Catalyst Screening by Electrospray Ionization Tandem Mass Spectrometry: Hofmann Carbenes for Olefin Metathesis

Martin August Otfried Volland,[b] Christian Adlhart,[a] Christoph Alexander Kiener,[b] Peter Chen,*[a] and Peter Hofmann*[b]

Abstract: A new screening methodology, which combines in situ synthesis of complexes with an assay by electrospray ionization tandem mass spectrometry (ESI-MS), is introduced in order to investigate highly active, cationic ruthenium–carbene catalysts in ring-opening metathesis polymerization (ROMP). The parameter space, whic is defined by systematic variation of four structural features of the catalyst $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}XRu{=}CHR']^+$ (the halogen ligand, the diphosphane bite-angle, the steric bulk of the phosphane, and the carbene ligand) and the variation of the metathesis substrate, is mapped out. Chloride as the anionic ligand X, a small chelating angle ($n=1$), and reduced steric demand of the substituents R (Cy versus *t*Bu) lead to the most reactive complex in acyclic olefin metathesis, whereas variation of the carbene moiety CHR′ has only a modest influence. The overall rate in the gas phase depends on the π-complex preequilibrium and metallacyclobutane formation, which was found to be the rate-determining step. In ROMP reactions backbiting has a profound influence on the overall rate. Moreover, we were able to establish that the reactivity trends determined in the gas phase parallel solution-phase reactivity. The overall rate in solution is also determined by a favorable dimer/monomer preequilibrium providing the active catalyst by facile dissociation of dicationic, dinuclear catalyst precursors.

Keywords: carbene ligands · high-throughput screening · mass spectrometry · metathesis · ruthenium

Introduction

The rapid or high-throughput screening of homogenous organometallic catalysts produced by variation of a lead structure is a much-desired goal, which, however, has been hampered by gaps in the needed technology.[1] Existing methodology for the screening of homogenous catalysts suffers from a two-fold limitation. Firstly, because parallel synthesis in microtiter plates,[2] microreactor arrays,[3] or on beads[4] (by split-pool methods) encodes catalyst identity spatially, that is, one well/one catalyst, one reactor/one catalyst, one bead/one catalyst, a multistep catalyst synthesis without intermediate purifications steps produces an identifiable product only when each step is quantitative and selective. The constraint upon the synthesis limits the structural types that can be screened to a small subset of possible catalysts, among which organometallic catalysts are especially poorly represented. Secondly, the high-throughput screen itself is usually based on the measurement of a simple physical indicator, for example, heat release,[5] color,[6] viscosity, refractive index,[7] etc., which may or may not have a direct connection to the activity or selectivity of the catalyst in question. Circumvention of the two-fold limitation requires the introduction of a new methodology. Recently we have shown that electrospray ionization tandem mass spectrometry is an excellent tool to test reactivity of organometallic catalysts.[8–11] We report here screening of structural variants of Hofmann's $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}XRu{=}CHR']^+$ ionic ring-opening metathesis polymerization (ROMP) catalysts[12]—the fastest homogenous ROMP catalysts in solution for olefins such as cyclooctene—by means of in situ synthesis of complexes combined with an assay by electrospray ionization tandem mass spectrometry. In situ synthesis combined with online "purification", reaction, and analysis in the mass spectrometer is an extremely fast method for assessment of

[a] Prof. Dr. P. Chen, Dipl.-Chem. C. Adlhart
Eidgenössische Technische Hochschule
Laboratorium für Organische Chemie
ETH Hönggerberg, 8093 Zürich (Switzerland)
Fax: (+41) 1-63-21280
E-mail: chen@org.chem.ethz.ch

[b] Prof. Dr. P. Hofmann, Dipl.-Chem. M. A. O. Volland, Dipl.-Chem. C. A. Kiener
Universität Heidelberg, Organisch–Chemisches Institut
Im Neuenheimer Feld 270, 69120 Heidelberg (Germany)
Fax: (+49) 6221-54-4885
E-mail: ph@phindigo.oci.uni-heidelberg.de

Supporting information for this article is available on the WWW under http://wiley-vch.de/home/chemistry/ or from the author. Kinetic data; typical logfile of one scan on a TSQ700 mass spectrometer including electrospray and CID parameters; geometries and energies for all calculated complexes.

  0947-6539/01/0721-4621 $ 17.50+.50/0

catalytic activity relative to conventional studies on the activity of Grubbs type ruthenium carbenes, which rely on preparative isolation and careful purification of every single compound.[13–24] The present work, in which 180 reactions (repeated 10 times each) were carried out in two weeks, maps out the parameter space defined by systematic variation of four structural features of the catalyst $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}XRu{=}CHR']^+$ (the halogen ligand, the diphosphane bite-angle, the steric bulk of the phosphane, and carbene ligand (Figure 1)), and the variation of the metathesis substrate.

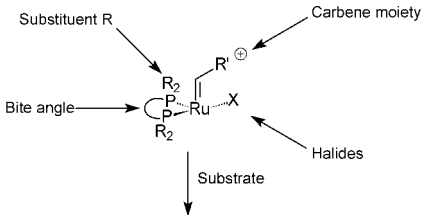
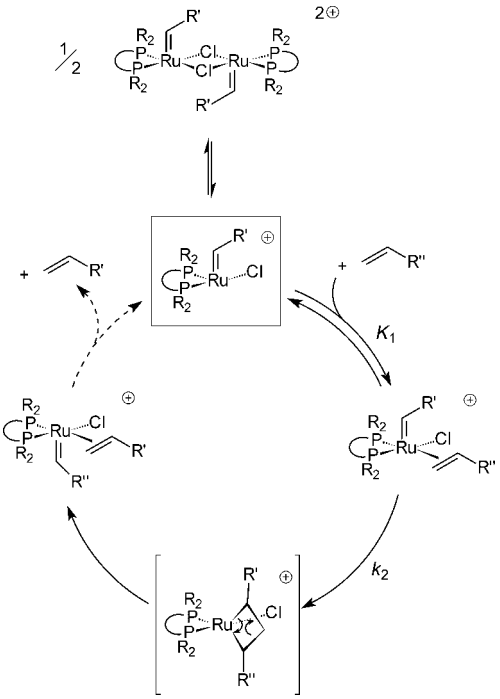


Figure 1. Screening of structural variants of Hofmann's $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}XRu{=}CHR']^+$ cationic ROMP catalysts

The reactivity data show systematic trends, which, moreover, upon quantitative analysis provide key mechanistic details regarding the metathesis reaction.

