circ_m(g)$, of methane, methanol, water, and ethane from Pedley *et al.* [28], were used to determine enthalpies of formation of alkylene carbonates. Comparison of the calculated and experimental data is given in table 7. Enthalpies of formation of alkylene carbonates derived via the atomization procedure. Both the bond separation reactions 1 and 2 were practically indistinguishable. They were also in an excellent agreement with the available experimental results as shown in table 7.

3.5. Structure–energy relationships: strain enthalpies H_S of alkylene carbonates

Conventional-strain enthalpy, H_S, of a molecule is defined as the difference between its experimental enthalpy of formation, $\Delta_f H^\circ_m(g)$, and the calculated sum of the Benson-type increments [29,30] for this molecule. The system of group additive increments based on the standard enthalpies of formation, $\Delta_f H^\circ_m(g)$, and molar enthalpies of vaporization, $\Delta^g_l H_m$, was established recently [13]. The summary of the group additivity values (GAV) is given in table 8. The new experimental values for $\Delta_f H^\circ_m(g)$ and $\Delta^g_l H_m$ of the cyclic alkyl carbonates (table 5) and increments from table 8 were used for the estimation of the strain enthalpies, $H_S = (\Delta_f H^\circ_m(g) - \Sigma$ increments), of these carbonates. The results on H_S are presented in table 9. Cyclic alkyl carbonates listed in table 9 present a typical example of similarly shaped molecules with the five-membered ring, where an alkyl substituent (methyl or ethyl) is attached to the ring. Hence the strain, H_S, of a molecule is expected to provide insight into the energetic interactions of an alkyl substituent R with the ring.

The strain enthalpies for all alkyl carbonates studied were found to be approximately 40 kJ · mol^{-1} and could be considered equal within the uncertainties of the experiment as expected for similarly shaped five-membered ring derivatives. The H_S value reflects the intrinsic strain, typical for the cyclic molecules, due to nonbonded interactions from steric effects of the carbon and oxygen atoms constituting the ring. No additional interactions of an alkyl substituent R with the ring could be detected. These strains in cyclic alkylene carbonates are also comparable to the strain, $H_S = 38.1$ kJ · mol^{-1}, of the cylopentane (see table 9). Such a similarity of strains in alkylene carbonates proves the consistency of the experimental data involved in the interpretation. For this reason, an additional correction term, which takes into account the strain of the five-membered ring (table 9), should be introduced for the prediction of $\Delta_f H^\circ_m(g)$.

Similar analyses were performed on vaporization enthalpies, $\Delta^g_l H_m$. As can be seen in table 9, the corrections for a five-membered

TABLE 7
Results of calculation of the standard enthalpies of formation $\Delta_f H^\circ_m(g)$ for the alkylene carbonates in the gaseous phase at $T = 298.15$ K

Compounds	$\Delta_f H^\circ_m$/(kJ · mol^{-1}) Atomization	$\Delta_f H^\circ_m$/(kJ · mol^{-1}) Equation (1)	$\Delta_f H^\circ_m$/(kJ · mol^{-1}) Equation (2)	$\Delta_f H^\circ_m$/(kJ · mol^{-1})[a] G3MP2	$\Delta_f H^\circ_m$/(kJ · mol^{-1}) Exp
Ethylene carbonate	−508.4	−509.5	−508.5	−508.8	−510.7 ± 0.9
Propylene carbonate	−552.3	−552.9	−551.9	−552.4	−553.9 ± 0.8
Butylene carbonate	−573.7	−573.8	−572.8	−573.4	−576.7 ± 1.2
Glycerine carbonate	−699.0		−699.5	−699.3	
Di-methyl carbonate	−569.5	−571.3	−570.4	−570.4	−571.0 ± 0.4 [13]
Di-ethyl carbonate	−638.4	−639.2	−638.3	−638.6	−637.9 ± 0.8 [13]
Methyl-cyclohexyl carbonate	−662.9	−661.5	−660.5	−661.6	−657.6 ± 4.2 [13]

[a] Average value from columns 2, 3, and 4.

TABLE 8
Group-additivity values for the calculation of enthalpy of formation, $\Delta_f H^\circ_m$, and enthalpy of vaporization, $\Delta^g_l H_m$, for alkylene carbonates at $T = 298.15$ K

Increment	$\Delta_f H^\circ_m(g)$/(kJ · mol^{-1})	$\Delta^g_l H_m$/(kJ · mol^{-1})	Increment	$\Delta_f H^\circ_m(g)$/(kJ · mol^{-1})	$\Delta^g_l H_m$/(kJ · mol^{-1})
C–(C)(H)$_3$	−41.32	5.69	C(O)(H$_3$)	−41.32	5.69
C–(C)$_2$(H)$_2$	−22.90	4.88	C(O)(H$_2$)(C)	−32.50	2.64
C–(C)$_3$(H)	−11.12	2.61	C(O)(H)(C$_2$)	−31.85	−1.28
C–(C)$_4$	−3.89	−0.47	C(O)(C$_3$)	−21.75	−6.30
(C–C)$_{1-4}$	2.34	0.10	Ph(O)	95.00	27.71
CO(O$_2$)	−487.64	27.04	Five-membered ring	39.5	25.3

TABLE 9
Strain in alkylene carbonates at $T = 298.15$ K

Compounds	$\Delta_f H^\circ_m(g)_{exp}$/(kJ · mol^{-1})	Σ_{incr}/(kJ · mol^{-1})[a]	H_S/(kJ · mol^{-1})[b]	$\Delta^g_l H_{m\,exp}$/(kJ · mol^{-1})	Σ_{incr}/(kJ · mol^{-1})[c]	GAV/(kJ · mol^{-1})[d]
Ethylene carbonate	−510.7 ± 0.9	−552.6	41.9	62.8 ± 0.1 [11]	24.4	30.5
Propylene carbonate	−553.9 ± 0.8	−553.9	39.4	60.2 ± 0.1 [11]	32.3	26.1
Butylene carbonate	−576.7 ± 1.2	−576.7	39.5	63.4 ± 0.2 [11]	34.1	24.4
Cyclopentane	−76.4 ± 0.8 [28]	−114.5	38.1	28.7 ± 0.1 [28]	39.1	4.3

[a] Sum of the increments from table 8, column 2.
[b] $H_S = (\Delta_f H^\circ_m(g) - \Sigma$ increments) was calculated as the difference between columns 2 and 3 from this table.
[c] Sum of the increments from table 8, column 3.
[d] GAV was calculated as the difference between columns 5 and 6 from this table.

ring for propylene carbonate (26.1 kJ · mol^{-1}) and butylene carbonate (24.4 kJ · mol^{-1}) are nearly the same, but significantly different from the unsubstituted five-membered ring correction of ethylene carbonate (30.5 kJ · mol^{-1}). This discrepancy demonstrates that the interactions of an alkyl substituent R with the ring are not negligible for this thermodynamic property. Thus an additional correction term for the alkyl substituted five-membered ring (table 9) should be included for the prediction of $\Delta_l^g H_m$. Surprisingly, the five-membered ring corrections for the unsubstituted five-membered ring for ethylene carbonate (30.5 kJ · mol^{-1}) and its alkyl derivatives are substantially larger (see table 9) than those of cyclopentane (4.3 kJ · mol^{-1}).

4. Conclusions

The group-additivity methods serve as a valuable tool for many scientists and engineers whose work involves thermodynamic characterization of elementary and overall reaction processes. New experimental thermochemical results for alkylene carbonates have been determined and extended available data for this chemical family. The use of the modern first principle calculations allowed the validation of the mutual consistency of the experimental data. Strain corrections derived in this work are useful for the prediction of the thermochemical properties of a broad range of organic compounds containing carbonate moiety.

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4.4 Organic Carbonates as Alternative Solvents for Asymmetric Hydrogenation

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Contributions

My contribution as co-author to this paper accounts 70%. I prepared the manuscript and accomplished most of the catalytic reactions.

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Organic Carbonates as Alternative Solvents for Asymmetric Hydrogenation

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ABSTRACT Organic carbonates like propylene carbonate (PC) or butylene carbonate (BC) belong to the class of aprotic, highly dipolar solvents (AHD). Interestingly, their potential as solvents for asymmetric catalysis has been overlooked for a long time. The aim of this work is to evaluate organic carbonates and other organic solvents like THF, CH_2Cl_2, and acetonitrile as well as members of the AHD-family (DMF, DMSO, etc.) as media for homogeneous asymmetric hydrogenation. For this reason cationic Rh-complexes based on chiral phosphine ligands were tested in the hydrogenation of typical benchmark substrates. In several trials, significant advantages of organic carbonates were found. In contrast to DMSO, DMF and acetonitrile, in PC and BC high conversion rates and excellent enantioselectivities were usually observed. *Chirality 00:000–000, 2009.*

KEY WORDS: asymmetric catalysis; green chemistry; hydrogenation; alternative solvents; propylene carbonate; butylene carbonate; solvent effects; rhodium

INTRODUCTION

Enantiopure compounds constitute important building blocks for synthesis of cosmetics,[1] pharmaceuticals[2] and for the preparation of chiral biodegradable polymers.[3,4] In recent decades several methodologies have been employed for their synthesis. In particular, asymmetric hydrogenation plays an important role and is frequently used as a key step in multistep reactions.[5] Enantioselective hydrogenation can be conducted on a large industrial scale by use of hydrogen as a cheap reducing agent.[6,7] As catalytically active metal especially rhodium(I), ruthenium(II) and iridium(I) have seen broad application. In combination with ancillary chiral phosphorus or nitrogen ligands as well as mixtures of them they offer a valuable tool for a range of different hydrogenations.[8]

Additionally to the choice of ligand, the proper set-up of the hydrogenation conditions is essential. Next to reaction temperature and hydrogen pressure, the nature of the solvent is crucial for achieving high yields and enantioselectivities. Widely used solvents like methanol, dichloromethane, tetrahydrofuran and toluene differ in scope and limitations. Methanol is known to be toxic. Dichloromethane, a broadly used solvent, is volatile and is therefore often replaced by the less volatile but toxic 1,2-dichloroethane. THF and toluene are also commonly used, but they are easy flammable. In recent investigations, fluorinated alcohols[9] and ionic liquids[10] displayed impressive results as solvents, but their use is limited due to their availability on a large scale, toxicity, viscosity and high prices. [For a review on the use of fluorinated alcohols in homogeneous catalysis.] Furthermore, there are several problems faced in the purification of ionic liquids.

With the ongoing discussion about alternative solvents in recent years we focused our work on the use of organic carbonates for asymmetric catalysis.[11] Divided in two subgroups (cyclic and alicyclic carbonates), organic carbonates offer a broad field of application. [For reviews on the use of organic carbonates, and for a recent review on the synthesis of organic carbonates see Ref. 12,13.] Alicyclic carbonates, like dimethyl carbonate[14] are environmentally friendly building blocks and can thus replace toxic reagents like phosgene or can be used for transesterifications and the synthesis of amides. They can also be used as low boiling solvents and fuel additives. In contrast, cyclic carbonates, e.g., propylene carbonate (PC) own a high boiling point and a low vapor pressure. The viscosity of organic carbonates is acceptable. In particular PC is inflammable and nontoxic. It can be therefore considered as "green solvent" also taking in mind its environmentally friendly synthesis from carbon dioxide and propylene oxide.[15–17]

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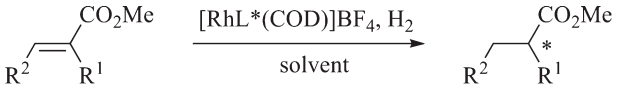
Currently, organic carbonates are widely used in batteries and for pharmaceutical and medical applications as well as for extraction. [For the perspectives of the application of organic carbonates, see Ref. 18.] First applications of PC were published in the 1960s by Nelson and the FLUOR Corporation.[19,20] PC was used for a purification process of natural gas due to its high carbon dioxide absorption property. In the 1980s PC was propagated as solvent for industrial scale hydroformylations.[21,22] Behr et al. showed the interesting behavior of PC to form temperature dependent multicomponent solvent systems (TMS) in Rh-catalyzed hydroformylations.[23,24]

In recent years, we investigated the use of organic carbonates, e.g., for the Ir-catalyzed asymmetric hydrogenation of unfunctionalized olefins.[11] It was shown that the isomerization of nonpolar olefins in the presence of the Ir-complex was slower in PC than in CH_2Cl_2. Because of high polarity of PC and its immiscibility with nonpolar solvents a two phase extraction procedure allowed efficient catalyst recycling, up to six cycles. Furthermore, Rh-catalysts with self-assembling ligands displayed increased reactivity accompanied by high enantioselectivity in PC in contrast to MeOH and CH_2Cl_2.[25] The use of organic carbonates is not only limited to catalysis with rhodium or iridium. Thus, high yields were observed in the Pd-catalyzed Sonogashira reaction[26,27] and excellent enantioselectivities in the Pd-catalyzed asymmetric allylic substitution.[28] In order to obtain nonpolar bulk chemicals, a Ru-catalyzed metathesis reaction was investigated in PC. Schäffner and Börner, unpublished results The metathesis products could be either extracted or evaporated out of PC.

Recently, we established a lab process of Rh-catalyzed hydrogenation followed by a distillative separation of the product out of PC.[29] Pure lactic acid esters were produced in high yields and with excellent enantioselectivities. This study also covered a full solvent screening to spotlight the importance of the choice of solvent. While we obtained full conversion and high selectivities in PC within in short reaction times the results deteriorated significantly when other typical solvents like CH_2Cl_2 or THF were used.[29]

PC can be affiliated to the group of aprotic highly dipolar solvents (AHD). Its polarity (E_T^N = 0.47) is similar to DMSO (0.44) and DMF (0.39) which also belong to the AHD group. The hydrogen bond acceptor properties (basicity = β) of PC (β = 0.39) meet those of acetonitrile



1: R^1 = NHAc, R^2 = Ph
2: R^1 = CH_2COOMe, R^2 = H
3: R^1 = NHAc, R^2 = H

Fig. 1. Rh-catalyzed asymmetric hydrogenation of benchmark substrates.

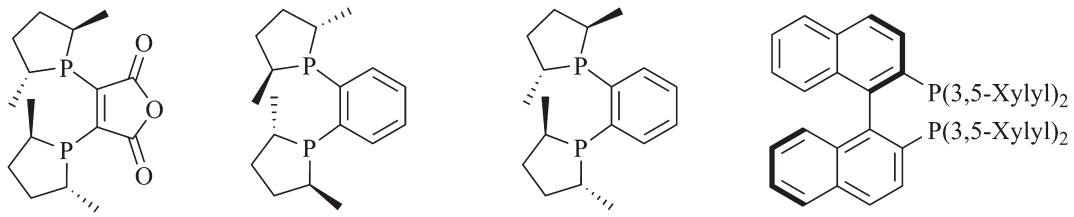
(β = 0.38). Although, acetonitrile (AN) has a polarity (E_T^N = 0.44) similar to PC and nearly the same hydrogen bond acceptor property it is not a member of the AHD group.[30] Therefore a comparison must necessarily consider organic carbonates and other member of the AHD group as well as acetonitrile.

Herein we will summarize results of the Rh-catalyzed asymmetric hydrogenations using some commonly employed functionalized olefins in organic carbonates (PC and BC) and other solvents of the AHD-class (DMF, DMSO, etc.) as well as in THF, CH_2Cl_2, and acetonitrile.

RESULTS AND DISCUSSION

For our experiments we used as prochiral benchmark substrates methyl α-acetylaminocinnamate (**1**), dimethyl itaconate (**2**) and methyl 2-acetamidoacrylate (**3**) (Fig. 1) which are commonly used in catalytic tests for asymmetric hydrogenations. (See, for e.g., the asymmetric hydrogenation of fluorinated alcohols and ionic liquids in Refs. 31,32.) F1,AQ3

As pre-catalysts, cationic complexes of the type [Rh(L*)(diolefin)]BF_4 {L* = chiral ligand; diolefin = norborna-2,5-diene (NBD) or 1,5-cyclooctadiene (COD)} based on the chiral ligands (2*R*,5*R*)-catASium M (**4**), (For application of catASium M as ligands in asymmetric hydrogenation, see Ref. 33,34) (2*S*,5*S*)-Me-DuPHOS (**5**) (for a comparison for the application of MeDUPHOS as ligand for asymmetric hydrogenations, see Ref. 35–37) and (*S*)-Xylyl-BINAP (**6**) (more about the application of Xylyl-BINAP as ligand in asymmetric hydrogenations, see Ref. 38, 39) were employed (see Fig. 2). The experiments were carried out at room temperature and 1 bar hydrogen pres- F2



(2*R*,5*R*)-cat*AS*ium M (2*S*,5*S*)-Me-DuPHOS (2*R*,5*R*)-Me-DuPHOS (*S*)-Xylyl-BINAP

(2*R*,5*R*)-**4** (2*S*,5*S*)-**5** (2*R*,5*R*)-**5** (*S*)-**6**

Fig. 2. Chiral ligands (L*).

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TABLE 1. Hydrogenation of methyl α-acetylaminocinnamate (1)[a]

Entry	Ligand	Solvent	H_2 (bar)	Time (min)	Conv. (%)[b]	ee (%)[b]
1	(2*R*,5*R*)-**4**	DMSO	1	1260	53	75 (*R*)
2	(2*R*,5*R*)-**4**	DMSO	10	40	4	75 (*R*)
3	(2*R*,5*R*)-**4**	DMF	1	120	>99	96 (*R*)
4	(2*R*,5*R*)-**4**	PC	1	120	>99	98 (*R*)
5	(2*R*,5*R*)-**4**	BC	1	160	>99	99 (*R*)
6	(2*R*,5*R*)-**4**	MeOH	1	180	>99[c]	94 (*R*)[c]
7	(2*R*,5*R*)-**4**	THF	1	180	>99[c]	99 (*R*)[c]
8	(2*R*,5*R*)-**4**	CH_2Cl_2	1	180	>99[c]	98 (*R*)[c]
9	(2*S*,5*S*)-**5**	DMSO	1	1260	7	4 (*R*)
10	(2*S*,5*S*)-**5**	DMSO	10	40	76	95 (*S*)
11	(2*S*,5*S*)-**5**	DMF	1	1380	9	24 (*S*)
12	(2*S*,5*S*)-**5**	DMF	10	40	>99	96 (*S*)
13	(2*R*,5*R*)-**5**	PC	1	180	>99[c]	99 (*R*)[c]
14	(2*S*,5*S*)-**5**	PC	10	40	93	97 (*S*)
15	(2*S*,5*S*)-**5**	BC	1	1200	40	89 (*S*)
16	(2*S*,5*S*)-**5**	BC	10	40	94	97 (*S*)
17	(2*R*,5*R*)-**5**	MeOH	1	180	>99[c]	98 (*R*)[c]
18	(2*R*,5*R*)-**5**	THF	1	180	>99[c]	97 (*R*)[c]
19	(2*R*,5*R*)-**5**	CH_2Cl_2	1	180	>99[c]	98 (*R*)[c]
20	(*S*)-**6**	DMSO	1	1260	2	12 (*S*)
21	(*S*)-**6**	DMSO	10	40	0	–
22	(*S*)-**6**	DMF	1	1560	12	28 (*S*)
23	(*S*)-**6**	DMF	10	40	10	28 (*S*)
24	(*S*)-**6**	PC	1	120	>99	60 (*S*)
25	(*S*)-**6**	BC	1	120	>99	68 (*S*)

[a]Hydrogenation conditions: 0.4 mmol of substrate **1**, 1 mol-% of [Rh(L*)(COD)]BF_4 {or 1 mol-% of [Rh(L*)(NBD)]BF_4 in the case of L* = (2*R*,5*R*)-**4**}, 2 ml of solvent; 1 bar hydrogenations under isothermal and isobar conditions or at 10 bar hydrogenations under isochor and isothermal conditions in a eightfold parallel autoclave device.
[b]Enantiomeric excess was determined by GC using 25 m γ-cyclodextrin, lipodex E (Machery und Nagel), silica, 130°C.
[c]See Ref. 11.

sure under isobar and isothermal conditions in a glass device equipped with a gas consumption detector. In case of low conversions, we conducted the reaction at 10 bar initial pressure in a eightfold stainless steel autoclave under isochoric conditions at constant temperature (25°C).

The reactions were run in dimethyl sulfoxide (DMSO), dimethyl formamide (DMF), acetonitrile (AN), propylene carbonate (PC) and butylene carbonate (BC). First trials in the hydrogenation of substrate **1** indicated that in acetonitrile at 1 bar all catalysts gave only poor conversion (3% after 21 h). Application of [Rh((2*R*,5*R*)-**4**)(NBD)]BF_4 showed high conversion rates and excellent enantioselectivities in DMF, PC and BC (Table 1, entries 3–5). The T1 reactivity was significantly lower in DMSO, although its polarity and basicity is similar to DMF (entries 1–2). These results spotlight the differences of both solvents. Hydrogenation at 10 bar pressure in DMSO showed no benefit. It could be shown that the low reactivity in DMSO does not depend on the catalyst (entries 1, 2 and 9, 10 and 20, 21). The best result in DMSO was achieved with the catalyst based on (2*S*,5*S*)-Me-DuPHOS (**5**) at 10 bar hydrogen pressure (76% conversion and 95% *ee*) (entry 10). On the other hand, superior results were obtained in BC and PC with (2*R*,5*R*)-**4** as ligand. Hydrogenation at 1 bar H_2-pressure was complete after 120 and 160 min with 98% *ee* and 99% *ee*, respectively (entries 4, 5). The results are comparable with those noted in the "standard" solvents MeOH, THF and dichloromethane (entries 6–8).

The catalyst generated from [Rh((2*R*,5*R*)-**5**)(COD)]BF_4 was less active in aprotic highly dipolar solvents than in THF, MeOH and CH_2Cl_2 (entries 9, 11, 13, 15, 17–19). Best results were obtained at 10 bar hydrogen pressure (entries 10, 12, 16). The Rh(I)-complex with (*S*)-Xylyl-BINAP (**6**) gave only satisfactory results in BC and PC (entries 24 and 25). The hydrogenations failed in DMSO at 1 bar as well as at 10 bar and only low conversion rates were observed in DMF (entries 20–23). It is noteworthy, that in most cases the enantioselectivities in BC were slightly higher than in PC, although, the reaction time in the latter solvent was longer (compare entries 4, 5, 13–16, 24 and 25).

With dimethyl itaconate (**2**) as substrate in DMSO no results were obtained, due to serious analytical difficulties caused by the solvent. Acetonitrile failed as solvent; no conversion was observed. The other results are listed in Table 2. The highest enantioselectivities were obtained in T2 PC with 99% and 98%, respectively (entries 3 and 11). In comparison to DMF, MeOH, THF and CH_2Cl_2 the use of PC is favored. In contrast to other catalysts, the complex based on (*S*)-**6** induced only poor *ee*-values (entries 17–19). The results in DMF with [Rh((2*R*,5*R*)-**4**)(NBD)]BF_4 were improved by running the reaction at 10 bar. The conversion rose from 28% up to 47% and the enantioselectivity

TABLE 2. Hydrogenation of dimethyl itaconate (2)[a]

Entry	Ligand	Solvent	H_2 (bar)	Time (min)	Conv. (%)[b]	ee (%)[b]
1	(2*R*,5*R*)-**4**	DMF	1	960	28	13 (*S*)
2	(2*R*,5*R*)-**4**	DMF	10	40	47	43 (*S*)
3	(2*R*,5*R*)-**4**	PC	1	70	>99	99 (*S*)
4	(2*R*,5*R*)-**4**	BC	1	180	>99	98 (*S*)
5	(2*R*,5*R*)-**4**	MeOH	1	180	>99[c]	60 (*S*)[c]
6	(2*R*,5*R*)-**4**	THF	1	180	>99[c]	86 (*S*)[c]
7	(2*R*,5*R*)-**4**	CH_2Cl_2	1	180	>99[c]	98 (*S*)[c]
8	(2*S*,5*S*)-**5**	DMF	1	960	48	*Rac*
9	(2*S*,5*S*)-**5**	DMF	10	40	73	73 (*R*)
10	(2*R*,5*R*)-**5**	PC	1	180	>99[c]	97 (*S*)[c]
11	(2*S*,5*S*)-**5**	PC	10	40	>99	98 (*R*)
12	(2*S*,5*S*)-**5**	BC	1	960	15	54 (*R*)
13	(2*S*,5*S*)-**5**	BC	10	40	89	95 (*R*)
14	(2*R*,5*R*)-**5**	MeOH	1	180	>99[c]	95 (*S*)[c]
15	(2*R*,5*R*)-**5**	THF	1	180	>99[c]	97 (*S*)[c]
16	(2*R*,5*R*)-**5**	CH_2Cl_2	1	180	>99[c]	80 (*S*)[c]
17	(*S*)-**6**	DMF	1	600	>99	*Rac*
18	(*S*)-**6**	PC	1	120	>99	8 (*S*)
19	(*S*)-**6**	BC	1	110	>99	3 (*S*)

[a]Hydrogenation conditions: 0.4 mmol of substrate **2**, 1 mol-% of [Rh(L*)(COD)]BF_4 {or 1 mol-% of [Rh(L*)(NBD)]BF_4 in the case of L* = (2*R*,5*R*)-**4**}, 2 ml of solvent; 1 bar hydrogenations under isothermal and isobar conditions or at 10 bar hydrogenations under isochor and isothermal conditions in a eightfold parallel autoclave device.
[b]Enantiomeric excess was determined by GC using 25 m γ-cyclodextrin, lipodex E (Machery and Nagel), silica, 130°C.
[c]See Ref. 11.

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TABLE 3. Hydrogenation of methyl 2-acetamidoacrylate (3)[a]

Entry	Ligand	Solvent	H_2 (bar)	Time (min)	Conv. (%)[b]	ee (%)[b]
1	(2*R*,5*R*)-**4**	DMSO	1	280	88	96 (*R*)
2	(2*R*,5*R*)-**4**	DMF	1	60	>99	98 (*R*)
3	(2*R*,5*R*)-**4**	AN	1	1260	10	95 (*R*)
4	(2*R*,5*R*)-**4**	PC	1	60	>99	98 (*R*)
5	(2*R*,5*R*)-**4**	BC	1	180	>99	99 (*R*)
6	(2*S*,5*S*)-**5**	DMSO	1	180	>99	98 (*S*)
7	(2*S*,5*S*)-**5**	DMF	1	70	82	98 (*S*)
8	(2*S*,5*S*)-**5**	AN	1	1260	5	80 (*S*)
9	(2*S*,5*S*)-**5**	PC	1	70	>99	>99 (*S*)
10	(2*S*,5*S*)-**5**	BC	1	130	>99	>99 (*S*)
11	(*S*)-**6**	DMSO	1	960	71	47 (*S*)
12	(*S*)-**6**	DMSO	10	40	53	47 (*S*)
13	(*S*)-**6**	DMF	1	180	>99	34 (*S*)
14	(*S*)-**6**	AN	1	1260	0	–
15	(*S*)-**6**	AN	10	40	8	–
16	(*S*)-**6**	PC	1	180	>99	38 (*S*)
17	(*S*)-**6**	BC	1	180	>99	48 (*S*)

[a]Hydrogenation conditions: 0.4 mmol of substrate **3**, 1 mol-% of $[Rh(L^*)(COD)]BF_4$ {or 1 mol-% of $[Rh(L^*)(NBD)]BF_4$ in the case of L* = (2*R*,5*R*)-**4**}, 2 ml of solvent; 1 bar hydrogenations under isothermal and isobar conditions or at 10 bar hydrogenations under isochor and isothermal conditions in a eightfold parallel autoclave device.
[b]Enantiomeric excess was determined by GC using 25 m γ-cyclodextrin, lipodex E (Machery und Nagel), silica, 130°C.
[c]See Ref. 11.

by 13–43% (compare entries 1 and 2). As already illustrated in Table 1, hydrogenations with the catalyst based on (2*S*,5*S*)-Me-DuPHOS (**5**) are strongly affected by the hydrogen pressure. With substrate **2** in DMF the enantioselectivity increased at 10 bar to 73% (entries 8 and 9). In BC the selectivity rose from 54% at 1 bar to 95% at 10 bar (entries 12 and 13). In PC the enantioselectivities achieved at 1 and 10 bar are comparable, 97% and 98%, respectively (entries 10 and 11).

Results of the asymmetric hydrogenation of methyl 2-acetamidoacrylate **(3)** are listed in Table 3. Because of the known high reactivity of this substrate, we were able to achieve some conversion even in acetonitrile with high enantioselectivity (entries 3 and 8). Hydrogenation using the less active catalyst derived from (*S*)-**6** ligand showed no conversion at ambient pressure and only 8% at 10 bar (entries 14 and 15). With the catalyst based on (2*R*,5*R*)-**4,** the best results were obtained in DMSO, DMF, PC and BC. Among these trials, the reaction in DMSO proceeded slightly slower but enantioselectivities were in all cases higher than 95% (entries 1–5).

Superior stereodiscrimination was noted in BC, whereas a longer reaction time was necessary in order to achieve full conversion (entry 5). Excellent results were also observed with (2*S*,5*S*)-Me-DuPHOS **(5)** in organic carbonates (entries 9 and 10). Even in DMSO the reaction was complete after 3 h with an enantioselectivity of 98% (entry 6).

Analogous to the results in Table 1, the catalyst based on (*S*)-**6** led only to moderate results. In DMSO the conversion was not complete after 16 h and the chiral product was generated only with 47% *ee* (entry 11). Higher reactivity in DMSO was found at 10 bar with the same enantioselectivity (entry 12). In DMF, PC and BC full conversion was observed after 3 h but the enantioselectivities still remained low (entries 13–17). Hydrogenation of **3** in BC instead of PC increased the enantioselectivity to 48% *ee* (entries 16 and 17).

A detailed screening of the Rh-catalyzed asymmetric hydrogenations was accomplished in order to find similarities and differences caused by different aprotic, highly dipolar solvents and acetonitrile. In several trials similar results in DMF, propylene carbonate (PC) and butylene carbonate (BC) were observed. In contrast, acetonitrile failed as solvent. This feature can be rationalized by its property to act as a strongly coordinating co-ligand. Surprisingly, superior enantioselectivities were noted in BC, but this advantage was frequently counterbalanced by longer reaction times in comparison to the use of PC. Unfortunately, BC is much more expensive than the later. In general, in both carbonates as solvent similar or even better results could be observed than in "standard" solvents like MeOH, THF and CH_2Cl_2. Together with their environmentally friendly properties, these "forgotten" solvents can really compete with usually applied media, but which are toxic (MeOH), easily inflammable (THF) or easy evaporating (CH_2Cl_2) solvents. A challenge for the use of carbonates as solvents is the separation of the products. With extractive methods,[11] multicomponent temperature depending solvent systems[23,24] and distillations[29] some innovative examples have been given in the recent literature. Moreover, the accumulated knowledge of separation methods for reactions in ionic liquids can be useful for carbonates as well. Propylene carbonate has a high potential to absorb CO_2 which can modify the polarity. This convenient method has recently been shown by Jessop and co-workers for other solvents.[40] Thus, the CO_2 modification could be used to separate catalysts from PC or highly polar substrates. Further research concerning this issue is in progress.

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4.5 Propylene Carbonate as a Solvent for Asymmetric Hydrogenations

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Contributions

My contribution as co-author to this paper accounts 40%. Several experiments were prepared by me and I significantly contributed to the draft of the manuscript.

Asymmetric Catalysis

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Propylene Carbonate as a Solvent for Asymmetric Hydrogenations**

*Jerome Bayardon, Jens Holz, Benjamin Schäffner, Vasyl Andrushko, Sergej Verevkin, Angelika Preetz, and Armin Börner**

Dedicated to Professor Rüdiger Selke

The correct choice of solvent is one of the central problems in synthetic chemistry, for in many cases the physical and toxicological properties of a solvent have a pivotal influence on its use on both the laboratory and industrial scale. Multiphase methods with immiscible solvents allow repeated recycling of the catalyst in homogeneous catalysis.[1] Prominent examples of this ecologically and economically sensible approach include catalyzed reactions in multiphase systems containing water,[2] fluorinated hydrocarbons,[3] supercritical CO_2,[4] and ionic liquids (ILs).[5]

Up to now organic cyclic carbonates, in particular propylene carbonate (PC), have not played a role as solvents for asymmetric hydrogenations. The few exceptions in homogeneous catalysis include the platinum-catalyzed hydrosilylation of unsaturated fatty acids investigated by Behr et al.[6] and regioselective, rhodium-catalyzed hydroformylation in PC as solvent.[7] Reetz et al. were successful in stabilizing palladium colloids with PC.[8]

Propylene carbonate is a dipolar aprotic solvent that has previously found application mainly in extractions, electrochemistry, cosmetics, and medicine. In addition to its excellent solvation properties, PC has valuable physical properties such as low viscosity, and it is essentially odorless. Like other organic carbonates PC is usually anhydrous, noncorrosive, nontoxic, and biodegradable.[9] Based on these properties organic carbonates offer a "safe" and environmentally friendly alternative to standard solvents such as CH_2Cl_2 and THF, as well as aromatic and toxic solvents.[10] Many alkyl carbonates are available commercially.[11]

In order to investigate the suitability of PC for asymmetric hydrogenations, rhodium-catalyzed asymmetric hydrogenations were initially carried out with a set of common olefins. The commercially available diphosphanes cat*A*Sium M,[12] Me-duphos,[13] binap,[14] tol-binap,[15] and josiphos[16] were used as ligands. The precatalysts were prepared by reaction of the ligands with $[Rh(cod)_2]BF_4$ in PC in situ (cod = 1,5-cyclooctadiene).

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For comparison the hydrogenations were carried out in parallel in MeOH, THF, and CH_2Cl_2. The results for methyl α-acetylaminocinnamate and dimethyl itaconate are listed in Table 1 and Table 2. It is clear from these measurements that PC is ideally suited for asymmetric hydrogenation, since similar or even higher enantioselectivities are achieved with comparable reactivity.[17]

Table 1: Rhodium-catalyzed asymmetric hydrogenation of methyl α-acetylaminocinnamate with different phosphane ligands.[a]

	ee [%][b]			
Ligand	PC	MeOH	THF	CH_2Cl_2
cat*A*Sium M	97	94	99	98
Me-duphos	99	98	97	98
binap	43	14	45	32
tol-binap	50	4	47	35
josiphos	79	77	86	–

[a] Complexes of the type $[Rh(cod)_2]BF_4$ (L = ligand) were used as catalysts; cat*A*Sium M = 2,3-bis[(2*R*,5*R*)-2,5-dimethylphospholanyl]maleic acid anhydride, Me-duphos = 1,2-bis[(2*R*,5*R*)-2,5-dimethylphospholanyl]benzene, binap = (*R*)-2,2′-bis(diphenylphosphanyl)-1,1′-binaphthyl, tol-binap = (*R*)-2,2′-bis(di-*p*-tolylphosphanyl)-1,1′-binaphthyl, josiphos = (*R*)-1-[(*S*)-2-diphenylphosphanyl)ferrocenyl]ethyldicyclohexylphosphane. Substrate/cat. 100:1, 7.5 mL solvent, $p(H_2) = 1$ bar (isobar), 25 °C. [b] Determined by GC, 25 m γ-cyclodextrin, lipodex E (Machery und Nagel), silica, 130 °C, complete conversion after 3 h.

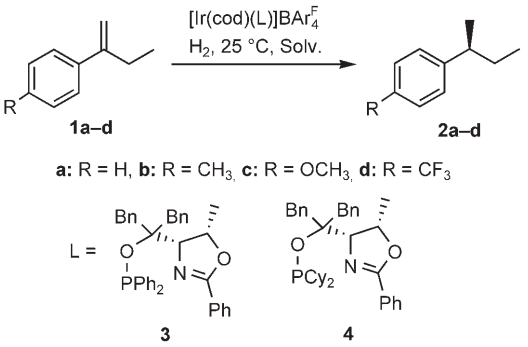
Table 2: Rhodium-catalyzed asymmetric hydrogenation of dimethyl itaconate with different phosphane ligands.[a]

	ee [%][b]			
Ligand	PC	MeOH	THF	CH_2Cl_2
cat*A*Sium M	95	60	86	98
Me-duphos	97	95	97	80
binap	73	4	19	77
tol-binap	78	0	5	75
josiphos	99	88	92	–

[a] Complexes of the type $[Rh(cod)_2]BF_4$ (L = ligand) were used as catalysts; substrate/cat. 100:1, 7.5 mL solvent, $p(H_2) = 1$ bar (isobar), 25 °C. [b] Determined by GC, 25 m γ-cyclodextrin, lipodex E (Machery und Nagel), silica, 130 °C, complete conversion after 3 h.

Since PC is not miscible with nonpolar solvents, a two-phase reaction would allow catalyst recycling. The requirement is that the catalyst is soluble in PC and the product is more soluble in the nonpolar solvent than in PC. This is not the case for the amino acid and dicarboxylate in Tables 1 and 2. In contrast, in the hydrogenation of nonfunctionalized

olefins, the alkanes formed are highly soluble in hexane. Iridium complexes with the oxazoline phosphites **3** and **4** as ligands were used as catalysts (Scheme 1);[18] these ligands are known to be suitable for the hydrogenation of styrene



Scheme 1. Asymmetric hydrogenation of *p*-substituted α-ethylstyrene.

derivatives such as **1a–d** based on the work of Pfaltz et al.[19] As can be seen from Table 3, similar enantioselectivity values were obtained in PC, although reaction times were significantly greater in PC than in CH_2Cl_2. Most results show the known dependency of enantioselectivity on hydrogen pressure.[19]

Table 3: Iridium-catalyzed asymmetric hydrogenation of styrene derivatives in PC and CH_2Cl_2.[a]

Substr.	Solv.	H_2 [atm]	[Ir(cod)(**3**)]BAr$^F_4$		[Ir(cod)(**4**)]BAr$^F_4$	
			t [h][b]	*ee* [%][c]	*t* [h][b]	*ee* [%][c]
1a	PC	50	4	61 (*S*)	4	76 (*S*)
1a	CH_2Cl_2	50	3	64 (*S*)	3	52 (*S*)
1a	PC	1	6	46 (*S*)	4	83 (*S*)
1a	CH_2Cl_2	1	0.1	78 (*S*)	0.1	86 (*S*)
1b	PC	50	4	62 (*S*)	4	78 (*S*)
1b	CH_2Cl_2	50	1	73 (*S*)[d]	2	56 (*S*)[d]
1b	PC	1	7	47 (*S*)	2	85 (*S*)
1b	CH_2Cl_2	1	0.5	88 (*S*)[d]	0.5	91 (*S*)[d]
1c	PC	50	4	61 (*S*)	4	74 (*S*)
1c	CH_2Cl_2	50	1	71 (*S*)[d]	2	58 (*S*)[d]
1c	PC	1	6	54 (*S*)	2	82 (*S*)
1c	CH_2Cl_2	1	0.5	90 (*S*)[d]	0.5	94 (*S*)[d]
1d	PC	50	4	30 (*S*)	4	74 (*S*)
1d	CH_2Cl_2	50	1	46 (*S*)[d]	2	54 (*S*)[d]
1d	PC	1	7	5 (*S*)	6	66 (*S*)
1d	CH_2Cl_2	1	0.5	59 (*S*)[d]	0.5	88 (*S*)[d]

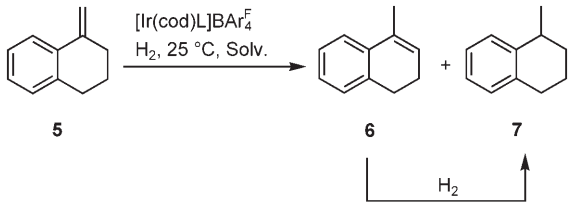
[a] Conditions: 0.4 mmol substrate, 0.004 mmol [Ir(cod)L]BAr$^F_4$, 2 or 8 mL solvent (Solv.), 25 °C. [b] Time for complete conversion. [c] Determined by GC or HPLC. [d] Data from Ref. [19].

In Table 4 the results of a detailed study of the hydrogenation of 1-methylene-1,2,3,4-tetrahydronaphthalene (**5**; Scheme 2) at different hydrogen pressures and temperatures are compared with the results obtained in CH_2Cl_2. The chiral product **7** is formed in this reaction as well as the isomerized olefin **6** as an intermediate, which can also be hydrogenated. The hydrogenation of **5** under normal pressure leads to a mixture of **6** and **7** with conversions of 74–100 %. The fraction

Table 4: Iridium-catalyzed asymmetric hydrogenation of **5** in PC and CH_2Cl_2.[a]

Lig.	Solv.	H_2 [atm]	*t* [h]	Conv. [%][b]	**6**/**7**[b]	*ee* [%][c]
3	PC	50	4	100	7:93	8.3 (*R*)
3	CH_2Cl_2	50	3	100	0:100	25.7 (*S*)
3	PC	1	20	85	62:38	3.5 (*R*)
3	CH_2Cl_2	1	3	85	50:50	28.6 (*S*)
4	PC	50	4	100	13:87	81.3 (*R*)
			8	100	4:96	82.1 (*R*)
4	PC	85	4	100	5:95	82.1 (*R*)
4	PC	100	4	100	3:97	82.4 (*R*)
4	CH_2Cl_2	50	3	100	0:100	16.9 (*R*)
4	PC	1	20	74	63:37	73.2 (*R*)
4	CH_2Cl_2	1	3	100	71:29	46.3 (*R*)

[a] Conditions: 0.4 mmol substrate, 0.004 mmol [Ir(cod)L]BAr$^F_4$, 2 or 8 mL LM, 25 °C. [b] Determined by NMR spectroscopy and GC on chiral phase. [c] Determined by GC on chiral phase.

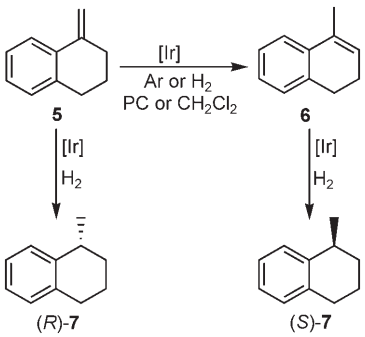


Scheme 2. Asymmetric hydrogenation of 1-methylene-1,2,3,4-tetrahydronaphthalene (**5**).

of the hydrogenation product **7** is usually higher for reactions in CH_2Cl_2 than those in PC.

Only very low enantioselectivities were obtained with the use of [Ir(cod)(**3**)]BAr$^F_4$ (BAr$^F_4$ = B(C$_6$H$_3$(CF$_3$)$_2$)$_4$); the best value in CH_2Cl_2 was about 28.6 % *ee*. For the hydrogenation with iridium catalysts with the ligand **4** the results in PC were significantly better than those in CH_2Cl_2 (increase by about 60 % *ee*). Further improvement to 82.4 % *ee* was obtained with an increase in pressure.

To explain these differences, the isomerization of the external olefin **5** to the internal olefin **6** was investigated initially in the presence of the iridium catalyst but without hydrogen atmosphere (Scheme 3). DFT calculations confirm that **6** is significantly more stable than **5** with its exocyclic double bond.[20] NMR spectroscopic investigations show that the isomerization proceeds more slowly in PC than in CH_2Cl_2.[21]



Scheme 3. Studies on the isomerization and hydrogenation of olefins.

By use of the same catalyst, products with opposite configurations are obtained in the hydrogenation of **5** and **6**. The exocyclic olefin is almost exclusively stereoselectively hydrogenated in PC. In contrast, the parallel hydrogenation of **5** and **6** in CH_2Cl_2 leads to a mixture of *R* and *S* products and thus to a lower enantioselectivity.[22]

The use of PC would be especially beneficial if the separation of the expensive catalyst in a two-phase mixture were possible. The yellow iridium complex [Ir(cod)(**4**)]BAr^F_4 (Figure 1) is located exclusively in the PC phase.

Figure 1. Two-phase system composed of *n*-hexane and PC with [Ir(cod)(**4**)]BAr^F_4.

In a typical experiment olefin **5** was hydrogenated in PC and the product was removed by extraction with *n*-hexane. The catalyst can be used up to five times without significant loss in enantioselectivity or an increase in the formation of isomer **6** (Table 5), although an increase in reaction time was observed. The iridium complex probably passes in part into the hexane phase, which could explain the loss in reactivity on repeated use. Modification of the ligand to improve catalyst solubility in PC could be of help.

Table 5: Recycling experiments with the catalyst [Ir(cod)(**4**)]BAr^F_4 and olefin **5** as substrate in PC.[a]

Cycle[b]	*t* [h]	Conv. [%]	**6**/**7**[c]	*ee* [%]
1	4	100	1.5:98.5	83.1 (*R*)
2	6	100	3:97	84.6 (*R*)
3	20	100	2:98	83.7 (*R*)
4	20	100	1.5:98.5	83.4 (*R*)
5	20	100	1.5:98.5	83.4 (*R*)
6	20	100	2:98	79.2 (*R*)
7	20	85	4.5:95.5	58.8 (*R*)
8	20	63	5:95	50.5 (*R*)

[a] Conditions: 0.4 mmol substrate, 0.004 mmol [Ir(cod)(**4**)]BAr^F_4, $p(H_2) = 85$ bar, 2 mL LM, 25 °C. [b] The catalyst was reused after liquid–liquid extraction with *n*-hexane. [c] Determined by NMR spectroscopy and GC on chiral phase.