For specific examples, we were able to confirm by independent synthesis and evaluation of selected compounds that reactivity trends determined in this gas phase study are paralleled in solution. In the solid state, as well as in solution, the $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}ClRu{=}CHR']^+$ ions dimerize to form dicationic, dinuclear complexes $[\{\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}ClRu{=}CHR'\}_2]^{2+}$. By crossover and trapping experiments it was shown that monomeric species are formed in solution.[12b, 25] In a second preequilibrium step these monomeric, cationic, ruthenium–carbene complexes are believed to form an olefin π complex. Product formation presumably proceeds via the metallacyclobutane according to the *Chauvin* metathesis mechanism (Scheme 1).[26]



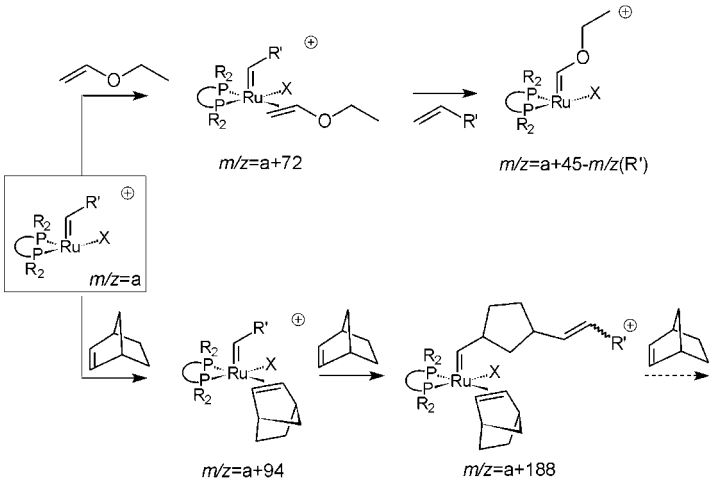
Scheme 1. Proposed mechanism for olefin metathesis by dicationic dinuclear complexes $[\{\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}ClRu{=}CHR'\}_2]^{2+}$.

Results and Discussion

General results: In order to determine the factors responsible for intrinsic reactivities of the non-coordinated catalyst monomers, electrospray ionization tandem mass spectrometry was employed. This allows us to select the monomeric cations and examine their specific reactivities towards olefins, apart from the monomer–dimer preequilibrium that is present in solution.[10, 12b, 27] Baseline-resolved spectra on a Finnigan LCQ DECA ion trap were taken to ensure the absence of the dicationic dimer, nominally at the same mass-to-charge ratio, by means of isotope distribution. The effects of the variations of these compounds will be discussed below.

Preparing the complexes with cyclohexyl-substituted phosphanes in situ by addition of the phosphane to the Grubbs complex, and mass-selecting the desired monomeric cations in the first quadrupole prior to the collision cell, we assessed the reactivity of these complexes. A direct comparison of in situ prepared $[(dcpe\text{-}\kappa^2P)Cl_2Ru{=}CHPh]$ (dcpe = bis(dicyclohexylphosphino)ethane) and isolated $[(dcpe\text{-}\kappa^2P)Cl_2Ru{=}CHPh]$ (characterized by NMR) showed the same behavior of the $[(dcpe\text{-}\kappa^2P)ClRu{=}CHPh]^+$ ion within error bounds. This was taken as validation of the in situ preparation of desired complexes.

Different test reactions for olefin metathesis with acyclic (ethyl vinyl ether, propyl vinyl ether, and 1-butene) and cyclic substrates (norbornene and cyclopentene) were carried out (Scheme 2).



Scheme 2. Examples for olefin metathesis with acyclic or cyclic substrates in the gas phase

Figure 2 shows a daughter-ion spectrum of $[(dcpm\text{-}\kappa^2P)ClRu{=}CH(p\text{-}C_6H_4Me)]^+$, (dcpm = bis(dicyclohexylphosphino)-methane) *m/z* 649, after reaction with ethyl vinyl ether in the collision cell. The metathesis product, *m/z* 603, the ethyl vinyl