The results illustrate the considerable potential of PC in asymmetric hydrogenation. In the reaction of functionalized olefins, the results obtained are similar to or better than those obtained in standard solvents. The asymmetric hydrogenation of nonfunctionalized olefins appears particularly interesting, since then a nonpolar product is formed which can be removed by extraction and the catalyst can be used repeatedly. Further asymmetric catalysis in PC and other organic carbonates is currently under investigation.

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4.6 Rhodium-catalyzed asymmetric hydrogenation with self-assembling catalysts in propylene carbonate

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Contributions

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Rhodium-catalyzed asymmetric hydrogenation with self-assembling catalysts in propylene carbonate

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Abstract

Propylene carbonate (PC) may serve as a perfect solvent in the asymmetric rhodium-catalyzed hydrogenations of functionalized olefins like methyl *N*-acetamido acrylate and methyl α-(Z)-*N*-acetamido cinnamate using chiral self-assembling catalysts. In several examples superior reaction rates and enantioselectivities were found in comparison to the use of dichloromethane, commonly used as a solvent. The performance of the catalyst is influenced by the bulk of the phosphorus ligands. A ^{31}P NMR spectrum registered in PC showed the same self-assembling architecture as found in other nonprotic solvents.

During the last 35 years an enormous number of trivalent phosphorus ligands has been developed for different types of homogeneous asymmetric catalysis using 'soft' metals like rhodium, ruthenium, iridium and palladium.[1] For a long time bidentate ligands dominated the field. Only in recent years catalysts based on monodentate ligands have also shown outstanding enantioselectivities.[2] Due to their easier way of synthesizing, ligands with only one ligating atom became a promising alternative. The gap between bidentate ligands and monodentate ligands was closed with the concept of self-assembling catalysts. Thereby two monodentate ligands are linked together in a metal complex by hydrogen bonds[3] or a second metal.[4] Breit's group developed self-assembling catalysts based on hydrogen-bond interactions in relation to the naturally occurring DNA.[5] For example, ligands related to an A-T base-pair are suitable and can be even used in combinatorial approaches.[6] The usefulness of this concept was shown, for example, in the Ru-catalyzed anti-Markovnikov hydration of terminal alkynes.[7]

Recently, we gave evidence that self-assembling Rh-catalysts can be employed in the asymmetric hydrogenation.[8] High enantioselectivities were found in nonpolar solvents like CH_2Cl_2. In this solvent hydrogen bonds stabilize the formation of the 'pseudo-chelate' **IIA** (Fig. 1). In contrast, the use of polar solvents like MeOH decreased the ees. Unfortunately, the high stereoselectivities in the nonpolar solvent were accompanied by low reaction rates, whereas in alcohol as solvent a fast reaction took place. Obviously both the effects are a consequence of the disturbance of the hydrogen bonds in the polar solvent (Fig. 1, **IIB**). In a subsequent work we found that both the beneficial effects can be combined by running the reaction in fluorinated alcohols, which do not affect the hydrogen bonds.[9] Alternatively,

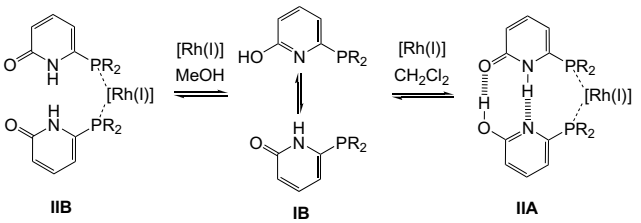

Fig. 1. Self-assembly of 6-phosphino-2-pyridone ligands in the presence of Rh(I) in dependence on the solvent.

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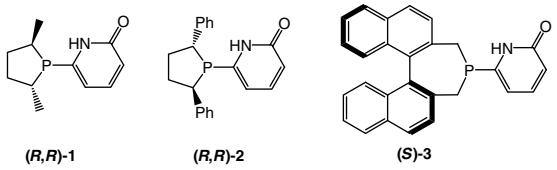
Breit and co-workers designed unique ligands for the Rh-catalyzed hydroformylations, which can act as 'pseudo-chelate ligands' even in protic solvents.[10]

In our ongoing search for cheaper and environmental friendly alternatives we were interested to investigate also the potential of propylene carbonate (PC) for the hydrogenation reaction.

In general, organic carbonates such as PC own perfect properties as solvents like a high boiling point and low toxicity.[11] PC is biodegradable and odorless. Only a very few applications of organic carbonates in homogenous catalysis were described. Thus Behr et al. used PC in the Pt-catalyzed hydrosilylation reactions of unsaturated fatty acid esters.[12] Reetz and Lohmer found that stabilization of Pd clusters takes place in PC and therefore used them advantageously for the Heck reaction with styrenes.[13] Recently, we showed for the first time the potential of PC in asymmetric Rh- and Ir-catalyzed hydrogenations of functionalized and nonfunctionalized olefins using bidentate P,P- and P,N-ligands.[14] An efficient catalyst recycling was possible by extraction of the product with *n*-hexane.

Herein, we will demonstrate that PC is also a highly suitable solvent for the asymmetric hydrogenation with self-assembling catalysts. For our studies we used three different pyridone based phosphines as ligands, which have been described recently.[8] Ligands **1** and **2** are based on a phospholane, whereas ligand **3** is derived from a phosphepine. All three ligands are capable of self-assembling via hydrogen-bond interactions in CH_2Cl_2 or fluorinated alcohols.[8,9]



As substrates the benchmark olefins **4**–**6** have been used (Fig. 2).

All hydrogenations were carried out in a 1 atm hydrogenation vessel with an automatically registrating hydrogen device under isothermal (25 °C) and isobaric conditions. The precatalysts of the type $[Rh(cod)(L_2)]BF_4$ (L = chiral ligand) were prepared in situ prior to the hydrogenation under an argon atmosphere. In some cases, a prehydrogenated catalyst was prepared by treatment of the precatalyst under hydrogen in PC. No significant differences were obtained in reactivity or selectivity between these two methods of preparation. The results of the hydrogenations are summarized in Table 1.

In general, the enantioselectivity is strongly dependent on the size of the phosphine unit. With all three prochiral substrates highest ee-values were achieved with the Rh-complex derived from phosphepine ligand (*S*)-**3** (84–99% ee). This catalyst also gave superior rates. In detail, in the asymmetric hydrogenation of methyl α-(*Z*)-*N*-acetamido cinnamate (**4**) with ligand (*R*,*R*)-**1** a significant higher reactivity was observed in PC than in dichloromethane, while similar ees yielded (entries 1 and 2). The reactivity in PC dropped when the bulkier ligand **2** was used, but hydrogenation was still faster in PC than in CH_2Cl_2 (entries 4 and 5). The ee decreased slightly from 70% to 63%. When phosphepine **3** was used the reaction proceeded a bit faster in dichloromethane than in PC and gave higher ees (entries 6 and 7) (Fig. 2).

Remarkably, no increase of reactivity but similar ees were observed when ligand **1** was used in the hydrogenation of dimethyl itaconate (**5**) (entries 10 and 11). With ligand **2** the reactivity increased significantly in PC but in comparison to CH_2Cl_2 the ee dropped from 47% to 28% (entries 12 and 13). In case of ligand **3** a similar reaction time with a slightly decreased enantioselectivity was noted in PC (entries 14 and 15).

Lastly, PC was used as solvent in the hydrogenation of methyl *N*-acetamido acrylate (**6**). In each case faster reactions with higher enantioselectivities were obtained in PC in comparison to CH_2Cl_2. For example, the catalyst with phospholane **1** as ligand converted the substrate in PC ca. 8x faster into the chiral product than in CH_2Cl_2 (entries 16 and 17). The reaction with catalyst based on ligand **2** took profit from the reaction in PC in terms of reactivity as well as of enantioselectivity (entries 18 and 19). The catalyst with ligand **3** displayed a higher enantioselectivity in PC (entries 20 and 21), whereas the high reaction rate observed in methylene chloride remained constant.

Since PC is chiral we were interested to investigate also the effect of this solvent in enantiopure form. Thus, the use of (−)-(*S*)-PC decreased the reactivity of the catalysts of (*R*,*R*)-**1** and (*S*)-**3** but did not affect the enantioselectivity (entry 3) or even afforded a slight increase (entry 9). Using (+)-(*R*)-PC ligand (*S*)-**3** gave the hydrogenation product of **4** with an ee similar to that observed in racemic PC (entry 8). Interestingly the reactivity of the catalyst was again lowered in comparison to the use of racemic or (*S*)-PC (compare entries 7–9).

To confirm the self-assembling architecture of the catalyst in PC a Rh-complex of ligand **1** was exemplarily investigated by ^{31}P NMR spectroscopy (Fig. 3). The complex was formed by reaction of $[Rh(cod)_2]BF_4$ and 2 equiv of **1** in PC. The ^{31}P NMR spectrum showed the two characteristic doublets of doublets at δ 54.3 ppm ($J(Rh,P) = 146.8$ Hz, $J(P,P) = 36.7$ Hz) and 49.9 ppm ($J(Rh,P) = 140.2$ Hz, $J(P,P) = 36.5$ Hz). This clearly gives proof for the two nonequivalent P-nuclei quite similar to the arrangement found in deuterated dichloromethane.[8]

In summary, we have shown that PC can be the solvent of choice in the Rh-catalyzed asymmetric hydrogenation with self-assembling catalysts. In several instances enhanced reactivity and in some cases superior ees were found. The observed higher rates in PC in comparison to CH_2Cl_2 is remarkable, because they do not reflect the higher hydrogen solubilities (at 1.013 bar H_2 and 25 °C) in CH_2Cl_2 (9.3×10^{-3}) compared to PC (1.4×10^{-3}) expressed as mole H_2 in 1 L of solvent. Thus, in spite of the fact that about eight times less H_2 is placed at the

Table 1
Hydrogenation of prochiral olefins in dichloromethane and propylene carbonate (PC)[a]

Entry	Ligand	Substrate	Ratio[b]	Solvent	Time (min)	Conv.[c] (%)	ee[c] (%)
1	(*R*,*R*)-**1**	**4**	100:2:1	CH_2Cl_2	1400	100[d]	69 (*R*)[d]
2	(*R*,*R*)-**1**	**4**	100:2:1	PC	75	100	70 (*R*)
3	(*R*,*R*)-**1**	**4**	100:2:1	(−)-(*S*)-PC	360	15	70 (*R*)
4	(*R*,*R*)-**2**	**4**	50:2:1	CH_2Cl_2	1400	59[d]	70 (*S*)[d]
5	(*R*,*R*)-**2**	**4**	50:2:1	PC	600	100	63 (*S*)
6	(*S*)-**3**	**4**	100:2:1	CH_2Cl_2	10	100[d]	94 (*R*)[d]
7	(*S*)-**3**	**4**	100:2:1	PC	15	100	89 (*R*)
8	(S)-**3**	**4**	100:2:1	(+)-(*R*)-PC	80	81	91 (*R*)
9	(*S*)-**3**	**4**	100:2:1	(−)-(*S*)-PC	80	100	94 (*R*)
10	(*R*,*R*)-**1**	**5**	50:2:1	CH_2Cl_2	1300	88[d]	83 (*S*)[d]
11	(*R*,*R*)-**1**	**5**	50:2:1	PC	1200	86	80 (*S*)
12	(*R*,*R*)-**2**	**5**	50:2:1	CH_2Cl_2	3120	48[d]	47 (*R*)[d]
13	(*R*,*R*)-**2**	**5**	50:2:1	PC	1200	100	28 (*R*)
14	(*S*)-**3**	**5**	100:2:1	CH_2Cl_2	20	100[d]	99 (*S*)[d]
15	(*S*)-**3**	**5**	100:2:1	PC	25	100	95 (*S*)
16	(*R*,*R*)-**1**	**6**	100:2:1	CH_2Cl_2	80	100[d]	51 (*R*)[d]
17	(*R*,*R*)-**1**	**6**	100:2:1	PC	11	100	55 (*R*)
18	(*R*,*R*)-**2**	**6**	50:2:1	CH_2Cl_2	1140	100[d]	12 (*S*)[d]
19	(*R*,*R*)-**2**	**6**	50:2:1	PC	180	100	22 (*S*)
20	(*S*)-**3**	**6**	100:2:1	CH_2Cl_2	10	100[d]	85 (*R*)[d]
21	(*S*)-**3**	**6**	100:2:1	PC	10	100	94 (*R*)

[a] Conditions: the catalyst was prepared by stirring $[Rh(cod)_2]BF_4$ with 2 equiv of the ligand in solvent for 20 min under argon or hydrogen, the substrate was added and hydrogenation was conducted under 1 atm H_2 pressure.
[b] Ratio: substrate/ligand/$[Rh(cod)_2]BF_4$.
[c] Determined by GC using 25 m γ-cyclodextrin, Lipodex E (Machery and Nagel), silica, 130 °C.
[d] Data from Ref. 8.

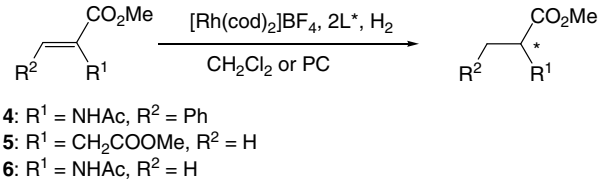


Fig. 2. Rh-catalyzed hydrogenation of prochiral olefins.

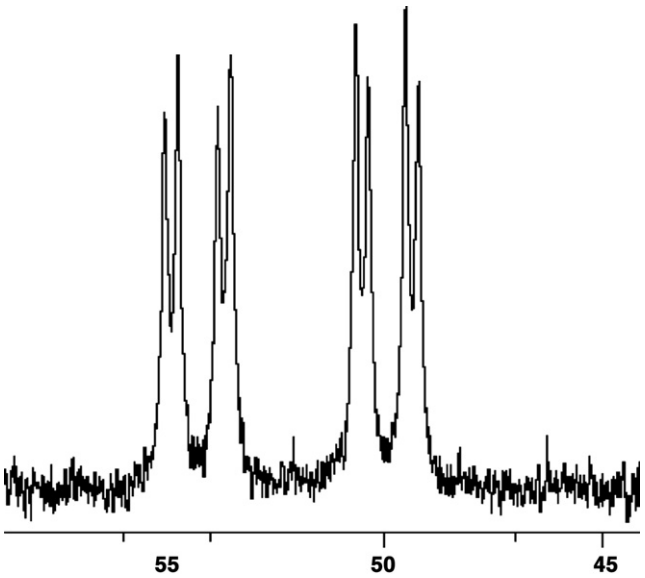


Fig. 3. ^{31}P NMR spectrum of $[Rh(cod)((R,R)\text{-}\mathbf{1})_2]BF_4$ showing Rh–P and P–P couplings (solvent: propylene carbonate/$CDCl_3$).

disposal for the hydrogenation in PC, reaction rates are substantially higher in this solvent. This issue will be addressed in a forthcoming publication.[15]

Acknowledgements

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4.7 Rhodium-Catalyzed Asymmetric Hydrogenation of Unsaturated Lactate Precursors in Propylene Carbonate

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Contributions

My contribution as co-author to this paper accounts 80%.

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Rh-Catalyzed Asymmetric Hydrogenation of Unsaturated Lactate Precursors in Propylene Carbonate

Benjamin Schäffner,[a] Vasyl Andrushko,[a] Jens Holz,[a] Sergey P. Verevkin,[b] and Armin Börner*[a, b]

In memory of Ariane Beutler

The asymmetric hydrogenation of α-acetoxy acrylates to O-acetyl lactates with Rh catalysts based on chiral bisphospholane ligands was investigated in propylene carbonate (PC) as "green" solvent. In contrast to DuPHOS-type ligands, catASium M ligands lead to full conversion of the substrate in PC and induce excellent enantioselectivities for ethyl ester and methyl ester substrates (>98%). Moreover, the undesired opening of the maleic anhydride moiety of the catASium M ligand observed in MeOH can be prevented under these conditions. The chiral product can be easily separated from the carbonate solvent by distillation. In this way, an ecologically benign process for the production of enantiopure lactic acid derivatives was established which offers a highly efficient catalytic transformation in a green solvent under mild conditions (1–10 bar H_2).

Introduction

Enantiopure lactic acid has become increasingly important as a building block for the synthesis of biodegradable chiral polylactic acids (PLAs), which have a similar application range to polyethylene terephthalate (PET).[1] In general, the monomer is produced from sugar feedstocks by fermentation, but also chemical synthesis may provide an interesting alternative, in particular in those cases where sustainable methods are employed. There is no doubt that homogeneous catalysis plays an important role in these pioneering methodologies. In particular, asymmetric hydrogenation has reached a high level of application and is used as a key environmentally friendly technology in the synthesis of several chiral compounds in industry.[2] To this end, homogeneous rhodium(I), ruthenium(II), or iridium(I) catalysts based on chiral phosphorus ligands play an important role.[3]

Many chiral ligands have been synthesized in the last decades to overcome the limitations in the hydrogenation of standard, but also sophisticated, substrates (e.g. unusual amino acid precursors, vinyl alcohols, unsaturated phosphonic acid esters, non-functionalized and highly substituted olefins).[2,3] In general, chiral ligands can be classified by their coordination abilities (mono- or bidentate, e.g. P,P or P,N), by the nature of the backbone and the source of chirality (atropisomers, metallocene, chiral C skeleton, stereogenic phosphorus etc.). Fine tuning of the ligand is mainly achieved by modifications of steric features (like the bite angle α) as well as by alteration of the electronic surrounding at the metal center, and leads to families of ligands covering in the best case several dozens of strongly related individuals. Popular examples represent commercially available bisphospholanes of the cat*A*-*S*ium M series[4] and those of the DuPHOS family[5] (Figure 1). Appropriate ligands from these two classes show superior behavior in the Rh-catalyzed hydrogenation of a broad range of substrates. Although the general structures are related, in some cases striking differences in the catalytic features have been noted.[6]

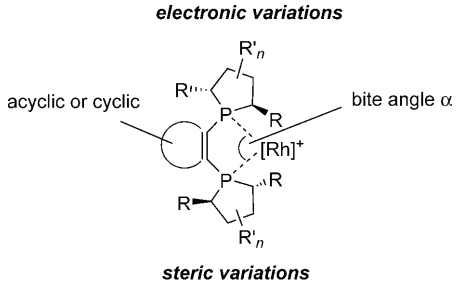

Figure 1. Electronic and steric fine-tuning with bisphospholane Rh catalysts.

Besides the choice of the appropriate ligand, the proper setup of the reaction conditions is essential to class a catalytic reaction as sustainable. In particular, the selection of the solvent is an obligatory step in the screening process. Commonly used solvents like methanol, tetrahydrofuran, dichloromethane, and toluene differ strongly in their use and limitations. Also, more sophisticated solvents like fluorinated alcohols[7] and ionic liquids[8] may display impressive properties. However, the limitations for these special solvents such as high prices, toxici-

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ty, or problems with purification have to be taken into consideration.

Since a few years, we have focused on the use of organic carbonates. This class of solvent can be divided into two subgroups: The non-cyclic carbonates are used as synthetic reagents (e.g. ester synthesis) and have seen some application as low-boiling solvents. In contrast, cyclic carbonates, especially propylene carbonate (PC), have a much higher boiling point and a low vapor pressure. They are inflammable and show only low viscosity. Of particular value from an ecological point of view is the low toxicity and easy biodegradability of PC. According to these properties, PC can be considered as an ecologically and economically benign solvent ("green" solvent). Moreover, it can be synthesized in an environmentally friendly way from propylene oxide (the latter can be derived from propylene and H_2O_2 through HPPO technology)[9] by reaction with supercritical CO_2 using transition-metal catalysts.[10] PC belongs to a class of aprotic highly dipolar (AHD) solvents. Its physical properties are rather unique and are only met by those of acetonitrile, which is not a member of the AHD group (Figure 2).[11]

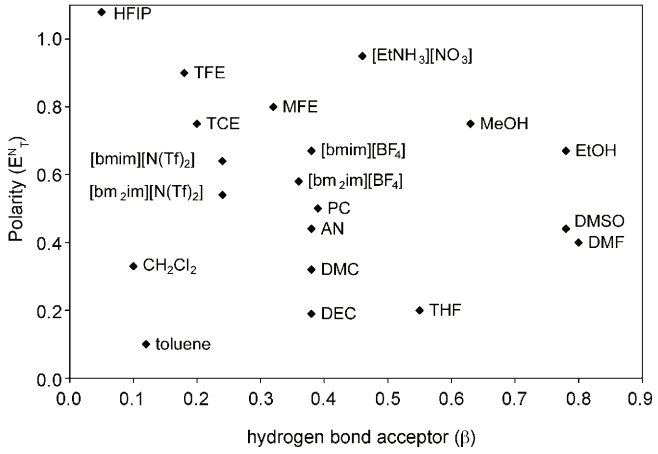


Figure 2. Polarity and hydrogen-bond acceptor values of selected solvents (HFIP = hexafluoroisopropanol, TFE = trifluoroethanol, MFE = monofluoroethanol, TCE = trichloroethanol, DMSO = dimethyl sulfoxide, DMF = dimethyl formamide, AN = acetonitrile, DMC = dimethyl carbonate, DEC = diethyl carbonate; for ionic liquids: bmim = 1-butyl-3-methyl-1,3-imidazolium ion, bm_2im = 1-butyl-2,3-dimethyl-1,3-imidazolium-ion, Tf = triflate).

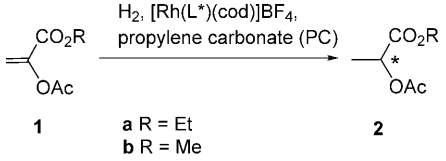
PC is established in industry for pharmaceutical and medical applications and is applied as a solvent for extractions and coating processes. In the 1980s, it was applied by the Mortreux group as a solvent for the synthesis of aldehydes on the industrial scale[12] and later on in mixtures with benzene for platinum-catalyzed electrochemical hydroformylations using bidentate phosphine ligands and iron or tin as co-catalysts.[13] In academic research, PC has been employed to stabilize Pd clusters in Heck reactions.[14] Behr et al. suggested it as a solvent in Rh-catalyzed hydroformylation reactions in temperature-dependent multicomponent solvent systems (TMS).[15] Bradley and co-workers employed PC for the asymmetric heterogeneous Ir-catalyzed hydrogenations of ketones.[16] We investigated the use of PC as solvent in homogeneous Rh- and Ir-catalyzed hydrogenations of functionalized and unfunctionalized olefins. With unpolar substrates, a recycling of the Ir catalyst was possible by simple extraction with *n*-hexane.[17] In the Rh-catalyzed hydrogenation with self-assembling catalysts in PC, an impressive increase in the rate of reaction was noted.[18] Recently, PC was identified as a beneficial solvent in Pd-catalyzed asymmetric allylic alkylations, aminations,[19] and in Sonogashira reactions.[20] A detailed study of catalyst generation from Rh precatalysts in PC was also reported.[21]

Herein, we compare the results obtained in the Rh-catalyzed asymmetric hydrogenation of unsaturated lactic acid precursors using several bisphospholane ligands.[22] The main focus is the use of PC as an environmentally benign solvent.