0947-6539/01/0721-4622 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 21

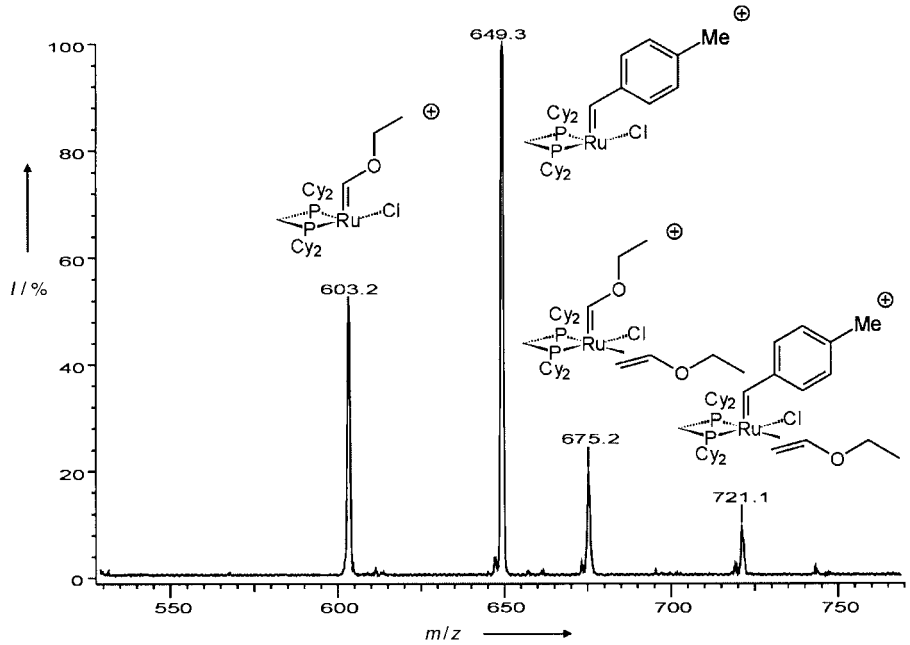


Figure 2. Daughter-ion spectrum of [(dcpm-κ^2P)ClRu=CH(p-C_6H_4Me)]$^+$, m/z 649, and collision with ethyl vinyl ether in the collision octopole at low energy (nominal 1 eV).

ether adduct, m/z 721, as well as the ethyl vinyl ether adduct to the product (thus at least two collisions), m/z 675, are formed.

In order to examine the nature of the adduct complex with vinyl ethers, control experiments with diethyl ether were carried out. [(dcpm-κ^2P)ClRu=CHOEt]$^+$ was prepared in situ and allowed to collide with diethyl ether at 180 mTorr in the atmospheric pressure ionization (API) region. The possible diethyl ether adduct [(dcpm-κ^2P)ClRu=CHOEt(OEt$_2$-κ^1O)]$^+$ was not observed under these conditions. However, if [(dcpm-κ^2P)ClRu=CHOPr]$^+$ collides with ethyl vinyl ether instead of diethyl ether under identical conditions, formation of the adduct [(dcpm-κ^2P)ClRu=CHOPr(H$_2$C=CHOEt)]$^+$ is observed. While this suggests that the vinyl ethers do not coordinate through the oxygen atom, the assumend π-adduct complex still cannot be differentiated from the metallacyclobutane on the bases of m/z alone. Therefore, in a cross experiment, the complexes [(dcpm-κ^2P)ClRu=CHOPr(H$_2$C=CHOEt)]$^+$ and [(dcpm-κ^2P)ClRu=CHOEt-(H$_2$C=CHOPr)]$^+$ were prepared in the API region and fragmented with Ar in the second octopole. Under mild conditions (1.4 mTorr Ar, 5 eV nominal kinetic energy) only loss of the added vinyl ether was observed. The absence of any metathesis cross products in both cases indicates that the species formed is the π-adduct complex rather than the metallacyclobutane.

A low-resolution daughter ion spectrum of [(dtbpm-κ^2P)ClRu=CH−CH=CPh$_2$]$^+$, (dtbpm = bis(di-*tert*-butylphosphino)methane) m/z 633, and subsequent collision with propyl vinyl ether was carried out to confirm formation of the desired product [(dtbpm-κ^2P)ClRu=CH-OC$_3$H$_7$]$^+$, m/z 513 (Figure 3). Analysis of the isotope patterns proves that a product with the expected molecular formula is formed.

Anionic ligand variation: The results of the reaction of [(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)(X)Ru=CH−CH=C(CH$_3$)$_2$]$^+$ (X = Cl, Br, I, OTf) with 1-butene are summarized in Table 1.[28, 29]

As has been reported for the Grubbs system[15] the chloride ligand leads to the most active compound. Reactivity in the Hofmann system is reduced by the factor of 20 when chloride is replaced by iodide. We were unable to synthesize the expectedly more reactive fluoride complex, neither by replacement of a chloride by fluoride starting from the dinuclear [{(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)(Cl)Ru=CH−CH=C(CH$_3$)$_2$}$_2$]-[OTf]$_2$ nor by replacement of a triflate by fluoride starting

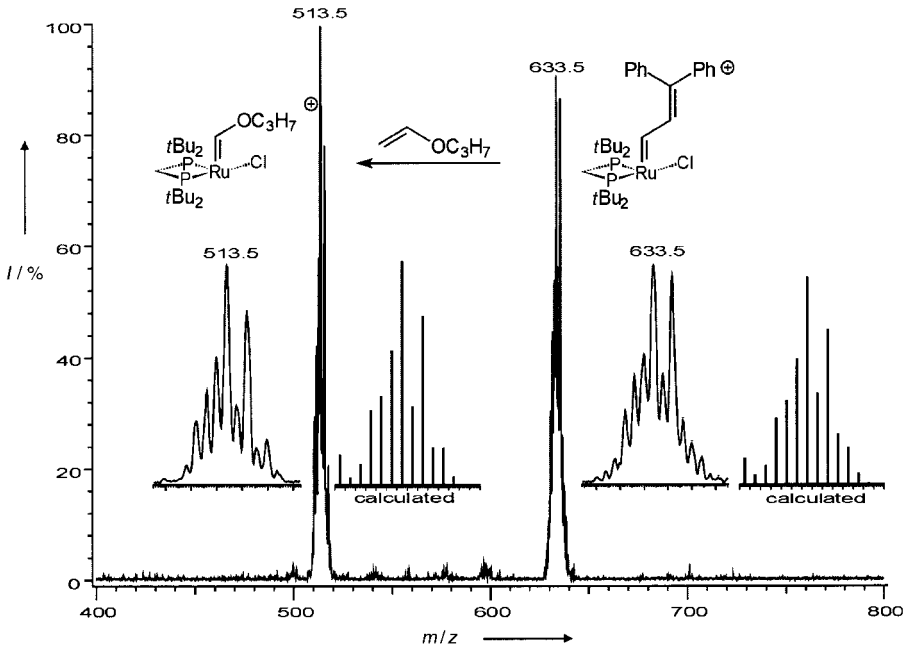
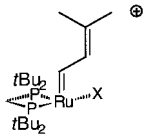


Figure 3. Low-resolution daughter-ion spectrum of [(dtbpm-κ^2P)ClRu=CH−CH=CPh$_2$]$^+$, m/z 633, collision with ethyl vinyl ether in the collision octopole at low energy (nominal 1 eV) and high-resolution Q2 scan.