Results and Discussion

Hydrogenation Experiments

Prochiral α-acetoxy acrylic acid esters **1a,b** were chosen as precursors for lactic acid esters (Scheme 1). Burk et al. reported the hydrogenation of **1a** with a cationic Rh catalyst based on



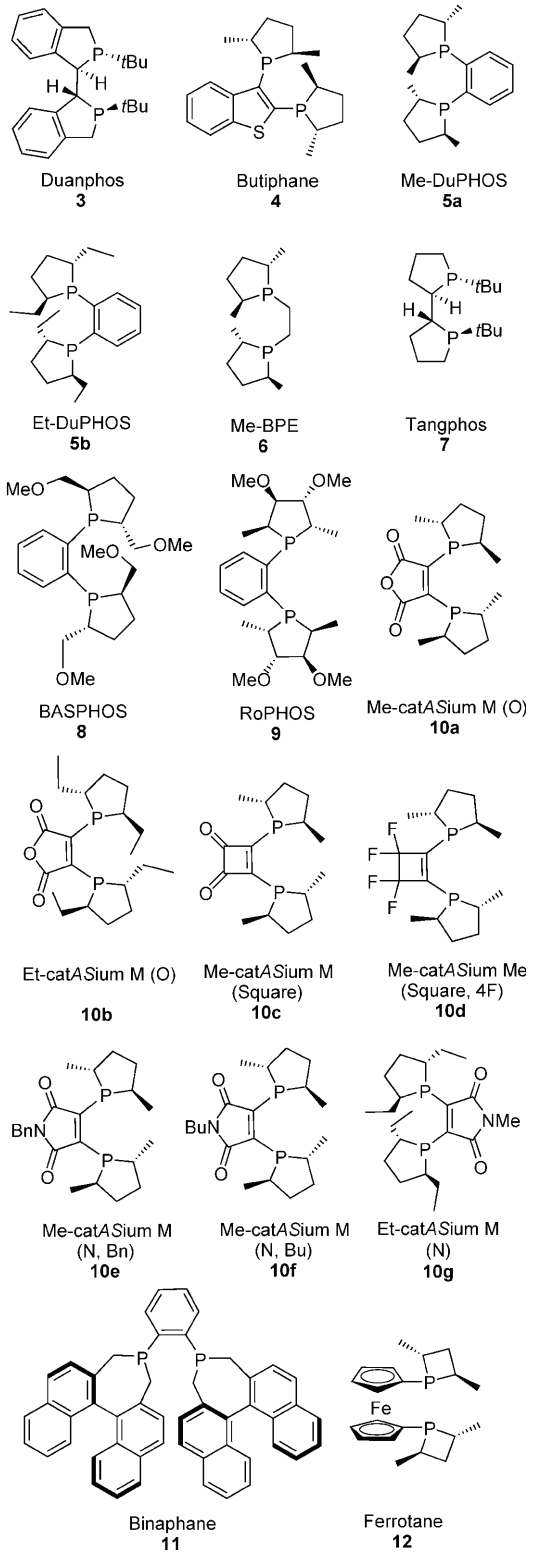
Scheme 1. Asymmetric hydrogenation of lactic acid precursors.

Me-DuPHOS in MeOH and achieved remarkable enantioselectivities (>99% *ee*, 2–12 h, at about 4 bar initial H_2 pressure).[23]

To broaden the set of catalysts in a preliminary screening we also tested a range of other bisphospholanes, as well as Binaphane (**11**) and Ferrotane (**12**), which offer a maximum in structural and electronic variation (Scheme 2). For these hydrogenation tests, an initial hydrogen pressure of 10 bar was applied using PC as solvent. The results are summarized in Table 1.[24]

Our results clearly show that small changes in the structure of the bisphospholanes may have dramatic effects on the catalytic reaction. Rh catalysts based on the ligands Me-DuPHOS (**5a**), BASPHOS (**8**), and Me-cat*A*Sium M (O) (**10a**) are very active. Noteworthy is also the good performance of the catalyst with bisphosphepine ligand **11**.

In subsequent optimization reactions, we focused on the ligands **5a** and **10a** from the DuPHOS family and the cat*A*Sium M series, respectively. Both are commercially available even on an industrial scale. Moreover, and in contrast to BASPHOS which is synthesized from D-mannitol in a multistep approach,[25] both enantiomeric forms of the ligands **5a** and **10a** are on the market and allow therefore the production of L- and D-lactic acids. In the optimization, also other solvents such as MeOH, CH_2Cl_2, and THF were considered for comparison (Table 2). In general, good to excellent enantioselectivities



Scheme 2. Heterocyclic phosphine ligands used in these investigations.

were induced using both ligands and independent of the solvent used. More striking is the effect of the solvent and the initial hydrogen pressure on the reaction time independent of whether ligand **5a** or **10a** was used. Whereas fast reactions occur in all solvents (Table 2, entries 2, 4, 6) at 10 bar with the

Table 1. Preliminary screening of chiral phosphine ligands in the Rh-catalyzed hydrogenation of ethyl *O*-acetoxy acrylate (**1a**) in PC.[a]

Entry	Ligand	Conversion [%]	*ee* [%]
1	**3**	7	75 (*R*)
2	**4**	4	42 (*S*)
3	**5a**	>99	89 (*S*)
4	**6**	5	19 (*R*)
5	**7**	4	42 (*S*)
6	**8**	>99	>99 (*S*)
7	**9**	2	35 (*S*)
8	**10a**	>99	97 (*R*)
9	**10c**	>99	81 (*R*)
10	**10d**	>99	65 (*S*)
11	**10e**	4	43 (*R*)
12	**10f**	2	21 (*R*)
13	**11**	>99	95 (*S*)
14	**12**	52	49 (*S*)

[a] 10 bar initial H_2 pressure, 1 mol % [Rh(L)(cod)]BF_4 catalyst, 0.4 mmol substrate **1a**, 2 mL PC, 40 min hydrogenation.

Table 2. Rh-catalyzed hydrogenation of ethyl *O*-acetoxy acrylate (**1a**) with Me-DuPHOS (**5a**) and Me-cat*A*Sium M (O) (**10a**) as ligands.[a]

Entry	Ligand	$p(H_2)$ [bar]	*t* [min]	Solvent	Conv. [%]	*ee* [%]
1	**5a**	1	1175	PC	>99	90 (*S*)
2	**5a**	10	40	PC	>99	89 (*S*)
3	**5a**	1	240	MeOH	>99	97 (*S*)
4	**5a**	10	40	MeOH	>99	98 (*S*)
5	**5a**	1	795	CH_2Cl_2	52	92 (*S*)
6	**5a**	10	40	CH_2Cl_2	73	65 (*S*)
7	**5a**	1	780	THF	>99	>99 (*S*)
8	**5a**	10	40	THF	87	96 (*S*)
9	**10a**	1	80	PC	>99	98 (*R*)
10	**10a**	1	70[b]	PC	>99	98 (*R*)
11	**10a**	1	70[b,c]	PC	>99	98 (*R*)
12	**10a**	10	40	PC	>99	97 (*R*)
13	**10a**	10	40[b]	PC	>99	98 (*R*)
14	**10a**	1	325	MeOH	>99	88 (*R*)
15	**10a**	10	40	MeOH	> 99	95 (*R*)
16	**10a**	10	40[d]	MeOH	>99	95 (*R*)
17	**10a**	1	50	CH_2Cl_2	43	96 (*R*)
18	**10a**	10	40	CH_2Cl_2	>99	94 (*R*)
19	**10a**	1	800	THF	35	94 (*R*)
20	**10a**	10	40	THF	>99	97 (*R*)
21	**10a**	1	210	GC[e]	>99	92 (*R*)

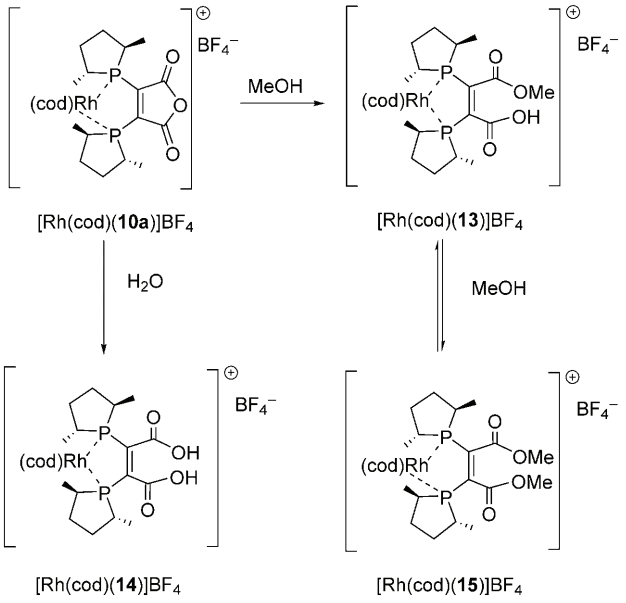
[a] 1 mol % [Rh(cod)(ligand)]BF_4 precatalyst, 0.4 mmol substrate, 2 mL solvent. [b] Using [Rh(nbd)(**10a**)]BF_4. [c] The precatalyst was prehydrogenated for 1 h in PC. [d] The precatalyst was stirred for 24 h in MeOH before use. [e] GC = glycerine carbonate.

[Rh(Me-DuPHOS)] catalyst, the hydrogenation is slowed down by a factor of 5–30 at 1 bar (entries 1, 3, 5, 7). The enantioselectivity of 98% is highest in MeOH and close to that reported by Burk et al.[23] Remarkably, the pressure effect is much less pronounced with **10a** as a ligand in PC (Table 2, entries 9, 12). Only a slight deceleration of the reaction at 1 bar as compared to that at 10 bar can be observed. This behavior is unique in comparison to other solvents. Thus, in THF or CH_2Cl_2 the reaction did not go to completion (Table 2, entries 17, 19). The

enantioselectivity is constantly high under all conditions. In a preliminary trial, we also used glycerine carbonate (GC; Table 2, entry 21). In comparison to PC, the reaction was more sluggish but still faster than in the other solvents.

In relation to the known effect of longer overall reaction times with precatalysts bearing 1,5-cyclooctadiene (cod) as the stabilizing counter ligand in comparison to norbornadiene (nbd),[21,26] we used also the corresponding nbd complex. With this precatalyst in hand, the overall reaction time could be slightly diminished (Table 2, entries 9, 10) at 1 bar H_2 pressure. Prehydrogenation of the nbd complex and addition of the prochiral substrate after 1 h did not improve the overall hydrogenation time. This observation gives clear evidence that the hydrogenation of the diolefin is very fast (Table 2, entry 11).

In methanol, the best results were obtained at 10 bar hydrogen pressure (Table 2, entries 14–16). At lower pressure, the enantioselectivity decreased to 88%. Besides the pressure dependency, a further reason for this effect could be the ring opening of the maleic anhydride backbone of ligand **10a** with MeOH to give the Rh complex of the acid monoester **13** at longer reaction times (Scheme 3).[27] ^{31}P NMR measurements



Scheme 3. Ring opening of the anhydride unit in **10a** in water or MeOH to give Rh complexes of diacid **14** and those of the esters **13** and **15**, respectively.

showed that [Rh(cod)(**10a**)]BF_4 [(CD_2Cl_2): $\delta = 63.8$ ppm ($^1J_{P,Rh} = 151.2$ Hz)] dissolved in MeOH was completely converted into [Rh(cod)(**13**)]BF_4 within 1 h [([D_4]MeOH): $\delta = 94.0$ ppm ($^1J_{P,Rh} = 151.7$ and 151.2 Hz, $^2J_{P,P} = 22.1$ Hz)] (Figure 3). Additionally, the Rh complex of diester **15** [$\delta = 93.5$ ppm ($^1J_{P,Rh} = 151.6$ Hz)] was found. However, its formation stopped at about 10% conversion. It seems that the saponification of **10a** to **14** proceeds in parallel to the formation of **13** by transesterification. Probably an equilibrium consisting of **13** and **14** exists in which **13** is highly preferred. In the presence of water, the Rh complex of diacid **14** was formed [$\delta = 94.0$ ppm ($^1J_{P,Rh} = 151.2$ Hz)]. [Rh-

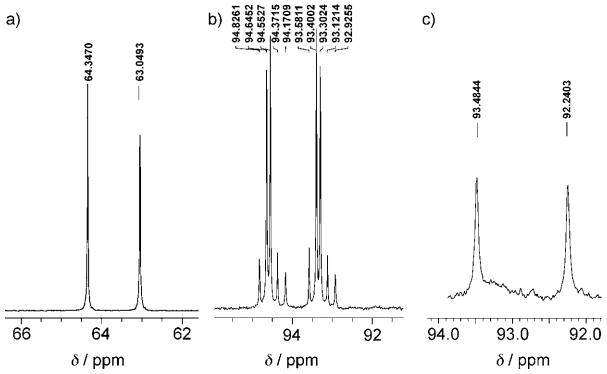


Figure 3. ^{31}P NMR spectroscopic results of the ring-opening process of [Rh(cod)(**10a**)]BF_4. a) [Rh(cod)(**10a**)]BF_4 in CD_2Cl_2; b) [Rh(cod)(**13**)]BF_4 in methanol after 1 h stirring at room temperature in [D_4]MeOH; c) [Rh(cod)(**14**)]BF_4 in $CDCl_3$ after treatment of [Rh(cod)(**10a**)]BF_4 with two drops of water.

(cod)(**13**)]BF_4 was used in the hydrogenation of **1a**, and similar results were achieved at 10 bar (Table 2, entry 16).

Bearing the best results with bisphospholane ligands in PC in mind, we used diethyl-substituted analogues **5b**, **10b**, and **10g** for further fine-tuning of the hydrogenation. With the relevant catalysts, the enantioselectivity could be optimized (Table 3). The complex derived from maleic anhydride ligand **10b** catalyzed the reaction about threefold faster than the cat-

Table 3. Rh-catalyzed hydrogenation of ethyl *O*-acetoxy acrylate (**1a**) in PC.[a]

Entry	Ligand	$p(H_2)$ [bar]	t [min]	Conv. [%]	*ee* [%]
1	**5b**	10	40	>99	>99 (*S*)
2	**10b**	1	70	>99	>99 (*S*)
3	**10b**	10	40	>99	>99 (*S*)
4	**10g**	1	210	>99	>99 (*S*)

[a] 1 mol % [Rh(cod)(ligand)]BF_4 catalyst, 0.4 mmol substrate, 2 mL solvent. [b] [Rh(nbd)(**10**)]BF_4 was used as precatalyst.

alyst based on the amide ligand **10g**. The result obtained with the corresponding complex derived from BASPHOS (entry 6, Table 1) and Et-DuPHOS (entry 1, Table 3), which also exceeded 99% *ee*, showed that the steric effect exerted by bulky alkyl groups in the 2- and 5-positions of the phospholane is pivotal for the achievement of high enantioselectivity in this particular reaction.

With the aim to optimize further the environmentally friendly reaction, we optimized the atom economy by replacement of the ethyl by methyl ester group in the prochiral substrate (**1b**; Table 4). To our surprise, the catalyst containing Me-DuPHOS (**5a**) failed with this substrate (Table 4, entry 1).[28] A poor conversion was observed even at 10 bar H_2 pressure. In contrast, complexes derived from Et-DuPHOS (**5b**), cat*AS*ium M ligands **10a** and **10b**, and BASPHOS (**8**) gave a clean reaction and afforded the desired chiral methyl *O*-acetyl lactate (**2a**) in excellent yield and with high enantioselectivity. From a com-

Table 4. Rh-catalyzed hydrogenation of methyl *O*-acetoxy acrylate (**1b**) in PC.[a]

Entry	Ligand	$p(H_2)$ [bar]	t [min]	Conv. [%]	ee [%]
1	**5a**	10	40	28	87 (S)
2	**5b**	10	40	>99	98 (S)
3	**8**[b]	10	40	>99	98 (*S*)
4	**10a**	10	40	>99	95 (*R*)
5	**10b**	10	40	>99	98 (*S*)

[a] 1 mol % [Rh(cod)(ligand)]BF4 catalyst, 0.4 mmol substrate, 2 mL solvent. [b] [Rh(nbd)(**8**)]BF_4 was used as precatalyst.

Table 5. Experiments to separate hydrogenation products **2b** and **2a** from the solvent PC by distillation.[a]

Entry	Product	p(vacuum) [mbar]	T(bath) [°C]	T(sump) [°C]	T(shell) [°C]	Yield [g] (%)[b]	Purity[c] [wt %]
1	**2b**	0.12	65	58	24	0.88[d] (96)	89
2	**2b**	7.5	107	94	53	5.78 (86)	100
3	**2b**	7.5	107	94	55	5.31 (79)	100[e]
4	**2a**	7.5	107	94	58	5.15 (77)	100

[a] The product mixtures were distilled using a HMS 500 C Spaltrohrkolonne from Fischer technology. All experiments were carried out with a mixture of 120 mL PC with 6.7 g of **2b** or **2a** (and mixtures). [b] Yield in comparison to the maximum amount of compound which can be distilled. [c] The purity was determined by ^{1}H NMR spectroscopy (300 MHz, $CDCl_3$). [d] The experiment was performed with 32 mL PC and 812 mg product. The product fraction was collected in a cooled flask (−78 °C). [e] A solution (120 mL) derived from the hydrogenation of 6.7 g of **1b** was used. The hydrogenation was stopped after 70 % conversion to analyze the possible separation of product and starting material in mixtures with PC. The product was free of PC but contained a mixture of **1b**/**2b** (14:86 wt %).

parison of the results, the importance of the substituents at the 2,5-position of the phospholane becomes clear again. The reason for the low yield with the Me-DuPHOS catalyst is not clear to now, but it shows nicely the subtle effect of small changes on the ligand structure on the outcome of the asymmetric hydrogenation.

Separation Experiments

The high boiling point is one of the advantages of PC as a solvent. On the other hand, separation of the product may become more complicated. For nonpolar substrates, satisfactory solutions have been found for this problem. Thus, extraction with *n*-hexane and the use of a temperature-dependent multicomponent solvent system are two established methods of separation.[15,17] More polar products derived from alkylation and amination protocols can be separated from PC by column chromatography with an eluent mixture of *n*-hexane and ethyl acetate greater than 6:1.[17,18]

Another possibility which will be considered herein is the distillation of products out of PC under vacuum. With boiling points of 176 °C for the methyl ester **2b** and 181 °C for ethyl ester **2a**, both hydrogenation products seem to be suitable for this procedure, taking into account the high boiling point of PC (242 °C). Preliminary trials to use a simple bulb-to-bulb vacuum distillation failed. Apparently, oxygen–oxygen interactions between the product and PC led to co-distilation of the high-boiling solvent also. An improved separation was achieved by employing a Spaltrohrkolonne (Table 5).

If high vacuum (0.12 mbar) was employed, the product fraction was collected in a cooled flask (−78 °C) but contained still 11 wt% PC (Table 5, entry 1). An improved separation was achieved at 7.5 mbar vacuum in a scaled-up approach. Under these conditions, the chiral product was collected at room temperature. The fraction was free of PC impurities and 86% of **2b** could be distilled out of the reaction phase (Table 5, entry 2). We proceeded with a mixture of **1b** and **2b**. In this approach, the hydrogenation was stopped at 70% conversion to analyze also the separation of the product from non-converted starting material and PC. From 6.7 g starting material in 100 mL PC, we collected 5.31 g of the first distillation fraction containing no PC and with a 86:14 wt% mixture of product (4.51 g; 92% yield) to starting material (Table 5, entry 3). In comparison to the experiment in Table 5, entry 2, the experiment showed that the yield of **2b** which was distilled out of the PC phase could be increased, if there is still starting material left in the distillation solution (92%:86%). The second fraction from the experiment in Table 5, entry 3, contained only 3% of product, 13% starting material, and 84% PC. The steam distillation temperature increased from 53.7 °C to 94 °C. It seems clear that this increase indicated the start of the distillation of PC. In the last experiment, compound **2a** was treated. The distillation needed much more time than in the case of **2b**, and only 77% could be isolated without contamination by PC (Table 5, entry 4). Unfortunately, only high-temperature conditions led to the best separation until now. Thus, reuse of the sensitive Rh catalysts is not feasible. Therefore, further investigations concerning this subject are necessary to enable efficient recycling of the catalyst.

Conclusions

The use of PC as solvent in the Rh-catalyzed asymmetric hydrogenations of α-acetoxy acrylates affords several ecological benefits. With cat*A*Sium M ligands, excellent conversion rates (100% yield) and enantioselectivities (>99% *ee*) could be achieved in the hydrogenation of ethyl α-acetoxy acrylate. In strong contrast to a related Me-DuPHOS-based catalyst, Rh complexes of cat*A*Sium M ligands were also highly active in the hydrogenation of the corresponding methyl ester. Separation of the product from the high-boiling solvent could be accomplished with a Spaltrohrkolonne. Besides a separation of the product from PC, we were able to enrich the product in the first fraction and unconverted starting material in the second fraction. With these results, we present the first approach for a successful separation of polar substrates out of propylene carbonate.

Experimental Section

General Remarks: All solvents were dried by conventional methods and stored under argon using Schlenk techniques. Substrates were synthesized as described in the literature.[29] All catalysts were used as metal complexes and were synthesized as $[Rh(cod)(ligand)]BF_4$ or $[Rh(nbd)(ligand)]BF_4$ complexes prior to use or were used as delivered from chemical suppliers without further purification. For the determination of conversion and enantioselectivity, a chiral GC column (50 m Chiraldex ß-pm; Astec) was used. For determination of the absolute configuration of **2b**, a chiral HPLC using an OD column by Chiralcel was used.[30] ^1H and ^{13}C NMR spectroscopic data were measured on solutions in $CDCl_3$ and $[D_4]MeOH$ at 300 MHz. Proton chemical shifts were referenced to tetramethylsilane as standard. Carbon chemical shifts were referenced to the carbon signal of the solvent at $\delta = 77.0$ ppm.