Table 1. Variation of halogen substituent X.

	X	k_{rel} 1-butene[28]
	F	not available
	Cl	1.00 (0.46 %)[29]
	Br	0.4
	I	0.046
	OTf	0.000

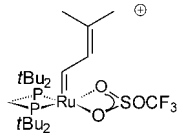


Figure 4. Proposed bidentate coordination of the triflate ligand in the gas phase that blocks the reactive site of $[(dtbpm\text{-}\kappa^2P)(OTf)Ru{=}CH{-}CH{=}C(CH_3)_2]^+$.

from the mononuclear bistriflate complex $[(tBu_2PCH_2P\text{-}tBu_2\text{-}\kappa^2P)OTf)_2Ru{=}CH{-}CH{=}C(CH_3)_2]$.

No reactivity towards the substrate 1-butene can be observed for triflate (OTf^-) under the outlined conditions. It is conceivable that bidentate coordination of the triflate ligand blocks the reactive coordination site as shown in Figure 4.[30]

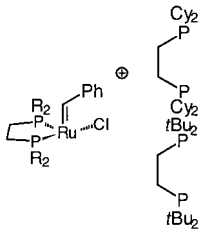
With these results in hand, chloride was chosen as the most suitable anionic ligand for the following studies.

Variation of phoshane ligands

Steric influence of phosphane ligands: Comparison of the reactivity of $[(dcpe\text{-}\kappa^2P)ClRu{=}CHPh]^+$ and $[(dtbpe\text{-}\kappa^2P)ClRu{=}CHPh]^+$ (dtbpe = bis(di-*tert*-butylphosphino)ethane) allows the direct investigation of the effect of steric differences between phosphane ligands. This comparison is free of electronic differences, due to the similarity of dcpe and dtbpe in donor strength and chelating angle. Our results reveal that the catalyst with the less bulky dcpe ligand reacts 55 times faster with ethyl vinyl ether than the catalyst with the more bulky dtbpe ligand (Table 2);[31] this underlines the profound influence of steric demand on metathesis.

Additionally, the equilibrium constant for the adduct complex of $[(L\text{-}\kappa^2P)ClRu{=}CHPh]^+$ and ethyl vinyl ether is considerably larger in case of the sterically less-demanding dcpe. We find a difference of a factor of 50 for the preequilibria constants K_1 between dcpe and dtbpe (Table 2 and Scheme 1). The significance of this increased formation of adduct will be discussed below. In summary, the overall metathesis rate is higher for the sterically less demanding phosphane.

Table 2. Comparison of the *t*Bu versus Cy phosphane ligands.

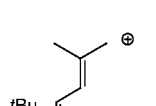
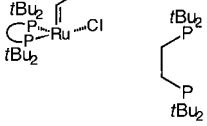
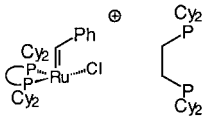
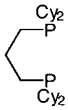
	k_{rel} norbornene[28]	k_{rel} ethyl vinyl ether[28]	K_{rel} ethyl vinyl ether[28]
	1.00 (0.01 %)[29]	1.0 (32 %)[29]	1.0 (0.0059)[29]
	0.00038	0.018	0.020

Influence of the chelating angle (bite angle): Variation of the ligand bite angle (P-Ru-P angle) from 74° to ≈180° has a profound effect on the reactivity towards different olefinic substrates as can be seen for $[\{tBu_2P(CH_2)_nPtBu_2\text{-}\kappa^2P\}XRu{=}CH{-}CH{=}C(CH_3)_2]^+$ ($n = 1,2$), $[\{Cy_2P(CH_2)_nPCy_2\text{-}\kappa^2P\}ClRu{=}CHPh]^+$ ($n = 1, 2, 3$), and $[(PCy_3)_2ClRuCHC_6H_5]^+$ (Table 3) (Cy = cyclohexane).

For the *t*Bu ligands, enlarging the bite angle from 74° to 86° decreases the rate by a factor of five for 1-butene up to a factor of 100 for ethyl vinyl ether.[12, 25] The same trend was observed in the case of the Cy ligands. The extreme case with a P-Ru-P angle of ≈180° is realized in $[(PCy_3)_2ClRuCHC_6H_5]^+$,[27] which shows no reactivity (neither formation of adduct nor metathesis product) towards olefinic substrates under these conditions.

Furthermore, the adduct to reactant ratio was determined for acyclic olefinic substrates (Table 3). With the exception of the two entries (1-butene: dtbpm vs dtbpe) for the adduct to reactant ratio, all complexes show a reduced tendency to form

Table 3. Influence of *t*Bu and Cy phosphane ligands.

	k_{rel} norbornene[28]	k_{rel} 1-butene[28]	k_{rel} ethyl vinyl ether[28]	K_{rel} 1-butene[28]	K_{rel} ethyl vinyl ether[28]
	1.00 (0.4 %)[29]	1.00 (0.5 %)[29]	1.00 (19 %)[29]	1.0 (0.009 %)[29]	1.0 (0.002)[29]
	0.034	0.20	0.011	300	0.2
	1.00 (88 %)[29]	1.0 (0.07 %)[29]	1.00 (42 %)[29]	1.00 (1.9)[29]	1.0 (0.04)[29]
	0.080	0.09	0.020	0.01	0.2
	–	0.01	0.003	0.001	0.04
$[(PCy_3)_2ClRu(CHPh)]^+$	0.000	0.000	0.000	0.000	0.000

0947-6539/01/0721-4624 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 21

adducts with an increased ligand bite angle. It should be noted that a second—and for some reactants even a third—insertion of norbornene was only observed for dtbpm systems, although dcpm is much more reactive towards norbornene in the first step. Moreover, no second insertion was detectable for any complex upon reaction with cyclopentene. In summary, the overall metathesis rate is reduced drastically for increased ligand bite angles.

Variation of the carbene moiety: Varying the carbene moiety has only a slight effect on reaction rates, relative to the large phosphane ligand influence. Interestingly for the Grubbs system, the benzylidene complexes are more reactive than the alkenylidene carbenes in the gas phase. However, in the cationic *cis* systems, this trend is reversed (Table 4).

The influence of the carbene moiety was investigated for the readily available *t*Bu systems. The reactivity of [(dtbpm-κ^2P)ClRu=CHR]$^+$ (R = CH=CPh$_2$, CH=C(CH$_2$)$_5$, CH=CMe$_2$ and CHMe$_2$) shows an increase in rate with an increased unsaturation in the carbene moiety (Table 5). In summary, changes in the carbene moiety have only a modest influence on the overall metathesis rate.

Linear free-energy relationships (LFERs): Reactivity studies with *para*-substituted benzylidene carbene moieties allowed the systematic investigation of electronic effects on rate and adduct to reactant ratio devoid of steric influence. Using the technique to prepare these complexes in situ by addition of the corresponding styrene to the Grubbs complex, subsequent treatment with either dcpm or dcpe and mass-selecting the desired product in the first quadrupole prior to the collision cell, the reactivity of these complexes was also easily assessed.

Linear free-energy relationship fits were performed according to Hammett with σ parameters[32] for the substituted carbene ligands (Figure 5). The corresponding ρ values are shown in Table 6. A positive ρ value is found for both the dcpm and the dcpe system. However, electron-withdrawing groups accelerate olefin metathesis more in the dcpe systems, which are also overall slower. The LFERs for the adduct to reactant ratio show that π-complex formation (adduct) occurs to a greater extent for electron-withdrawing groups. In summary, electron withdrawing groups on the carbene moiety slightly accelerate metathesis.

Secondary isotope effects: In order to examine possible secondary isotope effects, a deuterium label was introduced on the carbene carbon atom which changes hybridization during the metathesis reaction.[33] An inverse secondary isotope effect for the reaction of [(dcpm-κ^2P)ClRu=CHPh]$^+$ and [(dcpm-κ^2P)ClRu=CDC$_6$D$_5$]$^+$ with ethyl vinyl ether of $k_H/k_D = 0.92 \pm 0.02$ was found. The inverse secondary isotope effect for the reaction of [(dcpe-κ^2P)ClRu=CHPh]$^+$ and [(dcpe-κ^2P)ClRu=CDC$_6$D$_5$]$^+$ with ethyl vinyl ether was $k_H/k_D = 0.68 \pm 0.08$.

ROMP with norbornene: Norbornene was polymerized in the gas phase by Hofmann-type carbenes [{R$_2$P(CH$_2$)$_n$PR$_2$-κ^2P}-ClRu=CHR′]$^+$. For the Hofmann catalyst [(dtbpm-κ^2P)-ClRu=CH−CH(CH$_3$)$_2$]$^+$, up to three norbornene insertions were observable. Notably, the rate of the initiation and propagation step are identical within error bounds ($k_{init,rel} = 1.00$; $k_{prop,rel} = 1.06$).

Reversibility of ROMP: In a previous report we showed that we can directly test reversibility of ring-opening metathesis in the gas phase by using bifunctional substrates. These provide the product of a ring-opening metathesis reaction the chance to undergo a nondegenerate ring-closing metathesis to an isotopically or otherwise substituted complex distinguishable from the original complex by mass.[8] Along these lines, [(dtbpm-κ^2P)ClRu=CHR]$^+$ (R = CH=CPh$_2$ and CH=CMe$_2$) and [(dcpm-κ^2P)ClRu=CHPh]$^+$ were treated with 4-[(*Z*)-2-pentenyl-3,4,4,5,5,5,-$^2H_6$]-cyclopentene in the collision cell. The control experiment with 4-[(*Z*)-2-pentenyl-3,4,4,5,5,5,-$^2H_6$]-cyclopentane was also carried out. In contrast to the Grubbs system [{Me$_3$N(CH$_2$)$_2$Cy$_2$P}Cl$_2$-Ru=CHPh]$^+$ there is no indication for reversibility of ROMP (ROM-RCM reaction pathway) for the dtbpm and dcpm systems.

Table 4. Influence of carbene substituents.

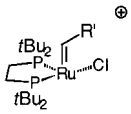
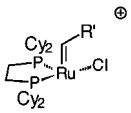
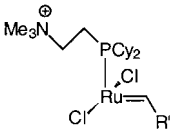
	R′	k_{rel} norbornene[28]	k_{rel} ethyl vinyl ether[28]	K_{rel} ethyl vinyl ether[28]
	CH=CMe$_2$	1.00 (0.01 %)[29]	–	–
	Ph	0.20	–	–
	CH=CMe$_2$	–	1.00 (2.2 %)[29]	0.070
	Ph	–	0.37	1.0 (0.017)[29]
	CH=CMe$_2$	–	14.1	0.3
	Ph	–	27	0.3

Table 5. Influence of carbene substituents.