General Procedure for Hydrogenation and Separation

A 2-L autoclave was evacuated and rinsed with argon five times. A solution of methyl-2-acetoxy acrylate or ethyl-2-acetoxy acrylate (139 mmol), Rh catalyst (0.55 mmol), and PC (360 mL) were injected by canula into the autoclave. The system was sealed and pressurized by using an initial hydrogen pressure of 10 bar. Hydrogen uptakes were monitored with a pressure-control device. A sample was taken at the end of the reaction to analyze the enantiomeric excess and conversion by GC. The solution was divided into three fractions of 120 mL, and each fraction was separated using a HMS 500 Spaltrohrkolonne from Fischer Technology. Optimal distillation conditions could be achieved at following temperatures: oil bath = 107 °C, sump = 94 °C, shell = 80 °C, top = 52–57 °C. The vacuum was adjusted to 7.5 mbar. The temperature of the bath and shell was slowly increased at the end of the distillation, and the fraction flask was changed if the top temperature enhanced to 94 °C (distillation of PC). The fractions were analyzed by ^1H NMR spectroscopy using $CDCl_3$.

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Keywords: asymmetric catalysis · homogeneous catalysis · hydrogenation · propylene carbonate · rhodium

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4.8 A *P**-chiral bisdiamidophosphite ligand with a 1,4:3,6-dianhydro-D-mannite backbone and its application in asymmetric catalysis

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Contributions

My contribution as co-author to this paper accounts 30%. I tested the ligand with standard organic solvents and propylene carbonate as shown in table 1 and 2.

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A *P**-chiral bisdiamidophosphite ligand with a 1,4:3,6-dianhydro-D-mannite backbone and its application in asymmetric catalysis

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Abstract

A novel readily available *P*,*P*-bidentate diamidophosphite ligand with *P**-stereocentres is prepared from an inexpensive C_2-symmetric 1,4:3,6-dianhydro-D-mannite. By using this efficient ligand, up to 98% ee is achieved in Pd-catalysed asymmetric allylic alkylation, up to 92% ee in Pd-catalysed asymmetric allylic amination and up to 87% ee in Rh-catalysed asymmetric hydrogenation. The influence of the precatalyst, substrate and solvent on the enantioselectivity is discussed.

Keywords: Asymmetric reactions; Phosphorus ligands; Rhodium; Hydrogenation; Palladium; Amination

Asymmetric metal complex catalysis is a powerful synthetic method for producing valuable chiral compounds.[1] To achieve the highest levels of reactivity and selectivity in enantioselective catalytic reactions, different reaction parameters must be explored and adjusted. In this optimisation process, a careful selection and design of the chiral ligand is perhaps the most crucial step, since the choice of the best ligand strongly depends on each particular reaction.[2] Therefore, the design of new ligands for efficient asymmetric catalysis remains a challenge of high importance. Diphosphines have played a dominant role amongst the phosphorus-containing ligands, but recently a group of less electron-rich organophosphorus compounds, phosphite ligands, have received much attention. These ligands are extremely attractive for catalysis because they are easy to prepare from the readily available starting materials and are also less sensitive to air than to phosphines. Hence, this makes it possible to develop protocols for the whole process including the ligand synthesis that do not necessitate the use of a glove box. In addition, phosphites are characterised by pronounced π-acidity and low cost.[3] At the same time, there are only a few examples of very promising *P*,*P*-bidentate phosphite-type ligands with stereogenic phosphorus atoms in the literature.[4]

Chiral diol-based phosphite ligands are readily available and are highly functionalised with several stereogenic centres.[2,3] A series of *P*,*P*-bidentate chiral phosphites with a 1,4:3,6-dianhydro-D-mannitol backbone and biphenyl or binaphthyl moieties was synthesised and screened in the search for high activities and selectivities in asymmetric hydrogenation and allylic substitution (some examples are shown in Fig. 1).[5]

On the other hand, we have recently reported the synthesis of *P**-mono- and *P**,*N*-bidentate diamidophosphites and demonstrated that they can serve as a new class of very efficient ligands for Pd-catalysed allylation.[6] Encouraged

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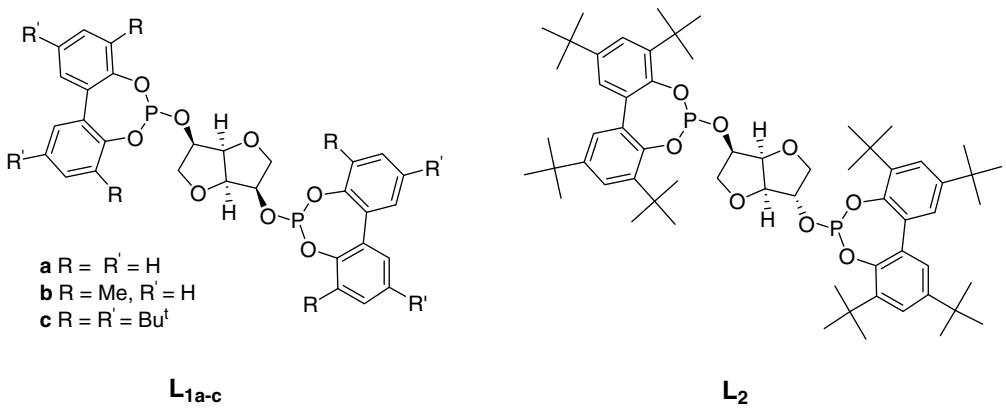


Fig. 1. Examples of *P*,*P*-bidentate phosphite ligands.

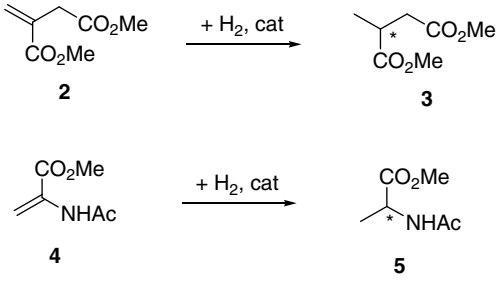
by these observations and motivated by our continuing efforts in the design and application of novel P^*-chiral ligands for use in asymmetric catalysis,[7] we have prepared P^*,P^*-bidentate bisdiamidophosphite compound **1** as a ligand for an application in asymmetric catalysis.

As stated above, the development of asymmetric catalysis requires access to the novel classes of structurally diverse phosphorus-containing ligands. Such diversity is quite difficult with phosphine ligands, whose syntheses can often require multiple steps.[8] Phosphite-type compounds, however, can be assembled in a much easier way by reacting alcohols or amines with phosphorus halides. In particular, bisphosphites can be readily prepared by the reaction between different phosphorochloridites and diols. The diol moiety bridges the two phosphite moieties and controls the bite angle of the resulting ligand. By using this strategy, we have synthesised very efficiently bisdiamidophosphite **1** in one step from the inexpensive 1,4:3,6-dianhydro-D-mannitol and (2*R*,5*S*)-2-chloro-3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]octane (Scheme 1). The reaction was performed in the presence of Et_3N (~1.1 equiv/OH) in THF.

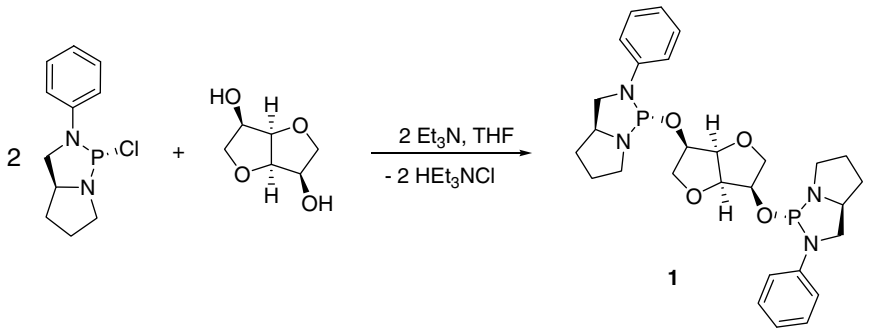
Compound **1** was obtained as a white powder after filtration, evaporation of THF from the filtrate and trituration of the resulting solid with hexane.[9] The new P^*,P^*-bidentate ligand **1** is stable on prolonged storage. Since the phosphorylating reagent is easily prepared from the readily accessible (*S*)-(2-anilinomethyl)pyrrolidine,[6a] **1** can be obtained on gram scale. As follows from the characteristic ^2J(C(8′),*P*) value (37.9 Hz) in the ^{13}C NMR spectrum,[9] the phosphorylation of 1,4:3,6-dianhydro-D-mannitol results in the exclusive formation of stereospecific bisdiamidophosphite **1** with the (*R*) configuration at the P^*-stereocentres (see Ref. 10 and references cited therein).

Asymmetric hydrogenation is a highly attractive strategy for the synthesis of optically active organic molecules of academic and/or industrial interest.[1] In this connection, we describe our results on the Rh-catalysed hydrogenation of dimethyl itaconate **2** and methyl 2-acetamidoacrylate **4** with ligand **1** (Scheme 2).

These benchmark substrates have been investigated with a wide variety of ligands carrying various donor groups.



Scheme 2. Rh-catalysed hydrogenation.



Scheme 1. Synthesis of P^*-chiral ligands.

Table 1
Rh-catalysed hydrogenation of α-dehydrocarboxylic acid esters ($[Rh(COD)_2]BF_4$/**1**, 1 bar H_2, 20 °C)[a]

Entry	Substrate	Solvent	Time (min)	ee[d,e] (%)
1	**2**	PC[b]	35	80 (*S*)
2	**2**	CH_2Cl_2	25	86 (*S*)
3[c]	**2**	CH_2Cl_2	120	81 (*S*)
4	**4**	PC	5	13 (*S*)
5	**4**	CH_2Cl_2	120	87 (*R*)

[a] 100% conversion in all cases.
[b] Propylene carbonate.
[c] $[Rh(COD)_2]SbF_6$ added as precatalyst.
[d] The conversion of substrate **2** and enantiomeric excess of **3** were determined by GC (Lipodex E, 25 m × 0.25 mm, 80 °C, 1 mL/min) or HPLC (Daicel Chiralcel OD-H, C_6H_{14}/*i*-PrOH = 98/2, 0.8 mL/min, 220 nm, $t(R) = 9.1$ min, $t(s) = 16.1$ min).
[e] The conversion of substrate **4** and enantiomeric excess of **5** were determined by GC (XE-valin(*tert*-butylamide) 4 × 0.25 mm, 85 °C, 1 mL/min).

We can therefore compare directly the efficacy of different ligand systems. The reactions were performed in propylene carbonate (PC) or CH_2Cl_2 at room temperature (with $[Rh(COD)_2]BF_4$ or $[Rh(COD)_2]SbF_6$, L/Rh = 1) according to the published procedures.[7a,11] In the transformation of **2** to succinate **3**, ligand **1** showed good enantioselectivity (81–86% ee), irrespective of the solvent and precatalyst (Table 1, entries 1–3). It is important to note that propylene carbonate as a reaction medium makes it possible to recycle the chiral catalyst successfully.[12]A good enantioselectivity (87%, Table 1, entry 5) was also obtained in the Rh-catalysed hydrogenation of substrate **4**, but only in CH_2Cl_2. In propylene carbonate, product **5** was formed with low optical purity and with the opposite (*S*) configuration (Table 1, entry 4).

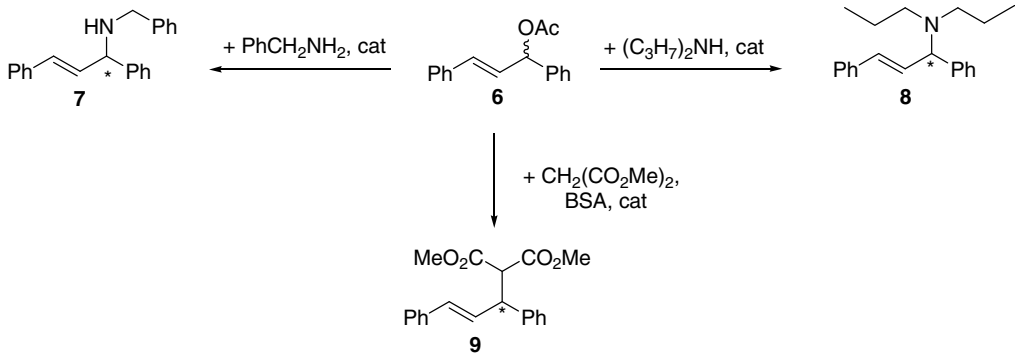
Allylic substitution is a versatile, widely used process in organic synthesis that can result in the enantioselective formation of carbon–carbon and carbon–heteroatom bonds.[13] To study further the potential of bisdiamidophosphite **1**, we tested it in the Pd-catalysed allylic substitution of (*E*)-1,3-diphenylallyl acetate **6** (which is widely used as a model substrate) with C- and N-containing nucleophiles (Scheme 3).

The reactions were performed in THF, propylene carbonate or CH_2Cl_2 at room temperature (with $[Pd(allyl)Cl]_2$ or $Pd(CF_3CO_2)_2$, L/Pd = 1 or 2) according to the published procedures.[6a,14,15] In the allylic amination of **6** with benzylamine and dipropylamine, the use of ligand **1** resulted in moderate to very good conversions and enantioselectivities in all the cases (Table 2). The best enantioselectivities of products **7** and **8** (92% and 90%, respectively) were obtained in CH_2Cl_2 at a molar ratio L/Pd = 1 (Table 2, entries 2 and 3). In the allylic alkylation of **6** with dimethyl malonate, bisdiamidophosphite **1** showed excellent enantioselectivity, up to 98% for (*S*)-**9** was obtained, CH_2Cl_2 being the solvent of choice (Table 2, entry 9). Interestingly,

Table 2
Pd-catalysed allylic amination of **6** with benzylamine and dipropylamine (20 °C) and allylic alkylation of **6** with dimethyl malonate (BSA, KOAc, 20 °C)

Entry	Precatalyst	L/Pd	Solvent	Time (h)	Conv. (%)	ee (%)
Allylic amination with benzylamine[a]						
1	$[Pd(allyl)Cl]_2$	1/1	PC	12	98	72 (*R*)
2	$[Pd(allyl)Cl]_2$	1/1	CH_2Cl_2	12	40	92 (*R*)
Allylic amination with dipropylamine[b]						
3	$[Pd(allyl)Cl]_2$	1/1	CH_2Cl_2	48	100	90 (+)
4	$[Pd(allyl)Cl]_2$	2/1	CH_2Cl_2	48	100	77 (+)
5	$[Pd(allyl)Cl]_2$	1/1	THF	48	57	76 (+)
6	$[Pd(allyl)Cl]_2$	2/1	THF	48	100	70 (+)
Allylic alkylation with dimethyl malonate[c]						
7	$Pd(CF_3CO_2)_2$	1/1	PC	14	78	67 (*S*)
8	$Pd(CF_3CO_2)_2$	1/1	CH_2Cl_2	14	91	86 (*S*)
9	$[Pd(allyl)Cl]_2$	1/1	CH_2Cl_2	48	72	98 (*S*)
10	$[Pd(allyl)Cl]_2$	2/1	CH_2Cl_2	48	80	95 (*S*)

[a] The conversion of substrate **6** and enantiomeric excess of **7** were determined by HPLC (Daicel Chiralcel OJ, C_6H_{14}/*i*-PrOH = 80/20, 0,5 mL/min, 254 nm).
[b] Enantiomeric excess of **8** determined by HPLC (Daicel Chiralcel OD-H, 1000/1/1 hexane/*i*-PrOH/$HN(Et)_2$, 0.4 mL/min, 254 nm, $t(+) = 8.2$ min, $t(-) = 9.1$ min). The conversion of **6** was determined according to ^1H NMR.
[c] The conversion of substrate **6** and enantiomeric excess of **9** were determined by HPLC (Daicel Chiralcel OD-H, C_6H_{14}/*i*-PrOH = 99/1, 0.6 mL/min, 254 nm).



Scheme 3. Pd-catalysed allylation.

the precatalyst $Pd(CF_3CO_2)_2$ provided higher conversion but reduced asymmetrising ability in comparison with $[Pd(allyl)Cl]_2$ (Table 2, entries 8 and 9).

In conclusion, bisdiamidophosphite **1** is an efficient ligand in asymmetric catalysis. In the Rh-catalysed hydrogenation of dimethyl itaconate **2**, ligand **1** was slightly inferior to $\mathbf{L_{1a-c}}$ (up to 86% and 98% ee, respectively), but in the Rh-catalysed hydrogenation of methyl 2-acetamidoacrylate **4** the enantioselectivities of the product **5** were almost equal (up to 87% and 89%).[5a] At the same time, in the Pd-catalysed allylic substitution of (*E*)-1,3-diphenylallyl acetate **6** with benzylamine and dimethyl malonate, ligands $\mathbf{L_{1c}}$ and $\mathbf{L_2}$ only gave up to 36% and 49% ee, respectively,[5b] being significantly lower than the enantioselectivities achieved with **1** (92% and 98%). Further testing of bisdiamidophosphite **1** in other benchmark asymmetric reactions is in progress in our laboratories.

Acknowledgements

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9. *Procedure for the preparation of 3,6-bis[(2′R,5′S)-3′-phenyl-1′,3′-diaza-2′-phosphabicyclo[3.3.0]octyloxy]-(3R,3aS,6R,6aS)-hexahydrofuro[3,2-b]furan* (**1**): A solution of 1,4:3,6-dianhydro-D-mannitol (0.73 g, 5 mmol) in THF (15 ml) was added dropwise at 20 °C over 20 min to a vigorously stirred solution of (2*R*,5*S*)-2-chloro-3-phenyl-1,3-diaza-2-phosphabicyclo[3.3.0]octane (2.41 g, 10 mmol) and Et_3N (1.45 ml, 10.4 mmol) in THF (25 ml). The mixture was then heated to the boiling point, stirred for 1.5 h and cooled to 20 °C. Solid $Et_3N{\cdot}HCl$ was filtered off, and the filtrate concentrated in vacuo (40 Torr). The residue was washed with hexane and dried for 45 min in vacuo (1 Torr) to give the desired product. Yield: 2.02 g (73%). White solid, mp 69–70 °C. Spectral data of **1**: ^{31}P NMR (100.6 MHz, $CDCl_3$): 123.1. ^{13}C NMR (100.6 MHz, $CDCl_3$): 26.3 (d, $^3J = 3.7$ Hz, C(7′)), 31.9 (s, C(6′)), 48.3 (d, $^2J = 37.9$ Hz, C(8′)), 54.7 (d, $^2J = 6.9$ Hz, C(4′)), 62.5 (d, $^2J = 8.4$ Hz, C(5′)), 71.3 (s, C(2) and C(5)), 72.7 (d, $^2J = 5.5$ Hz, C(3) and C(6)), 80.8 (d, $^3J = 1.8$ Hz, C(3a) and C(6a)), 115.0 (d, $^3J = 11.7$ Hz, CH_{Ar}), 119.2 (s, CH_{Ar}), 129.0 (s, CH_{Ar}), 145.5 (d, $^2J = 16.4$ Hz, C_{Ar}). MS (EI), *m*/*z* (*I*, %): 554 (8) $[M]^+$. Anal. Calcd for $C_{28}H_{36}N_4O_4P_2$: C, 60.64; H, 6.54; N, 10.10. Found: C, 60.89; H, 6.63; N, 9.89.
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4.9 Organic Carbonates as Alternative Solvents for Palladium-Catalyzed Substitution Reactions

Benjamin Schäffner, Jens Holz, Sergey P. Verevkin, Armin Börner,* *ChemSusChem* **2008**, *1*, 349-353.

Contributions

My contribution as co-author to this paper accounts 90%.

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Organic Carbonates as Alternative Solvents for Palladium-Catalyzed Substitution Reactions

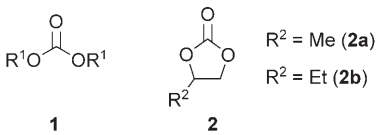
Benjamin Schäffner,[a] Jens Holz,[a] Sergey P. Verevkin,[b] and Armin Börner*[a, b]

Organic carbonates, such as propylene carbonate, butylene carbonate, and diethyl carbonate, were tested in the Pd-catalyzed asymmetric allylic substitution reactions of rac*-1,3-diphenyl-3-acetoxy-prop-1-ene with dimethyl malonate or benzylamine as nucleophiles. Bidentate diphosphanes were used as chiral ligands. The application of monodentate phosphanes capable of self-assembling with the metal was likewise tested. In the substitution reaction with dimethyl malonate, enantioselectivities up to 98% were achieved. In the amination reaction, the chiral product was obtained with up to 83%* ee*. The results confirm that these "green solvents" can be advantageously used for this catalytic transformation as an alternative to those solvents usually employed which run some risk of being harmful to the environment.*

Introduction

As a methodology with enormous effects in sustainability, catalysis has been well integrated as an essential tool in modern chemistry.[1] Especially for C–C or C–heteroatom couplings, the use of transition metals like palladium has been intensively explored.[2] Whereas in Heck,[3] Suzuki,[4] Sonogashira,[5] and Stille[6] reactions, turnover numbers (TON) and frequencies (TOF) are mostly the sticking point,[7] stereoselectivity is an important aspect in allylic substitution reactions to produce chiral compounds.[8] Over the last decade, several research groups synthesized phosphorus ligands with excellent reactivities and high enantioselective discriminating abilities for Pd-catalyzed allylic substitutions.[9] In general, standard organic solvents such as CH_2Cl_2, THF, alcohols, or toluene were used as reaction media. Besides their catalytic benefits, these solvents often present several disadvantages such as toxicity, low boiling points, and flammability, or they are environmentally hazardous. Ionic liquids have likewise been discussed and used as alternative solvents, however, their toxicological data, purification, and disposal of solvent waste are known to be problematic issues.[10] Therefore, replacement of these reaction media by less harmful solvents in catalytic reactions would combine two crucial aspects of sustainable chemistry.[11]

The employment of organic carbonates as solvents offers various benefits. In general, they can be differentiated into two groups: non-cyclic carbonates **1** and cyclic carbonates **2**. Carbonates of type **1** are used for the synthesis of other more specialized carbonate esters, amides, and oxazolidinones.[12] Carbonates of type **2**, such as propylene carbonate (PC, **2a**) or butylene carbonate (BC, **2b**), display some outstanding properties as solvents, including having a high boiling point,[13] being odorless, and displaying low toxicity. Until now, cyclic carbonates have been used frequently in cosmetics, medicine, electrochemistry, and in extractions as a "safe" solvent. Recently, BASF replaced toxic cresol with PC after an analysis of its eco-efficiency.[14] Another ecologically benign aspect concerns the environmental friendly synthesis of PC from propylene oxide and CO_2 in supercritical carbon dioxide.[15]



1 **2**

As a result of these advantages, it is rather surprising that up to now organic carbonates have not been featured much as a solvent in catalysis. Only a few examples can be found in the literature. Behr et al. showed the potential of PC in the platinum-catalyzed hydrosilylation of unsaturated fatty acid esters[16] and in rhodium-catalyzed hydroformylation reactions in temperature-dependent multicomponent solvent systems.[17] Reetz and Lohmer used PC for the stabilization of Pd clusters in Heck reactions.[18] Bradley and co-workers compared PC with other solvents in the hydrogenation of ethyl pyruvate in the presence of heterogeneous Pt/Al_2O_3 catalysts.[19] Recently, we reported the use of PC in homogeneously Rh- and Ir-catalyzed hydrogenations of functionalized and non-functionalized olefins.[20] Furthermore, efficient recycling of the catalyst was possible by extraction of the product with *n*-hexane. In addition, we showed the potential of PC in the Rh-catalyzed hydrogenation of functionalized olefins in the presence of self-assembling catalysts.[21]

Herein, we report our results on the use of organic carbonates in Pd-catalyzed asymmetric allylic substitution reactions.