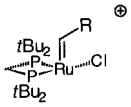
	R′	norbornene[28]	k_{rel} propyl vinyl ether[28]	ethyl vinyl ether[28]	K_{rel} propyl vinyl ether[28]	ethyl vinyl ether[28]
	CH=CPh$_2$	0.013	1.00 (54 %)[29]	1.00 (46 %)[29]	0.043	–
	CH=CMe$_2$	0.284	0.499	0.48	0.064	0.12
	CH=C$_6$H$_{10}$	0.026	0.153	0.121	0.083	0.15
	CHMe$_2$	1.00 (0.4 %)[29]	0.020	0.039	1.0 (0.024)[29]	1 (0.01)[29]

Table 6. Influence of carbene substituents.

	R′	k_{abs}[a]		K_{abs}[a]	
ethyl vinyl ether[33]	OMe	0.371	0.0076	0.0281	0.0021
	Me	0.380	0.0081	0.0881	0.0027
	H	0.455	0.0098	0.0404	0.017
	F	0.573	0.020	0.0317	0.066
	CF_3	0.538	0.026	0.100	0.12
Hammett ρ parameter[b]		0.23 ± 0.17	0.69 ± 0.39	–	–
LFER[b]		–	–	0.5 ± 0.8	2.0 ± 1.0

[a] Each rate (or adduct to reactant ratio) is the average of 10 measurements; the last representative digit at 95% confidence bounds based on a *t* distribution is given. [b] Hammett ρ and LFER parameters are given at 90% confidence bounds based on a *t* distribution.

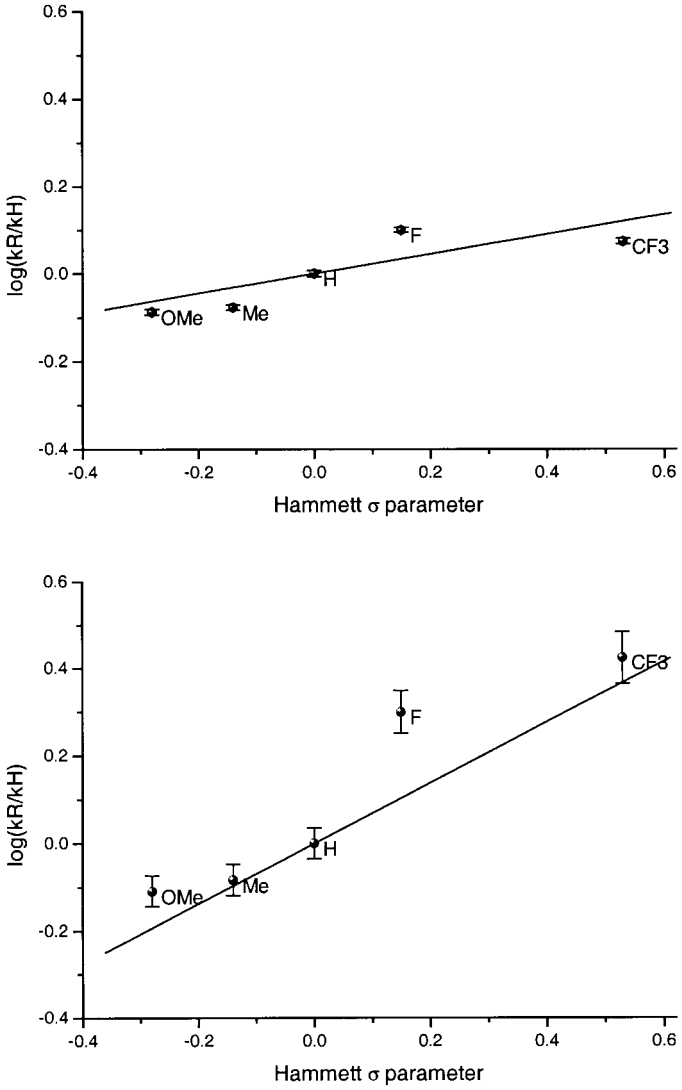


Figure 5. Top: Hammett plot for the relative rate data for [(dcpm-κ^2P)ClRu=CH(p-C_6H_4R')]$^+$ (R′ = OMe, Me, H, F, and CF_3) in Table 6. Bottom: Hammett plot for the relative rate data for [(dcpe-κ^2P)ClRu=CH(p-C_6H_4R')]$^+$ (R′ = OMe, Me, H, F, and CF_3) in Table 6. Least-squares fits constrained to go through the origin are shown.

Comparison of gas-phase and solution-phase results: In addition to the reactivity studies of [{(dtbpm-κ^2P)ClRu=CH−CH=C$(CH_3)_2$}$_2$][OTf]$_2$ and [{(dtbpe-κ^2P)ClRu=CH−CH=C$(CH_3)_2$}$_2$][OTf]$_2$ in the gas phase, solution-phase kinetics of the desired complexes were carried out. These complexes were synthesized and fully characterized. Their ROMP activity in CD_2Cl_2 at ambient temperature with cyclooctene as a substrate was determined by ^{1}H NMR spectroscopy in analogy to our previous report (Figure 6).[12b]

From the solution-phase kinetics we can derive that [{(dtbpm-κ^2P)ClRu=CH−CH=C$(CH_3)_2$}$_2$][OTf]$_2$ is at least 15 times faster than [{(dtbpe-κ^2P)ClRu=CH−CH=C$(CH_3)_2$}$_2$][OTf]$_2$ and the second-generation Grubbs catalyst tricyclohexylphosphane[1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidene](benzylidene)ruthenium dichloride (**3**).

In summary, cationic ruthenium–carbene complexes with small chelating angles prove to be the fastest ROMP catalysts for cyclooctene in solution.