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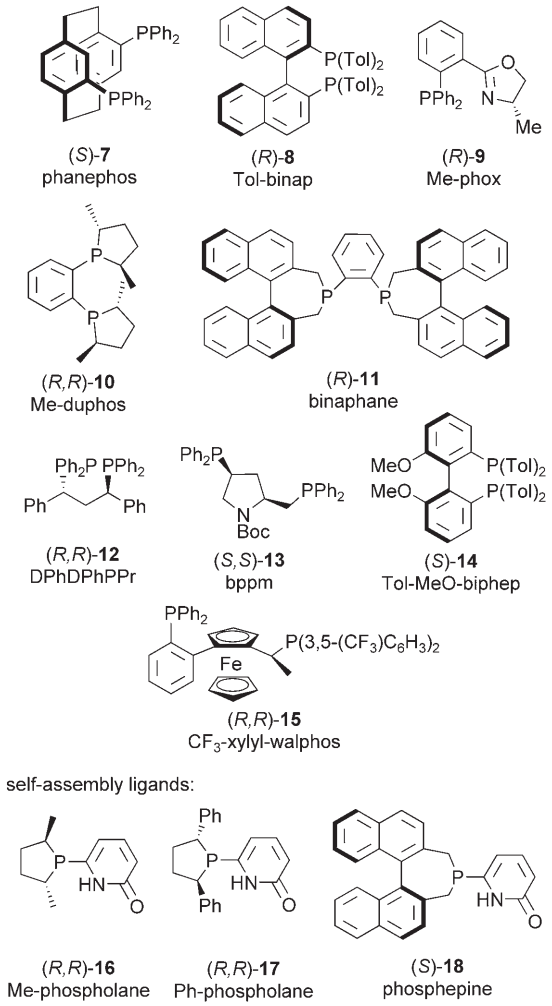
We employed ligands **7**–**15**, which are commercially available, for our studies (Scheme 1).[22] These phosphanes were selected to have the maximum variation in structure and electronic properties. We also gave attention to self-assembling ligands **16**–**18**. Phosphorus ligands of this type were originally introduced in homogeneous catalysis by Breit et al. and are able to build up hydrogen bonding in the coordination sphere of a metal.[23] Recently, we used such ligands successfully in Rh-catalyzed asymmetric hydrogenation[24] and in Pd-catalyzed allylic amination reactions.[25] We collected several pieces of evidence that the formation of the desired hydrogen-bonding-based assemblies is strongly affected by the choice of the solvent.[24,25] Moreover, we investigated the effect of such ligands in Rh-catalyzed hydrogenations in fluorinated alcohols.[26]

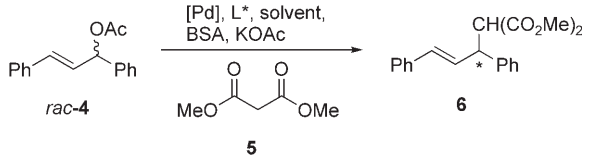


Scheme 1. Ligands studied in the Pd-catalyzed asymmetric allylic substitution reaction (Boc = *tert*-butyloxycarbonyl).[22]

Results and Discussion

Asymmetric Allylic Alkylation

For the Pd-catalyzed asymmetric allylic alkylation (AAA), *rac*-1,3-diphenyl-3-acetoxyprop-1-ene (**4**) and dimethyl malonate (**5**) were used in the presence of BSA/KOAc as base to afford the chiral product **6** (Scheme 2). The effect of commonly used solvent CH_2Cl_2 was compared with that of the organic carbonates PC, BC, and diethyl carbonate (DEC). The results of the AAA are collected in Table 1.



Scheme 2. Pd-catalyzed asymmetric allylic alkylation in different solvents (BSA = *N*,*O*-bis(trimethylsilyl)acetamide).

Table 1. Pd-catalyzed asymmetric allylic substitution of **4** with **5** using bidentate phosphanes **7**–**14**.

Entry	Pd source	Ligand	Solvent[a]	Yield [%][b]	*ee* [%][c]
1	$Pd(F_3CCO_2)_2$	**7**	CH_2Cl_2	80	44 (*S*)
2	$Pd(F_3CCO_2)_2$	**7**	PC	91	29 (*S*)
3	$Pd(F_3CCO_2)_2$	**7**	(*S*)-(−)-PC	89[d]	29 (*S*)
4	$Pd(F_3CCO_2)_2$	**7**	BC	76[d]	36 (*S*)
5	$Pd(F_3CCO_2)_2$	**7**	DEC	98[d]	35 (*S*)
6	$Pd(F_3CCO_2)_2$	**8**	PC	22	74 (*S*)
7	$Pd(F_3CCO_2)_2$	**8**	CH_2Cl_2	89	64 (*S*)
8	$Pd(F_3CCO_2)_2$	**8**	BC	12	29 (*S*)
9	$Pd(F_3CCO_2)_2$	**8**	DEC	13	64 (*S*)
10	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	CH_2Cl_2	92	96 (*R*)
11	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	PC	97	95 (*R*)
12	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	CH_2Cl_2	75[d,e]	97 (*R*)
13	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	PC	29[d,e]	90 (*R*)
14	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	BC	84[d]	98 (*R*)
15	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**9**	DEC	87[d]	95 (*R*)
16	$Pd(F_3CCO_2)_2$	**10**	CH_2Cl_2	6	n.d.[f]
17	$Pd(F_3CCO_2)_2$	**10**	PC	0	–
18	$Pd(F_3CCO_2)_2$	**11**	CH_2Cl_2	6	0
19	$Pd(F_3CCO_2)_2$	**11**	PC	8	0
20	$Pd(F_3CCO_2)_2$	**12**	CH_2Cl_2	8	12 (*R*)
21	$Pd(F_3CCO_2)_2$	**12**	PC	12	42 (*R*)
22	$Pd(F_3CCO_2)_2$	**13**	CH_2Cl_2	90	7 (*R*)
23	$Pd(F_3CCO_2)_2$	**13**	PC	79	16 (*R*)
24	$Pd(F_3CCO_2)_2$	**13**	BC	92	12 (*R*)
25	$Pd(F_3CCO_2)_2$	**13**	DEC	87	6 (*R*)
26	$Pd(F_3CCO_2)_2$	**14**	PC	9	n.d.[f]
27	$Pd(F_3CCO_2)_2$	**14**	CH_2Cl_2	41	58 (*S*)

[a] PC = propylene carbonate, DEC = diethyl carbonate, BC = butylene carbonate. [b] Yield of **6** determined by GC using hexadecane as internal standard. [c] Determined by chiral HPLC with Chiralpak AD-H column. Configurations are given in parentheses. [d] Reaction time 2 h. [e] 0 °C. [f] Not determined owing to contamination of one enantiomer with a by-product of unknown structure.

Some of the ligands were particularly designed for Rh- or Ir-catalyzed hydrogenations and gave the desired alkylation product only in moderate yield and with modest enantioselectivities (Table 1, entries 1–9, 16–27).[27] With Tol-binap (**8**), a strong dependence upon the solvent was noted (Table 1, entries 6–9). The product **6** was obtained in moderate yield in CH_2Cl_2, whereas in PC a loss of conversion was observed. However, the *ee* value was increased by 10% in PC (Table 1, entries 6 and 7). When non-cyclic diethyl carbonate or cyclic bu-

tylene carbonate were used, both the reactivity and *ee* value dropped in comparison to the effect with PC (Table 1, entries 8 and 9). The catalyst with Tol-MeO-biphep (**14**) as ligand showed the same tendency. In PC the reactivity decreased (Table 1, entries 26 and 27). Unfortunately it was not possible to determine the *ee* value in PC owing to contamination of one of the enantiomers with an unknown by-product. The catalysts based on the 1,3-diphosphane ligand **12** gave only low conversions and moderate *ee* values in PC (Table 1, entries 20 and 21). Application of ligands **7** and **13** afforded the chiral product in good yield in PC. The increase in reactivity goes along with a decrease in enantioselectivity from 44% *ee* in CH_2Cl_2 to 29% *ee* in PC (Table 1, entries 1 and 2). The use of a chiral PC did not show any effect (Table 1, entry 3), indicating that the solvent does not interfere during the enantiodiscriminating step. The use of BC or DEC did not increase the enantioselectivity significantly (Table 1, entries 4 and 5). With **13** as ligand, the *ee* was low in all the solvents used (Table 1, entries 22–25). The maximum yield (92%) was observed in BC, whereas the highest enantioselectivity in PC did not exceed 16%. The class of phox ligands as exemplified by **9** was first synthesized by Pfaltz and von Matt and is reputed to give excellent results in Pd-catalyzed allylic alkylations.[28] Also in our experiments, the ligand formed very active catalysts which gave **6** in high yields and good or even excellent enantioselectivities (Table 1, entries 10–15). Superior results were obtained in BC (85% yield, 98% *ee*) within 2 h (Table 1, entry 14). The catalyst displayed nearly the same reactivity in DEC as in BC (compare entries 14 and 15, Table 1). In PC, a yield of only 29% was observed but with a respectable 90% *ee* provided the reaction was carried out at 0 °C. Note, however, that superior results were observed under the same conditions in CH_2Cl_2 (compare entries 12 and 13, Table 1).

The effect of self-assembling ligands on the Pd-catalyzed alkylation is summarized in Table 2. We recently reported already the utility of these ligands in the AAA.[25,29] Results with the Me-phospholane ligand **16** are similar in CH_2Cl_2 and PC. In both solvents, good or excellent yields accompanied by good *ee* values were obtained (Table 2, entries 1 and 2). By changing the Pd precursor to $[Pd(\pi\text{-}C_3H_5)Cl]_2$, it was possible to increase the yield, however, the enantioselectivity remained constant (Table 2, entry 3). A slight amelioration of the *ee* value could be achieved by lowering the reaction temperature (Table 2, entry 4). In BC and DEC as solvents, the product **6** was obtained with nearly similar enantioselectivities but the yields were lower in comparison to those with PC or CH_2Cl_2 (Table 2, entries 6 and 7). We previously showed that the use of Ph-substituted phospholane **17** in the Pd-catalyzed AAA led to lower *ee* values than the application of its Me analogue **16**.[25] It seems that the bulky phenyl group prevents the achievement of higher *ee* values. In toluene and dichloromethane, the reactivity of the catalyst was low (Table 2, entries 8 and 10). In PC, the same catalytic system showed a high reactivity, but induced only a low *ee* (Table 2, entry 9). A small gain in enantioselectivity could be achieved by running the reaction at 0 °C. The reactions in toluene and in CH_2Cl_2 at 0 °C failed (Table 2, entries 10, 11).

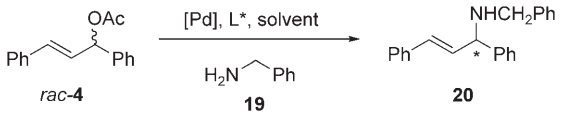
Table 2. Pd-catalyzed asymmetric allylic substitution of **4** with **5** using self-assembling ligands **16** and **17**.

Entry	Pd source	Ligand	Solvent	Yield [%][a]	*ee* [%][b]
1	$Pd(F_3CCO_2)_2$	**16**	CH_2Cl_2	87	67 (*R*)
2	$Pd(F_3CCO_2)_2$	**16**	PC	80	69 (*R*)
3	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**16**	PC	98	68 (*R*)
4	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**16**	PC	95[c,d]	74 (*R*)
5	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**16**	(*S*)-(−)-PC	98[c]	67 (*R*)
6	$Pd(F_3CCO_2)_2$	**16**	DEC	37	65 (*R*)
7	$Pd(F_3CCO_2)_2$	**16**	BC	56	68 (*R*)
8	$Pd(F_3CCO_2)_2$	**17**	CH_2Cl_2	56	22 (*R*)
9	$Pd(F_3CCO_2)_2$	**17**	PC	94	12 (*R*)
10	$Pd(F_3CCO_2)_2$	**17**	toluene	3	n.d.[e]
11	$Pd(F_3CCO_2)_2$	**17**	CH_2Cl_2	4[c,d]	n.d.[e]
12	$Pd(F_3CCO_2)_2$	**17**	PC	27[c,d]	18 (*R*)

[a] Yield of **6** determined by GC using hexadecane as internal standard. [b] Determined by chiral HPLC with Chiralpak AD-H column. Configurations are given in parentheses. [c] Reaction time 2 h. [d] 0 °C. [e] Not determined (see Table 1).

Asymmetric Allylic Amination

Benzyl amine (**19**) was used for the asymmetric allylic amination of **4** (Scheme 3). Only those ligands that showed some activity in the AAA were selected in this reaction (Table 3). To our surprise, in comparison to CH_2Cl_2 the use of PC diminished the enantioselectivity drastically when using phanephos (**7**). Whereas in dichloromethane an *ee* value of 43% was achieved, with racemic or enantiopure PC the amine **20** was obtained as a nearly racemic mixture (Table 3, entries 1 and 2). By using a catalyst/ligand ratio of 1:4, the *ee* value was slightly increased (Table 3, entry 3). A slight enhancement in the *ee* value was also noted by the employment of $[Pd_2(dba)_3]\cdot CHCl_3$ as precursor (dba = *trans*,*trans*-dibenzylideneacetone; Table 3, entry 4). The reaction was not affected by the use of enantiopure PC (Table 3, entries 5 and 6). Unfortunately, a by-product was formed when using ligand **8**, which led to difficulties during the measurement of the *ee* value. Additionally, the reactivity of the catalyst based on **8** in PC was low (Table 3, entries 5 and 6). The use of ligand **13** afforded **20** in good yield but with poor enantioselectivity only, independent of the solvent used. Best results were obtained with the Walphos ligand **15** (Table 3, entry 13). Again, the use of enantiopure PC did not lead to any improvements (Table 3, entries 14, 15).



rac-**4** **19** **20**

Scheme 3. Pd-catalyzed asymmetric allylic amination with **4** and benzylamine.

Finally, we tested the potentially self-assembling ligands **16**–**18** in the allylic amination (Table 4). With phospholane **16** as

Table 3. Pd-catalyzed asymmetric allylic amination of **4** with benzylamine (**19**) using catalysts with ligands **7**, **8**, **13**, and **15**.

Entry	Pd source	Ligand	Solvent	Yield [%][a]	*ee* [%][b]
1	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**7**[c]	CH_2Cl_2	95	43 (*R*)
2	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**7**[c]	PC	99	2 (*R*)
3	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**7**[c]	PC	99	12 (*R*)[d]
4	$[Pd_2(dba)_3]\cdot CHCl_3$	**7**[c]	PC	99	22 (*R*)[d]
5	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**7**[c]	(*S*)-(−)-PC	99	16 (*R*)[d]
6	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**7**[c]	(*R*)-(+)-PC	99	18 (*R*)[d]
7	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**8**	CH_2Cl_2	64	85 (*S*)
8	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**8**	PC	21	n.d.[e]
9	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**13**	CH_2Cl_2	98	15 (*R*)
10	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**13**	PC	86	4 (*R*)
11	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**13**	PC	89	13 (*R*)[e]
12	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**15**	CH_2Cl_2	96	84 (*R*)
13	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**15**	PC	99	59 (*R*)
14	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**15**	(*S*)-(−)-PC	96	58 (*R*)
15	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**15**	(*R*)-(+)-PC	97	58 (*R*)

[a] Yield of **6** determined by GC using hexadecane as internal standard. [b] Determined by chiral HPLC with Chiralcel OJ column, hexane/EtOH = 95:5. Configurations are given in parentheses. [c] Using (*R*)-phanephos (**7**). [d] Catalyst/ligand = 1:4. [e] Not determined (see Table 1).

Table 4. Pd-catalyzed asymmetric allylic amination of **4** with benzylamine (**19**) using ligands **16**–**18**.

Entry	Pd source	Ligand	Solvent	Yield [%][a]	*ee* [%][b]
1	$[Pd_2(dba)_3]\cdot CHCl_3$	**16**	CH_2Cl_2	77	81 (*R*)
2	$[Pd_2(dba)_3]\cdot CHCl_3$	**16**	PC	96	50 (*R*)
3	$[Pd_2(dba)_3]\cdot CHCl_3$	**16**	DEC	72	83 (*R*)
4	$[Pd_2(dba)_3]\cdot CHCl_3$	**16**	BC	18	80 (*R*)
5	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**17**	CH_2Cl_2	88	11 (*S*)
6	$[Pd(\pi\text{-}C_3H_5)Cl]_2$	**17**	PC	91	57 (*S*)
7	$[Pd_2(dba)_3]\cdot CHCl_3$	**18**	CH_2Cl_2	100[c]	82 (*S*)[c]
8	$[Pd_2(dba)_3]\cdot CHCl_3$	**18**	PC	74	55 (*S*)

[a] Yield of **6** determined by GC using hexadecane as internal standard. [b] Determined by chiral HPLC with Chiralcel OJ column, hexane/EtOH = 95:5. Configurations are given in parentheses. [c] Data from Ref. [25].

ligand, the best *ee* value was observed in DEC (83% *ee*, Table 4, entry 3), while the highest yield was obtained in PC (96%, entry 2). A low yield was also found in BC (Table 4, entry 4). With phospholane **17**, superior results were obtained in PC than in CH_2Cl_2 (compare entries 5 and 6, Table 4). The phosphepine ligand **18** performed better in CH_2Cl_2 than in PC (Table 4, entries 7 and 8). In all trials, the products were isolated by column chromatography.

Summary

The applicability of the green solvents propylene carbonate, butylene carbonate, and diethyl carbonate, was successfully proven for the first time in the Pd-catalyzed asymmetric allylic alkylation reaction using different phosphorus ligands. In comparison to environmentally unfriendly CH_2Cl_2, which is usually employed in this transformation, enhanced yields and enantioselectivities were noted in several cases. Especially Pd complexes with self-assembling ligands showed a similar or even better catalytic performance in organic carbonates. Thus, these new and environmentally benign solvents open up valuable alternatives for the fine-tuning of these catalytic reactions. Unfortunately, products of the alkylation and amination reactions considered herein are highly polar, therefore the only possibility for removal of the catalyst is chromatography. Studies are in progress to identify such reaction conditions and products that allow more efficient separations, as we recently demonstrated for the asymmetric hydrogenation reaction.[20]

Experimental Section

General procedures: All experiments were performed in Schlenk-type flasks under dry argon. Solvents were dried by conventional methods. ^1H and ^{13}C NMR data were measured in $CDCl_3$ at 300 MHz. Proton chemical shifts are referenced to TMS as standard. Carbon chemical shifts are referenced to the carbon signal of the solvent at $\delta = 77.0$ ppm. *rac*-1,3-Diphenyl-3-acetoxyprop-1-ene (**4**) was synthesized according to a reported procedure.[30]

General procedure for asymmetric allylic alkylations: $Pd(F_3CCO_2)_2$ (1.7 mg, 0.005 mmol, 1 mol%) or $[Pd(\pi\text{-}C_3H_5)Cl]_2$ (0.9 mg, 0.0025 mmol) and the ligand (1 mol% for bidentate ligands, 2 mol% for monodentate ligands) were dissolved in 2 mL solvent. After stirring the mixture at room temperature for 20 min, **4** (126.2 mg, 0.5 mmol), dimethyl malonate (0.171 mL, 1.5 mmol), BSA (0.372 mL, 1.5 mmol), and a trace of KOAc were added. After stirring the mixture for 14 h at room temperature, the mixture was filtered to remove any precipitates. In the screening process, the solution was diluted with ethyl acetate (8 mL) for GC and HPLC measurements. For calibration of GC, the product was isolated by flash chromatography by applying the filtered solution directly on a column of silica gel. The product was separated from PC with an eluent mixture of *n*-hexane/ethyl acetate.

Dimethyl 2-(1,3-diphenylallyl)malonate: The filtered reaction mixture was separated by column chromatography (*n*-hexane/EtOAc = 80:20; $R_f = 0.16$). ^1H NMR (300 MHz): $\delta = 3.36$ (s, 3H), 3.55 (s, 3H), 3.80 (d, 1H, $J = 10.8$ Hz), 4.12 (dd, 1H, $J = 10.8$, 8.3 Hz), 6.18 (dd, 1H, $J = 15.6$, 8.3 Hz), 6.32 (d, 1H, $J = 15.6$ Hz), 7.00–7.19 ppm (m, 10H). ^{13}C (75.5 MHz): $\delta = 49.3$, 52.5, 52.7, 57.7, 126.4 (overlapping), 127.2, 127.6, 127.9 (overlapping), 128.5 (overlapping), 128.8 (overlapping), 129.2, 131.2, 136.9, 140.2, 167.8, 168.3 ppm. The enantiomeric excess was determined by chiral HPLC (CHIRALPAK AD-H column, hexane/EtOH = 80:20, 3.0 mL min^{-1}, retention times $t_1 = 7.7$ min (*S*); $t_2 = 14.3$ min (*R*)).

General procedure for asymmetric allylic aminations: $[Pd_2(dba)_3]\cdot CHCl_3$ (2.6 mg, 0.0025 mmol, 1 mol%) or $[Pd(\pi\text{-}C_3H_5)Cl]_2$ (0.9 mg, 0.0025 mmol) and the ligand (1 mol% for bidentate ligands, 2 mol% for monodentate ligands) were dissolved in 2 mL solvent. After stirring the mixture at room temperature for 20 min, **4** (126.2 mg, 0.5 mmol) and benzylamine (0.164 mL, 1.5 mmol) were added. After stirring the mixture for 14 h at room temperature, the mixture was filtered to remove any precipitates. In the screening process, the solution was diluted with ethyl acetate (8 mL) for GC and HPLC measurements. For calibration of GC, the product was isolated by flash chromatography by applying the filtered solution directly on a column of silica gel. The product was separated from PC with an eluent mixture of *n*-hexane/ethyl acetate.

N-Benzyl-1,3-diphenylprop-2-en-1-amine: The filtered reaction mixture was separated by column chromatography (*n*-hexane/EtOAc =

90:10; $R_f = 0.13$). ^{1}H NMR (300 MHz): $\delta = 1.64$ (br s, 1H, NH), 3.68/3.73 (AB, 2H, $J = 13.4$ Hz), 4.32 (d, 1H, $J = 7.4$ Hz), 6.24 (dd, 1H, $J = 15.8$, 7.4 Hz), 6.50 (d, 1H, $J = 15.8$ Hz), 7.09–7.34 ppm (m, 15H). ^{13}C (75.5 MHz): $\delta = 51.5$, 64.6, 126.5 (overlapping), 127.0, 127.4 (overlapping), 127,5, 128.2 (overlapping), 128.5 (overlapping), 128.7 (overlapping), 130.4, 132.7, 137.0, 140.5, 142.9 167.8, 168.3 ppm. The enantiomeric excess was determined by chiral HPLC (CHIRALCEL OJ-H column, hexane/EtOH = 95:5, 1.0 mL min^{-1}, retention times $t_1 = 15.8$ min (*R*); $t_2 = 20.9$ min (*S*)).

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Keywords: alkylation · amination · carbonates · palladium · phosphane ligands

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[22] Phanephos = 4,12-bis(diphenylphosphanyl)-[2.2]-paracyclophane (**7**); Tol-binap = 2,2′-bis(di-*p*-tolylphosphanyl)-1,1′-binaphthyl (**8**); Me-phox = 2-[2-(diphenylphosphanyl)phenyl]-4-methyl-4,5-dihydrooxazole (**9**); Me-Duphos = 1,2-bis-(2,5-dimethylphospholano)benzene (**10**); binaphane = 1,2-bis(4,5-dihydro-3H-binaphtho[1,2-c:2′,1′-e]phosphepino)benzene (**11**); DPhDPhPPr = 1,3-diphenyl-1,3-diphenylphosphanylpropane (**12**); bppm = *N*-Boc-4-diphenylphosphanyl-diphenylphosphanyl methylpyrrolidine (**13**); Tol-MeO-biphep = 6,6′-dimethoxy-2,2′-bis(diphenylphosphanyl)-1,1′-biphenyl (**14**); CF_3-xylyl-walphos = 1-[2-(2′-diphenylphosphanylphenyl)ferrocenyl]ethyldi(bis-3,5-trifluoromethylphenyl)phosphane (**15**); Me-phospholane = 2,5-dimethyl-1-(1H-pyridin-6-on-2-yl)-phospholane (**16**); Ph-phospholane = 2,5-dimethyl-1-(1H-pyridin-6-on-2-yl)-phospholane (**17**); phosphepine = (1H-pyridin-6-on-2-yl)-phosphepine (**18**).
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4.10 Palladium-catalyzed Sonogashira coupling reactions of aryl chlorides without copper co-catalysts

Christian Torborg, Juan Huang, Thomas Schulz, Benjamin Schäffner, Alexander Zapf, Anke Spannenberg, Armin Börner, Matthias Beller,* *Chem. Eur. J.* **2009**, *15*, 1329-1336.

Contributions

My contribution as co-author to this paper accounts 20%. I significantly contributed to the draft of the manuscript and was initiator of the use of propylene carbonate in exchange of acetonitrile. Furthermore, I completed the NMR studies about catalyst formation in PC and toluene.

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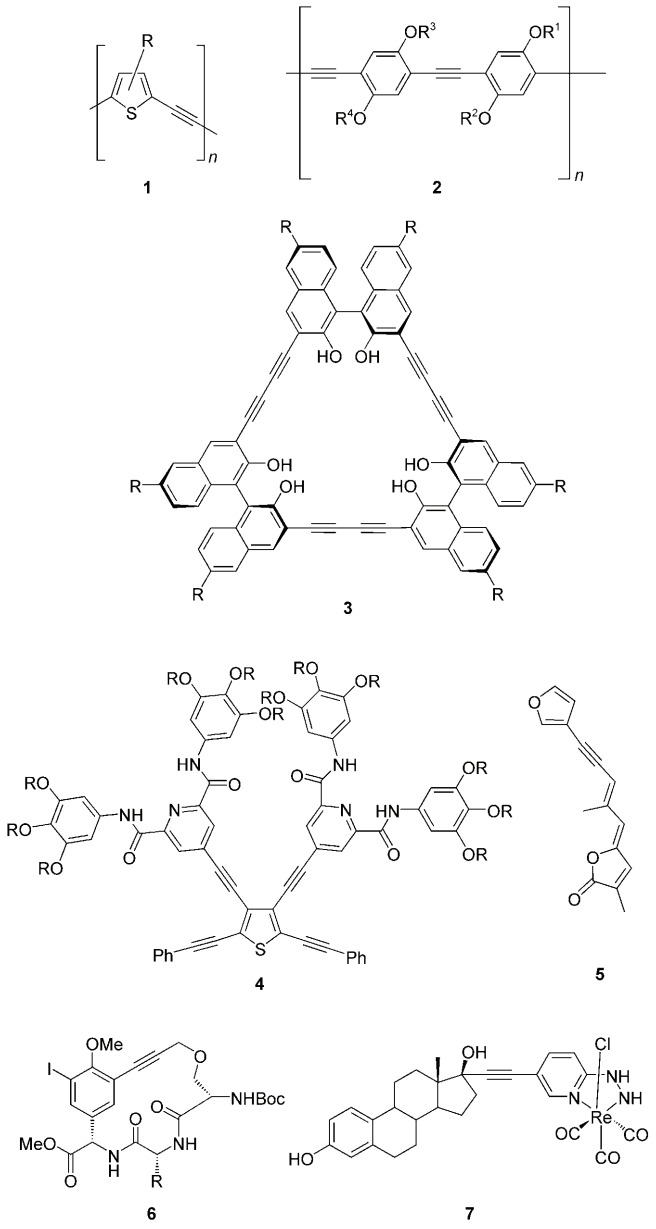
Improved Palladium-Catalyzed Sonogashira Coupling Reactions of Aryl Chlorides

Christian Torborg, Jun Huang, Thomas Schulz, Benjamin Schäffner, Alexander Zapf, Anke Spannenberg, Armin Börner, and Matthias Beller*[a]

The construction of C_{sp}–(aryl)C_{sp^2} bonds is an important transformation in organic chemistry. The resulting aryl alkynes are building blocks often encountered within natural products, pharmaceutical products, and molecular materials.[1] Due to the highly conjugated π system, this structural motif is found in organic semiconductors, and the respective products act as molecular sensors, light-emitting diodes, or polarizers for liquid-crystalline displays.[2] In recent years polyaryleneethynylenes (PAEs) and oligoaryleneethynylenes (OAEs) such as **1** and **2** (Scheme 1) have become an established class of conjugated polymers in addition to poly(*p*-phenylenevinylene)s (PPVs) and polyacetylenes. Moreover, arylene–ethynylene macrocycles (AEMs) (e.g. **3**) and macromolecules such as **4** possess interesting electronic properties and lead to defined nanostructures.[3,4] Apart from material science, the construction of aryl alkynes plays an important role in the synthesis of complex molecules of pharmaceutical and agrochemical interest (e.g. **5**,[5] **6**,[6] **7**[7]), even though the arylene–ethynylene structure itself does not often occur in natural products, which is in marked contrast to the corresponding vinylene–ethynylene motif.[8] However, the alkynylation of aromatic halides and subsequent cyclization is a widely used method for the synthesis of carbo-[9] and heterocycles[10] as well as intermediates of natural products.[11] It is undeniable that the most effective way to form aryl–alkyne bonds is still palladium-catalyzed coupling reactions of aromatic halides with alkynes in the presence of base and copper co-catalysts. Although this reaction was independently discovered by Cassar, Heck, and Sonogashira in 1975,[12] today it is generally known as the Sonogashira reaction, and numerous catalytic systems have been reported for this



Scheme 1. Examples for structures bearing the arylene–ethynylene motif.

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transformation.[13] During the last few years important catalyst developments have been described such as the minimization of the catalyst amount,[14] the activation of less-reactive starting materials (aryl chlorides, alkyl halides),[15] the selective transformation of more functionalized substrates,[16] and the application of cost effective and/or sustainable methods.[17] With respect to the latter point, aryl–alkyne coupling methods catalyzed by more cost-effective metals such as iron[18] or copper[19] have become an interesting alternative to Pd-catalyzed procedures regarding the efficient coupling of aryl iodides. However, so far there is no general procedure for the efficient coupling of deactivated aryl bromides and inexpensive aryl chlorides with these metals. A generally accepted mechanism[20] of the Sonogashira reaction consists of two catalytic cycles: a) the 'classic' palladium-based coupling reaction that involves the oxidative addition of an aryl (vinyl) halide (or triflate) R^1–X to a low-coordinate palladium(0) complex, then transmetalation of a copper-acetylide (formed in the second catalytic cycle) to generate a $R^1Pd(-C\equiv CR^2)L_2$ species, which subsequently undergoes a *cis–trans* isomerzation and reductive elimination to give the aryl (vinyl)–alkyne and the regenerated catalyst; and b) the so-called 'copper-cycle', in which the copper–acetylide is generated from the free alkyne in the presence of a base, which is often an amine. This latter cycle is poorly understood: for example, the in situ formation of a copper acetylide is not proven yet, although recently indirect evidence has been found.[21] In fact, most of the amines used are not basic enough to deprotonate the alkyne to provide an anionic species which can further react to the corresponding copper acetylide. Therefore, a π-alkyne–Cu complex, which makes the alkyne proton more acidic, is often proposed as an intermediate. With respect to further catalyst developments the application of copper-free (and also amine-free) protocols is of importance due to the environmental and economical advantages. However, to date, only a few examples of Sonogashira reactions without copper source have been described. Notably, Gelman and Buchwald discovered in 2003 a catalyst system consisting of $[PdCl_2(CH_3CN)_2]$ and the so-called XPhos ligand, which allowed a general coupling of aryl chlorides and aryl tosylates with various terminal alkynes.[15c,22] Although desilylation of trimethylsilylacetylene, an important substrate in the synthesis of larger molecules, was observed during the reaction, an excellent substrate scope was demonstrated. Interestingly from a mechanistic viewpoint, the same authors reported that the presence of copper iodide in the coupling of aryl chlorides with alkynes inhibits coupling reactions. Copper-free Sonogashira reactions were also described in water.[23] More recently, Yi et al. reported in 2006 the application of $[PdCl_2(PCy_3)_2]$ in the coupling of various aryl chlorides with alkynes under copper-free conditions with 3 mol% catalyst at 100–150 °C.[24] Activation of the alkyne without copper is supposed to proceed via formation of a $(\eta^2\text{-}RC\equiv CH)Pd^0L_2$ species.[25,26] However, the term 'copper-free' should be considered carefully, since commercially available palladium salts can contain traces of copper.[27]

For some years we have been interested in the development of palladium catalysts that can be applied for coupling reactions on both laboratory as well as industrial scale. In this respect we have developed palladacycles,[28] adamantylphosphines,[29] carbene ligands,[30] and 2-phosphino-*N*-arylindoles and -pyrroles.[31] More recently, we also reported the synthesis of 2-phosphino-*N*-arylimidazoles and their application in cross-coupling reactions of aryl chlorides and bromides.[32] Importantly, such monodentate *N*-substituted heteroaryl phosphines are conveniently synthesized by selective metalation at the 2-position of the respective *N*-substituted heterocycle (pyrrole, indole, imidazole). Thus, a variety of novel ligands is easily available and can be efficiently prepared in a modular synthesis. This is an important aspect, since the application of palladium-catalyzed coupling reactions in the fine chemical and pharmaceutical industry requires in general a fine-tuning of the catalytic system. Here, we describe for the first time the use of *N*-aryl-heteroarylphosphines in Sonogashira coupling reactions of aryl chlorides without the necessity to add copper salts. Inspired by the work of the Buchwald group on XPhos,[33] we synthesized the novel ligand [*N*-(2,6-diisopropylphenyl)-2-imidazolyl]-di-*tert*-butylphosphine L1 (Figure 1).

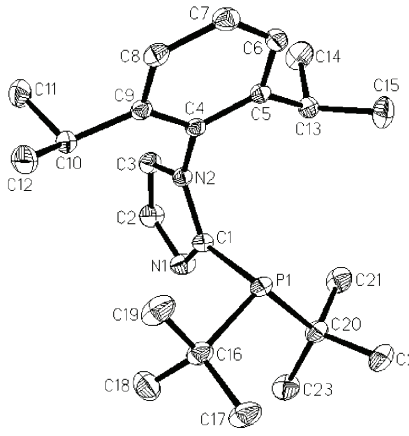
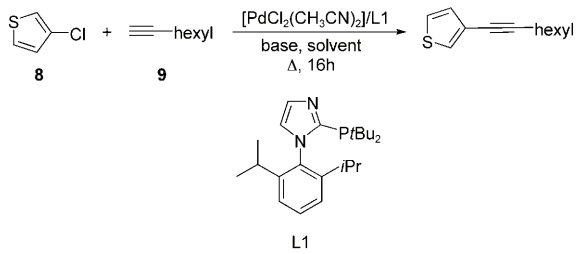


Figure 1. Molecular structure of L1. Hydrogen atoms are omitted for clarity. The thermal ellipsoids correspond to 30% probability.

Advantageously, this ligand is formed straightforwardly from easily available substrates (2,6-diisopropylamine, glyoxal, formaldehyde,[34] and chloro-di-*tert*-butylphosphine) in two steps. For our catalytic studies we chose the reaction of 3-chlorothiophene (**8**) and 1-octyne (**9**), which is a more challenging coupling reaction. Propylene carbonate (PC) was first chosen as solvent for the reaction. Its usage in coupling reactions offers several advantages including the possibility of catalyst recycling a) via extraction of the nonpolar product with nonpolar solvents from the reaction mixture[35] or b) as PC can form part of temperature-dependent multicomponent solvent systems (TMS systems).[36] To our delight the reaction proceeded with 1 mol% $[PdCl_2(CH_3CN)_2]$ and 8 mol% of phosphine ligand L1 in 76% yield at 90 °C (Table 1, entry 1).[37] Unfortunately, decreasing the Pd/ligand

Table 1. Sonogashira coupling of 3-chlorothiophene and 1-octyne without copper.[a]



Entry	Pd [mol%]	L [mol%]	Solvent	Base	Conv. [%]	Yield [%][b]
1	1	8	PC	Cs_2CO_3	8	76
2	1	3	PC	Cs_2CO_3	3	25
3	2	6	PC	Cs_2CO_3	4	30
4	1	8	toluene	Na_2CO_3	80	71
5	1	3	toluene	Na_2CO_3	73	68
6	1	2	toluene	Na_2CO_3	18	18
7	1	1	toluene	Na_2CO_3	10	10
8[c]	1	3	toluene	Na_2CO_3	90	87
9[d]	1	3	toluene	Na_2CO_3	45	45
10[e]	1	3	toluene	Na_2CO_3	18	2
11[f]	1	1	toluene	Na_2CO_3	60	40
12[g]	1	3	toluene	Na_2CO_3	90	86

[a] Reaction conditions: 3-chlorothiophene (1 equiv), 1-octyne (1.3 equiv), base (2.6 equiv), solvent (0.5 M), 16 h (reaction times not optimized). [b] GC yields (internal standard: hexadecane). [c] 2 equiv of 1-octyne and 4 equiv of base. [d] $Pd(OAc)_2$. [e] 1 mol% of CuI. [f] 2 equiv of 1-octyne and 4 equiv of base, 1 mol% of complex **10**. [g] 2 equiv of 1-octyne and 4 equiv of base, 1 mol% of complex **10**, 2 mol% L1.

ratio from 1:8 to 1:3 lowered the product yield (Table 1, entries 2 and 3) significantly. Apparently, the reaction in propylene carbonate needs an excess of ligand, which may be explained by partial displacement of the ligand by solvent molecules.[38] In contrast to the reaction in propylene carbonate, the Sonogashira coupling in toluene with sodium carbonate as base yielded the desired 3-octinylthiophene in good yield at lower ligand concentration (Table 1, entries 4 and 5). However, an excess of ligand is obviously needed (Table 1, entries 6 and 7). The best yield is obtained by addition of two equivalents of the alkyne (Table 1, entry 9, 87% yield); most likely because the Pd^{II} species is reduced to the catalytically active Pd^0 species by the alkyne in the first place. After a standard procedure,[39] complex **10** was prepared from one equivalent of $[PdCl_2(CH_3CN)_2]$ and one equivalent of L1. Remarkably, X-ray analysis showed a η^2-P,N chelation of L1 to the metal center (Figure 2).[40] Time-dependent ^{31}P NMR experiments showed that this complex is also formed from a mixture of one equivalent of $[PdCl_2(CH_3CN)_2]$ and three equivalents of L1 in propylene carbonate as well as in toluene. Therefore it is most likely that it is also present in the reaction mixture and should act as a precursor for a monoligated Pd^0 species. Monoligated Pd^0 species are supposed to be the catalyst in coupling reactions, if bulky biarylphosphines like L1 are applied.[41] With the phosphine already attached to the metal center, the creation of the catalytically active species is considered to be easier from **10** than from a mixture of $[PdCl_2(CH_3CN)_2]$ and L1.

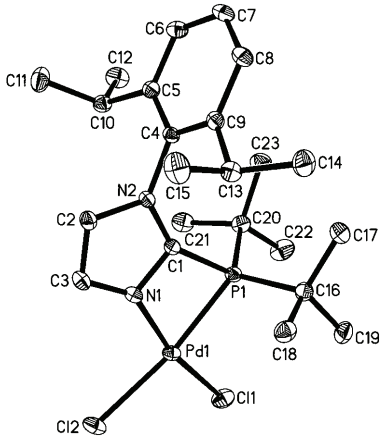
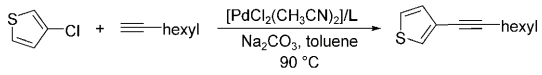
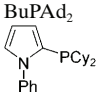
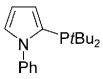
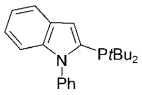
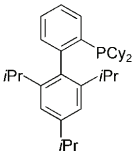
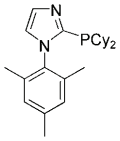
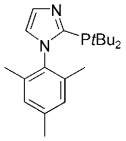
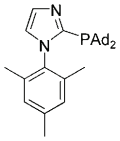
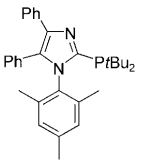
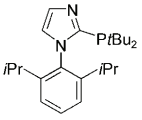
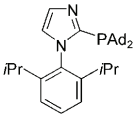


Figure 2. Molecular structure of **10**. Hydrogen atoms are omitted for clarity. The thermal ellipsoids correspond to 30% probability.

For the same reasons, an excess of ligand is not necessary any more. Hence, complex **10** was directly applied in the reaction (Table 1, entry 11). However, the reaction yielded only 40% of the coupling product under optimized conditions; with an additional 2 mol% of L1, the same activity of the catalyst was observed as with 1 mol% of $[PdCl_2(CH_3CN)_2]$ and 3 mol% of L1 (Table 1, entry 12). In agreement with the observation by Buchwald et al., inhibition of the reaction is observed when CuI was applied as co-catalyst (Table 1, entry 10). Next, a series of commercially available phosphines and novel dialkyl-2-(*N*-arylimidazolyl)phosphines were compared in the model reaction. Selected results of this ligand screening are shown in Table 2. Not surprisingly, triphenylphosphine (Table 2, entry 1), but also sterically hindered, basic ligands such as tri-*tert*-butylphosphine (employed as the HBF_4 salt; Table 2, entry 2) and cataCXium A (Table 2, entry 3) showed no reactivity without any copper co-catalyst, too. Similarly, *N*-aryl-2-phosphinopyrroles and *N*-aryl-2-phosphinoindoles (Table 2, entries 4–6) gave no conversion. Unexpectedly, even XPhos (Table 2, entry 7) showed only low reactivity under these conditions. However, significant amounts of the desired coupling product are obtained in the presence of the tested imidazole-based phosphine ligands. Among this class of ligands the following trends can be observed: within the applied *N*-mesityl-substituted ligands the di-1-adamantyl derivative gave the best result (Table 2, entry 10, 55% yield), while the yield drops significantly going over the corresponding 2-(di-*tert*- butylphosphino)imidazole ligand (Table 2, entry 9) to the sterically less demanding 2-(dicyclohexylphosphino)imidazole (Table 2, entry 8). Evidently, the more sterically hindered ligands gave favorable catalytic results probably because they accelerate the reductive elimination. Comparing entries 9 and 11 in Table 2, the ligand substituted with two phenyl rings in the backbone gave a better yield and selectivity (47% yield; 58% conversion). However, ligand L1 (Table 2, entry 12) showed the best performance compared to all other ligands tested. Interestingly, the corresponding 2-(di-1-adamantyl)phosphine (Table 2, entry 13) gave only

Table 2. Reaction of 3-chlorothiophene and 1-octyne using different phosphine ligands.[a]

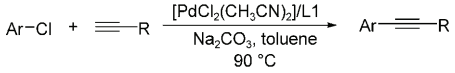


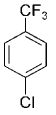
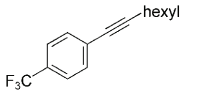
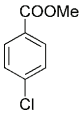
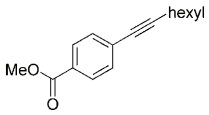
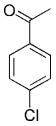
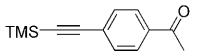
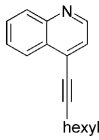
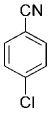
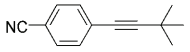
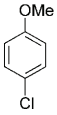
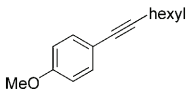
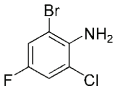
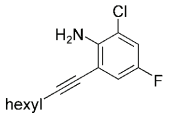
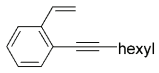
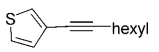
Entry	Ligand	Conversion [%]	Yield [%][b]
1	PPh_3	0	0
2	$P(tBu)_3$*HBF_4	3	0
3	$BuPAd_2$	0	0
4		2	0
5		3	0
6		7	0
7		34	6
8		19	1
9		76	21
10		63	55
11		58	47
12		73	68
13		31	25

[a] Reaction conditions: 3-chlorothiophene (1 equiv), 1-octyne (1.3 equiv), Na_2CO_3 (2.6 equiv), $[PdCl_2(CH_3CN)_2]$ (1 mol%), ligand (3 mol%), toluene (0.5 M), 90 °C, 16 h (reaction times not optimized). [b] GC yields (internal standard: hexadecane).