Screening results: In this work we have introduced a new methodology for catalyst screening. The problem of the twofold limitation encountered in typical catalyst screening methods, that is, limited synthetic access and lack of a direct analytical probe for catalyst activity, has been solved by combination of in situ synthesis with online "purification", reaction, and analysis in the mass spectrometer. First, the synthesis of the complexes—necessary only in micromolar amounts—has neither to be clean nor quantitative; even if the desired complex is only a side product, a complete study of reactivity can be carried out. Secondly, the mass spectrometer enables us to directly monitor intensities (= concentration) of reactants and products with different *m/z*. Given the time needed to work out a clean synthesis, purification, and crystallization of a single compound, the screening offers a tremendous strategic advantage. In practice, this means that screening of libraries generated in situ can be done prior to the targeted synthesis of any particular structure in pure form.

With 180 experiments (repeated 10 times each) we were able to map out in two weeks the parameter space defined by systematic variation of four structural features of the catalyst, [{$R_2P(CH_2)_nPR_2$-κ^2P}XRu=CHR′]$^+$ (the halogen ligand, the diphosphane bite-angle, the steric bulk of the phosphane, and carbene ligand) and the variation of the metathesis substrate. A pitfall of the in situ synthesis is the possible formation of structural isomers that can not be distinguished on the basis of *m/z* alone. Therefore, we synthesized, isolated, and characterized [(dcpe-κ^2P)Cl_2Ru=CHPh] independently by NMR spectroscopy and compared its reactivity with the reactivity of the in situ synthesized [(dcpe-κ^2P)Cl_2Ru=CHPh] in our

0947-6539/01/0721-4626 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 21

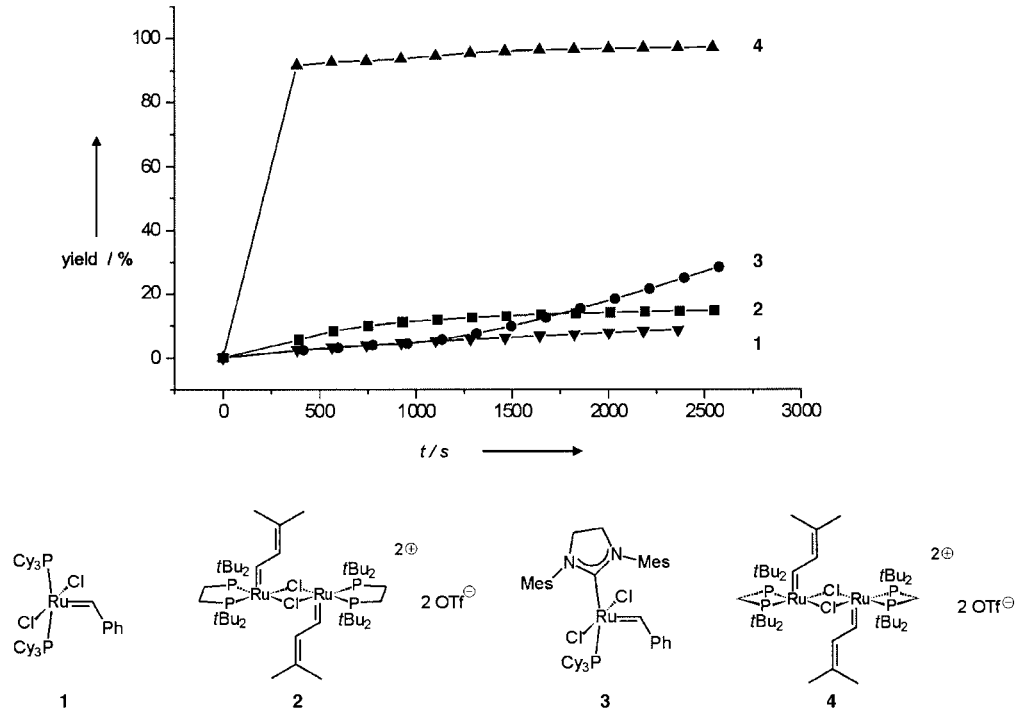


Figure 6. ROMP of cyclooctene in solution. Comparison of polycyclooctenamer production as followed by ^{1}H NMR spectroscopy. $T = 298$ K; 0.5 mL CD_2Cl_2; c(cyclooctene):c(Ru) = 12500:1.

experimental setup. Within error bounds the [(dcpe-κ^2P)-ClRu=CHPh]$^+$ ions derived from both sources showed the same behavior upon reaction with olefins in the mass spectrometer; this validates the in situ library formation.

The gas-phase screening results are significant for catalyst tuning if the observed trends correlate to catalysis in solution. We find experimentally that the influence of the bite angle on reactivity in the gas phase is paralleled in solution. Also, in other reports, comparability of gas- and solution-phase reactivity trends in organometallic reactions was shown.[8, 9, 34] The reactivity trends can be summarized as follows: The chloride complexes are more reactive relative to bromide and iodide complexes. We can also state that, in general, a decrease in steric bulk (Cy ligand versus *t*Bu ligand), a small bite angle, and electron-withdrawing groups on the carbene substituents, accelerate the metathesis reaction.

Key mechanistic details: The advantage using mass spectrometry for investigation of key mechanistic details is the explicit exclusion of solution-phase preequilibria in the gas phase, in which the catalytically active species is directly examined.[27] In addition, we can observe certain intermediates, such as the π complex or the transient metathesis products. For mechanistic discussion we only take into account the exothermic metathesis reactions[35] with either ethyl vinyl ether or propyl vinyl ether for two reasons: first of all, in case of norbornene, with mass spectrometry as our analytical technique we cannot distinguish between a π-adduct complex and a ROM product. Secondly, for the nearly thermoneutral metathesis reaction of our catalysts with 1-butene, we cannot exclude reverse reaction after passing through the metallacyclobutane. The possible reversibility makes the 1-butene results unsuitable for the following mechanistic considerations.