25% yield, even though it is considered to be more bulky. Finally, the Sonogashira reaction without added copper co-catalyst in the presence of ligand L1 was studied in more detail. Table 3 demonstrates that good to excellent results can be obtained under mild conditions in the case of activated aryl and heteroaryl chlorides using 1 mol% catalyst

Table 3. Sonogashira coupling of various aryl and heteroaryl chlorides with different alkynes.[a]



Entry	Aryl chloride	Alkyne	Product	Yield [%][b]
1				97
2				93
3				75
4				97
5[c]				42
6				87
7				64
8				31
9				87
10				73
11				77
12[c]				83
13[c]				45

[a] Reaction conditions: 3-chlorothiophene (1 equiv), 1-octyne (2 equiv), Na_2CO_3 (4 equiv), $[PdCl_2(CH_3CN)_2]$ (1 mol%), L1 (3 mol%), toluene (0.5 M), 90 °C, 16 h (reaction times not optimized). [b] Yield of isolated product. [c] 0.5 mol% $[PdCl_2(CH_3CN)_2]$, 1.5 mol% L1. [d] 2 equiv aryl halide, 1 equiv alkyne.

(Table 3, entries 1–4; 75–97% yield). Moreover, electron-rich aryl chlorides such as 4-chloroanisole react readily with 1-octyne in 87% yield (Table 3, entry 6). Notably, amino groups are tolerated under these conditions as shown by the reaction of 2-bromo-6-chloro-4-fluoroaniline, which is converted into the corresponding 2-subsituted product (Table 3, entry 7). The reaction of 2-chlorostyrene with 1-octyne gave an interesting highly conjugated coupling product (Table 3, entry 8). This reaction also shows that the catalyst system is chemoselective for the coupling of the alkyne, as no stilbene or stilbene oligomers are observed. Finally, 3-chlorothiophene was allowed to react with various alkynes. In addition to the reaction of 1-octyne (87%; Table 3, entry 9) also reactions with cyclopentyl-, triethylsilyl-, and phenylacetylene proceeded smoothly (73–83%; Table 3, entries 10–12).

In summary, palladium-catalyzed Sonogashira couplings have been performed in the presence of *N*-substituted heteroaryl phosphines without copper co-catalysts for the first time. In general, good to excellent coupling results of a variety of aryl and heteroaryl chlorides—including challenging substrates—have been obtained in the presence of [*N*-(2,6-diisopropylphenyl)-2-imidazolyl]-di-*tert*-butylphosphine L1 at low catalyst loading. Various functional groups including amino, silyl, and vinyl groups are tolerated under these conditions, in contrast to previously reported copper-free procedures. The novel procedure is cost effective and benign with respect to solvent, base, and avoiding the addition of copper salts.

Experimental Section

General: All reactions were performed under an argon atmosphere using standard Schlenk techniques. All starting materials and reactants were used as received from commercial suppliers, except toluene, which was distilled from sodium and stored under argon before use. Phosphine ligands and complexes were stored in Schlenk flasks but weighed under air. NMR spectra were recorded on an ARX300 (Bruker) spectrometer; chemical shifts are given in ppm and are referenced to the residual solvent peak. Mass spectra were recorded on an AMD 402 double-focusing, magnetic sector spectrometer (AMD Intectra). GC-MS spectra were recorded on a HP 5989A (Hewlett Packard) chromatograph equipped with a quadropole analyzer. Gas chromatography analyses were realized on a HP 6890 (Hewlett Packard) chromatograph using a HP 5 column. Melting points were measured on a SMP3 (Stuart) and are not corrected.

X-ray structure determinations: Data were collected with a STOE-IPDS diffractometer using graphite-monochromated $Mo_{K\alpha}$ radiation. The structures were solved by direct methods [SHELXS-97: G. M. Sheldrick, University of Göttingen, Germany, **1997**] and refined by full-matrix least-squares techniques against F^2 [SHELXL-97: G. M. Sheldrick, University of Göttingen, Germany, **1997**]. XP (Bruker AXS) was used for graphical representations.

CCDC-712744 (L1) and CCDC-712745 (**10**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Sonogashira reaction of aryl chlorides: A 25 mL Schlenk tube was evacuated and backfilled with argon. It was charged with $[PdCl_2(CH_3CN)_2]$ (2.59 mg, 0.01 mmol), L1 (11.2 mg, 0.03 mmol), and Na_2CO_3 (424 mg, 4 mmol). If it was a solid, the (hetero)aryl chloride was also added at that point. Then, toluene (2 mL), the corresponding (hetero)aryl chloride (if liquid) (1 mmol), and the alkyne (2 mmol) were added successively under argon atmosphere. The reaction mixture was heated up to 90 °C for 16 h (reaction times not optimized) while it was stirred vigorously. After cooling to room temperature, the mixture was then quenched with water (3 mL), and the aqueous phase was extracted with diethyl ether (3×4 mL). The organic phases were combined, concentrated, and the desired product was isolated by column chromatography (cyclohexane or cyclohexane/ethyl acetate mixtures). Alternatively, the reaction mixture was quenched with water (3 mL) and diluted with diethyl ether (8 mL). Hexadecane was then added as an internal standard and quantitative analysis was performed by gas chromatography.

(4-Acetylphenylethynyl)trimethylsilane: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.75–7.71 (m, 2H, 2×H_{arom}), 7.41–7.35 (m, 2H, 2×H_{arom}), 2.43 (s, 3H, CH_3(C=O)), 0.11 ppm (s, 9H, Si(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 197.5 (CH_3(*C*=O)), 136.5 (C_{arom}), 132.2 (C_{arom}), 128.3 (C_{arom}), 128.1 (C_{arom}), 104.2 (C_{acetyl}–C_{arom}), 98.3 (*C*-Si(CH_3)), 26.8 (CH_3(C=O)), 0.00 ppm (Si(CH_3)$_3$); MS (70 eV): *m/z* (%): 216 (18) [M^+], 201 (100), 158 (9), 143 (7); HRMS: calcd for $C_{13}H_{16}OSi$: 216.09649; found: 216.09620.

3-(Phenylethynyl)thiophene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.49–7.39 (m, 3H, 3×H_{arom}), 7.33–7.19 (m, 4H, 4×H_{arom}), 7.16–7.09 ppm (m, 1H, 2×H_{arom}); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 131.6 (C_{arom}), 129.9 (C_{arom}), 128.6 (C_{arom}), 128.4 (C_{arom}), 128.3 (C_{arom}), 125.4 (C_{arom}), 123.2 (C_{arom}), 122.3 (C_{arom}), 88.9 (C_{acetyl}), 84.5 ppm (C_{acetyl}); MS (70 eV): *m/z* (%): 184 (100) [M^+], 152 (11), 139 (24); HRMS: calcd for $C_{12}H_8S$: 184.03412; found: 184.03381.

3-(Cyclopentylethynyl)thiophene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.36–7.28 (m, 1H, H_{arom}), 7.23–7.16 (m, 1H, H_{arom}), 7.08–7.01 (m, 1H, H_{arom}), 2.78 (quin, $J =$ 8.0 Hz, 1H, CH), 2.07–1.85 (m, 2H), 1.84–1.43 ppm (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 130.1 (C_{arom}), 127.4 (C_{arom}), 124.9 (C_{arom}), 123.1 (C_{arom}), 94.1 (C_{acetyl}), 75.1 (C_{acetyl}), 33.9 (CH-CH_2), 30.8 (CH), 25.1 ppm (CH(CH_2)CH_2);. MS (70 eV): *m/z* (%): 176 (87) [M^+], 161 (13), 147 (100), 134 (30) 128 (18), 121 (18), 115 (18), 108 (23), 97 (10), 91 (11), 77 (9), 69 (8), 63 (11), 45 (10); HRMS: calcd for $C_{11}H_{12}S$: 176.06542; found: 176.06560.

3-(1-Octynyl)thiophene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.35–7.29 (m, 1H, H_{arom}), 7.23–7.16 (m, 1H, H_{arom}), 7.07–7.01 (m, 1H, H_{arom}), 2.36 (t, $J =$ 7.0 Hz, 2H, C_{acetyl}-CH_2), 1.65–1.19 (m, 8H, (CH_2)$_4$$CH_3$), 0.89 ppm (t, $J =$ 7.0 Hz, 3H, (CH_2)$_4$$CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 130.1 (C_{arom}), 127.5 (C_{arom}), 125.0 (C_{arom}), 123.1 (C_{arom}), 90.0 (C_{acetyl}-C_{arom}), 75.6 (C_{acetyl}-CH_2), 31.4, 28.8, 28.7, 22.6, 19.4 (C_{acetyl}-CH_2), 14.1 ppm ((CH_2)$_4$$CH_3$); MS (70 eV): *m/z* (%): 192 (54) [M^+], 163 (22), 149 (45), 135 (61), 123 (100), 115 (52), 108 (22), 97 (32), 91 (17), 77 (26), 63 (13), 45 (17); HRMS: calcd for $C_{12}H_{16}S$: 192.09644; found: 192.09672.

2-Methyl-4-(3-thiophenyl)-3-butyn-2-ol: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.36–7.32 (m, 1H, H_{arom}), 7.20–7.14 (m, 1H, H_{arom}), 7.04–6.99 (m, 1H, H_{arom}), 2.19 (br s, 1H, OH), 1.53 ppm (s, 6H, 2× CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 129.9 (C_{arom}), 128.7 (C_{arom}), 125.3 (C_{arom}), 121.8 (C_{arom}), 93.4 (C_{acetyl}-$C(CH_3)_2OH$), 77.3 (C_{acetyl}-C_{arom}), 65.7 (*C*-(CH_3)$_2$OH), 31.5 ppm ((CH_3)$_2$); MS (70 eV): *m/z* (%): 166 (33) [M^+], 151 (100), 135 (7), 123 (10), 108 (13), 89 (6), 75 (6), 69 (6), 63 (11) 43 (59); HRMS: calcd for $C_9H_{10}OS$: 166.04469; found: 166.04494.

1-Methoxy-4-(oct-1-ynyl)benzene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.35–7.27 (m, 2H, 2×H_{arom}), 6.83–6.75 (m, 2H, 2×H_{arom}), 3.78 (s, 3H, OCH_3), 2.36 (t, $J =$ 6.9 Hz, 2H, CH_2(C_5H_{11})), 1.63–1.18 (m, 8H, CH_2(C_4H_8)CH_3), 0.88 ppm (t, $J =$ 6.9 Hz, 3H, CH_2(C_4H_8)CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 159.0, 132.9, 116.3, 113.8, 88.9, 80.2, 55.3, 31.4, 28.9, 28.7, 22.6, 19.5, 14.1 ppm; MS (70 eV): *m/z* (%): 216 (51) [M^+], 187 (19), 173 (38), 159 (38), 145 (100), 130 (15), 115 (29), 102 (28); HRMS: calcd for $C_{15}H_{20}O$: 216.15087; found: 216.15080.

Methyl-4-(oct-1-ynyl)benzoate: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 7.95–7.87 (m, 2H, 2×H_{arom}), 7.44–7.37 m, 2H, 2×H_{arom}), 3.86 (s, 3H, CH_3(C=O)), 2.38 (t, $J =$ 7.0 Hz, 2H, CH_2(C_5H_{11})), 1.64–1.20 (m, 8H, CH_2-(C_4H_8)CH_3), 0.87 ppm (t, $J =$ 7.0 Hz, 3H, CH_2(C_4H_8)CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 166.6 (CH_3O(*C*=O)), 131.5 (C_{arom}), 129.4 (C_{arom}), 129.0 (C_{arom}), 128.8 (C_{arom}), 94.0 (C_{acetyl}-CH_2), 80.1 (C_{acetyl}-C_{arom}), 52.1 (CH_3O(C=O)), 31.4, 28.6, 28.6, 22.6, 19.5 (C_{acetyl}-CH_2), 14.1 ppm ((CH_2)$_4$$CH_3$); MS (70 eV): *m/z* (%): 244 (36) [M^+], 213 (29), 201 (45),

173 (35), 143 (52), 129 (100), 115 (43); HRMS: calcd for $C_{16}H_{20}O_2$: 244.14578; found: 244.14578.

3-Chloro-5-fluoro-2-(oct-1-ynyl)aniline: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 6.98–6.86 (m, 2H, 2×H_{arom}), 4.60–4.00 (br s, 2H, 2×NH_2), 2.48 (t, $J=$ 7.0 Hz, 2H, $CH_2(C_5H_{11})$), 1.66–1.25 (m, 8H, $CH_2(C_4H_8)CH_3$), 0.88 ppm (t, $J=7.0$ Hz, 3H, $CH_2(C_4H_8)CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=$ 155.6, 152.4, 141.1 (d, $J=2.4$ Hz), 118.6 (d, $J=11.5$ Hz), 116.6 (dd, $J=$ 39.4 Hz, 24.5 Hz), 110.3 (d, $J=10.1$), 97.8, 75.9 (d, $J=3.6$), 31.4, 28.7, 28.7, 22.6, 19.6, 14.1 ppm; IR (ATR): $\tilde{\nu}=3484$, 3385, 3082, 2955, 2928, 2857, 2223, 1589, 1572, 1469, 1301, 1201, 1157, 1069, 850, 793, 728 cm^{-1}; MS (70 eV): *m/z* (%): 253 (87) [M^+], 224 (20), 210 (18), 196 (26), 182 (100), 175 (19), 158 (29), 149 (44), 126 (23); HRMS: calcd for $C_{14}H_{17}ClFN$: 253.10281; found: 253.10287.

4-(3,3-Dimethylbut-1-ynyl)benzonitrile: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 7.56–7.49 (m, 2H, 2×H_{arom}), 7.55–7.38 (m, 2H, 2×H_{arom}), 1.29 ppm (s, 9H, $C(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=132.1$, 131.9, 129.2, 118.7, 110.7, 103.5, 78.0, 30.8, 28.2. MS (70 eV): *m/z* (%): 183 (20) [M^+], 168 (100), 153 (31), 140 (13); HRMS: calcd for $C_{13}H_{13}N$: 183.10425; found: 183.10477.

1-(Oct-1-ynyl)-2-vinylbenzene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.58$–7.52 (m, 1H, 1×H_{arom}), 7.43–7.35 (m, 1H, 1×H_{arom}), 7.30–7.12 (m, 3H, 2×H_{arom}, 1×H_{vinyl}), 5.78 (dd, $J=17.7$ Hz, 1.2 Hz, 1H, 1×H_{vinyl}), 5.32 (dd, $J=11.0$ Hz, 1.2 Hz, 1H, 1×H_{vinyl}), 2.46 (t, $J=6.9$ Hz, 2H, $CH_2(C_5H_{11})$), 1.70–1.20 (m, 8H, $CH_2(C_4H_8)CH_3$), 0.91 ppm (t, $J=6.9$ Hz, 3H, $CH_2(C_4H_8)CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=138.8$, 135.2, 132.5, 127.7, 127.4, 124.5, 122.9, 115.0, 95.4, 78.9, 31.4, 28.8, 28.7, 22.6, 19.6, 14.1 ppm; MS (70 eV): *m/z* (%): 212 (1) [M^+], 169 (16), 155 (59), 141 (100), 128 (44), 115 (67); HRMS: calcd for $C_{16}H_{20}$: 212.15595; found: 212.15596.

1-(Oct-1-ynyl)-4-(trifluoromethyl)benzene: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.54$–7.42 (m, 4H, 4×H_{arom}), 2.40 (t, $J=7.1$ Hz, 2H, 2×C_{acetyl}-CH_2), 1.67–1.21 (m, 8H, $(CH_2)_4CH_3$), 0.89 ppm (t, $J=4.6$ Hz, 3H, $(CH_2)_4CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=131.8$, 129.2 (q, $J=23.6$ Hz), 128.0, 125.2 (q, $J=3.8$ Hz), 124.1 (q, $J=272.1$ Hz), 93.4, 79.5, 31.4, 28.6, 28.5, 22.6, 19.5, 14.1 ppm; MS (70 eV): *m/z* (%): 254 (44) [M^+], 235 (26), 225 (81), 211 (98), 197 (45), 183 (100), 170 (37), 159 (62), 129 (78) 115 (40); HRMS: calcd for $C_{15}H_{17}F_3$: 254.12769; found: 254.12722.

Triethyl(thiophen-3-ylethynyl)silane: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 7.46 (dd, $J=3.0$ Hz, 1.1 Hz, 1H, 1×H_{arom}), 7.22 (dd, $J=5.0$ Hz, 3.0 Hz, 1H, 1×H_{arom}), 7.11 (dd, $J=5.0$ Hz, 1.2 Hz, 1H, 1×H_{arom}), 1.03 (t, $J=$ 7.9 Hz, 9H, $Si(CH_2CH_3)_3$), 0.66 ppm (t, $J=4.9$ Hz, 6H, $Si(CH_2CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=130.3$, 129.5, 125.1, 122.6, 101.1, 91.4, 7.5, 4.5 ppm; IR (ATR): $\tilde{\nu}=3109$, 2953, 2934, 2910, 2873, 2151, 1005, 945, 869, 779, 722, 680 cm^{-1}; MS (70 eV): *m/z* (%): 222 (13) [M^+], 193 (99), 165 (100), 137 (83), 111 (16); HRMS: calcd for $C_{12}H_{18}SSi$: 222.08930; found: 222.08877.

4-(Oct-1-ynyl)quinoline: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.79$ (d, $J=$ 4.5 Hz, 1H, 1×H_{arom}), 8.29–8.01 (m, 2H, 2×H_{arom}), 7.75–7.48 (m, 2H, 2×H_{arom}), 7.39 (d, $J=4.5$ Hz, 1H, 1×H_{arom}), 2.53 (t, $J=7.1$ Hz, 2H, C_{acetyl}-CH_2), 1.74–1.23 (m, 8H, $(CH_2)_4CH_3$), 0.95–0.79 ppm (m, 3H, $(CH_2)_4CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=149.8$, 148.1, 130.8, 129.8, 129.7, 128.2, 126.9, 126.1, 123.6, 101.1, 31.4, 28.7, 28.5, 22.6, 19.8, 14.1 ppm; MS (70 eV): *m/z* (%): 237 (100) [M^+], 208 (34), 194 (52), 180 (59), 166 (71), 153 (45), 139 (36); HRMS: calcd for $C_{17}H_{19}N$: 237.15120; found: 237.15135.

Complex 10: m.p. >245 °C (decomp); ^{1}H NMR (300 MHz, CD_2Cl_2): $\delta=$ 7.57 (dd, $J=2.6$ Hz, 1.5 Hz, 1H, H_{imid}), 7.49 (t, $J=7.8$ Hz, 1H, 4-H_{arom}), 7.27 (d, $J=7.8$ Hz, 2H, 3-H_{arom}, 5-H_{arom}), 7.02 (dd, $J=1.5$ Hz, 0.6 Hz, 1H, H_{imid}), 2.29 (sep, $J=6.8$ Hz, 2H, 2×$CH(CH_3)_2$), 1.42 (s, 9H, $C(CH_3)_3$), 1.37 (s, 9H, $C(CH_3)_3$), 1.23 (d, $J=6.9$ Hz, 6H, $CH(CH_3)_2$), 0.97 ppm (d, $J=6.9$ Hz, 6H, $CH(CH_3)_2$); ^{13}C NMR (75 MHz, CD_2Cl_2): $\delta=146.6$, 132.5, 131.9, 128.2, 128.1, 127.7, 125.0, 38.9 (d, $J=9.6$ Hz), 30.0 (d, $J=3.8$ Hz), 29.4, 27.6, 21.3 ppm; ^{31}P NMR (120 MHz, CD_2Cl_2): $\delta=53.7$; IR (ATR): $\tilde{\nu}=3162$, 3140, 2962, 2923, 2866, 1457, 1444, 1173, 1132, 813, 805, 787, 770, 763 cm^{-1}; HRMS (ESI, [M^+ Na^+]): calcd for $C_{23}H_{37}Cl_2N_2NaPPd$: 573.10026; found: 573.09955.

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Russian	basic

List of Publications

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Contributions to journals:

1) T. Schulz, C. Torborg, S. Enthaler, B. Schäffner, A. Spannenberg, H. Neumann, A. Börner, M. Beller, **Imidazol-based Ligands for a General Palladium-catalyzed Amination of Aryl Halides with Ammonia**, *Chem. Eur. J.* **2009**, DOI: 10.1002/chem.200802678.

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Patents:

1) B. Schäffner, V. Andrushko, A. Börner **Efficient and highly enantioselective Rh-catalyzed hydrogenation of unsaturated precursors with chiral bisphospholanes as ligands**, DE-Patent, Application No. 08011786.4, 30.06.2008.

Talks:

1) B. Schäffner, **Asymmetric Catalysis in Organic Carbonates**, 11th spring symposia of Young Chemists Forum of the GDCH, Essen, Germany.

2) B. Schäffner, **Organic Carbonates – Useful Solvents for industry and science**, 4th symposium of the RTG 1213 Rostock, Germany.

3) B. Schäffner, **Application of Organic Carbonates in Catalysis,** RTG 1213 Rostock, Germany.

4) B.Schäffner, **Synthesis of new heterobimetallic catalysts and their application in the rhodium catalyzed hydrogenation**, BASF/Ludwigshafen, Germany.

Poster Contributions:

1) B. Schäffner, V. Andrushko, A. Preetz, S. P. Verevkin, A. Börner **Organic Carbonates as Alternative Solvents**, Green Solvents – Process in Science and Application Friedrichshafen, Germany.

2) B. Schäffner, J. Bayardon, V. Andrushko. J. Holz, C. Torborg, M. Beller, A. Börner **Catalysis in propylene carbonate – a double benefit to sustainability**, Green Solvents – Process in Science and Application Friedrichshafen, Germany.

3) B. Schäffner, V. Andrushko, A. Preetz, S. P. Verevkin, A. Börner **Organic Carbonates as Alternative Solvents**, 16th ORCHEM Weimar, Germany.

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Eidesstattliche Erklärung

Ich versichere hiermit an Eides statt, dass ich die vorliegende Arbeit selbstständig angefertigt und ohne fremde Hilfe verfasst habe, keine außer den von mir angegebenen Hilfsmitteln und Quellen dazu verwendet habe und die den benutzten Werken inhaltlich und wörtlich entnommenen Stellen als solche kenntlich gemacht habe.

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