The proposed reaction path in Scheme 1 implies a free energy profile for strongly exergonic reactions such as in the case of ethyl vinyl ether as shown in Figure 7.[35]

From the observed preequilibrium for the formation of the π complex **B**, we can deduce that **B** is slightly higher in energy

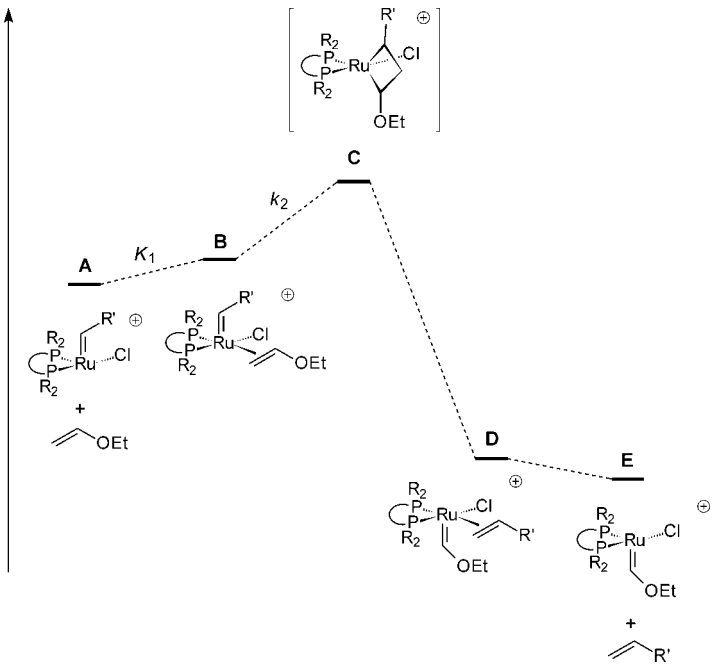


Figure 7. Proposed free-energy profile for the olefin metathesis with ethyl vinyl ether.

than **A**. We assume the preequilibrium to be fast because it is just a coordination or dissociation of an olefin to a low-coordinate metal center with a small barrier. Whether the metallacyclobutane **C** is a transition state or an intermediate is not decisive for our kinetic interpretation, as long as the step from **B** to **C** is rate determining. Since the reaction is strongly exergonic, ring opening to the π-complex **D** is irreversible and subsequent olefin dissociation to **E** is fast.

Steric effects: Comparison of the data for [(dcpe-κ^2P)ClRu=CHPh]$^+$ and [(dtbpe-κ^2P)ClRu=CHPh]$^+$ (Table 2) allows the separation of electronic and steric influences, since these two complexes differ only in the steric demand of the ligand.[31] A factor of 50 for the metathesis rate as well as for the fast olefin-binding preequilibrium K_1 (**A** $\rightleftharpoons$ **B**) is observed. Assuming a rate-determining step k_2, the ratio of the constant K_1 accounts for essentially all of the difference in rate for the metathesis reaction [Eq. (1)].

$$d[P]/dt = k_2[\text{adduct}] = (k_1/k_{-1})(k_2)[\text{reactant}][\text{olefin}] = K_1k_2[\text{reactant}][\text{olefin}] \quad (1)$$

Interestingly this means that the activation energy for step **B** to **C** must be nearly the same for these two systems (Figure 8). From the olefin complexation constant K_1 it can be derived that the olefin binds ≈2.7 kcal mol^{-1} more tightly to the sterically less-demanding dcpe complex than to the dtpbe complex.

Stereoelectronic effects: Changing the bite angle of the phosphane ligand by increasing chelate ring size changes both the electronic and steric properties of the complex. Enlarging the P-Ru-P angle from ≈74° (four-membered chelate ring)[12] to ≈86° (five-membered chelate ring),[12] and then further to the six-membered chelate ring reduces the reaction rate by a factor of 300.[36] The extreme case with a P-Ru-P angle of ≈180° is achieved in [$(PCy_3)_2$ClRu=CHC_6H_5]$^+$, for which we detect no reactivity towards olefins. Two different explanations for this observation are possible. Either, as we have outlined in a previous communication, in the extreme case of ≈180° a ruthenium carbyne hydride rather than a ruthenium carbene may be present in the gas phase, as has been demonstrated for the Werner systems in solution.[37] In order to become a metathesis-active ruthenium–carbene catalyst, the carbyne hydride must undergo a 1,2-hydride shift, adding an unfavorable preequilibrium to the observed gas-phase rate. Reduction of the bite angle from ≈180° to ≈74° may shift the carbyne hydride to carbene preequilibrium towards the carbene. However, it has to be pointed out that Werner could not observe the formation of the ruthenium carbyne hydride in solution upon attempted abstraction of a chloride with a Lewis acid from the Grubbs catalyst.[37] Alternatively, the large rate deceleration may be due to an increase of the energy barrier for the rate-determining metathesis step upon enlargement of the chelating angle, which is supported by DFT calculations. Use of a model system with $H_2P(CH_2)_nPH_2$ ligands allows assessment of electronic influences without considerable steric influences. Density functional theory (DFT) calculations at the B3LYP/LANL2DZ level on the model systems [($H_2PCH_2PH_2$-κ^2P)ClRu=CH_2]$^+$ and [{$H_2P(CH_2)_2PH_2$-κ^2P}ClRu=CH_2]$^+$ indeed show an increase of the energy barrier for the formation of the metallacyclobutane, starting from the olefin π complex, of 2.0 kcal mol^{-1}.[38] Within an Arrhenius model this difference in activation energy results in a rate acceleration by a factor of 20 for the smaller chelate ring.

From [(dtbpm-κ^2P)ClRu=CH−CH=CMe_2]$^+$ to [(dtbpe-κ^2P)-ClRu=CH−CH=CMe_2]$^+$ the experimental rate of metathesis with ethyl vinyl ether is decreased by a factor of ≈100, whereas the π complexation is decreased by a factor of ≈5 (Table 3). The missing factor of ≈20 is readily explained by the different energies of activation for the metathesis step **B** to

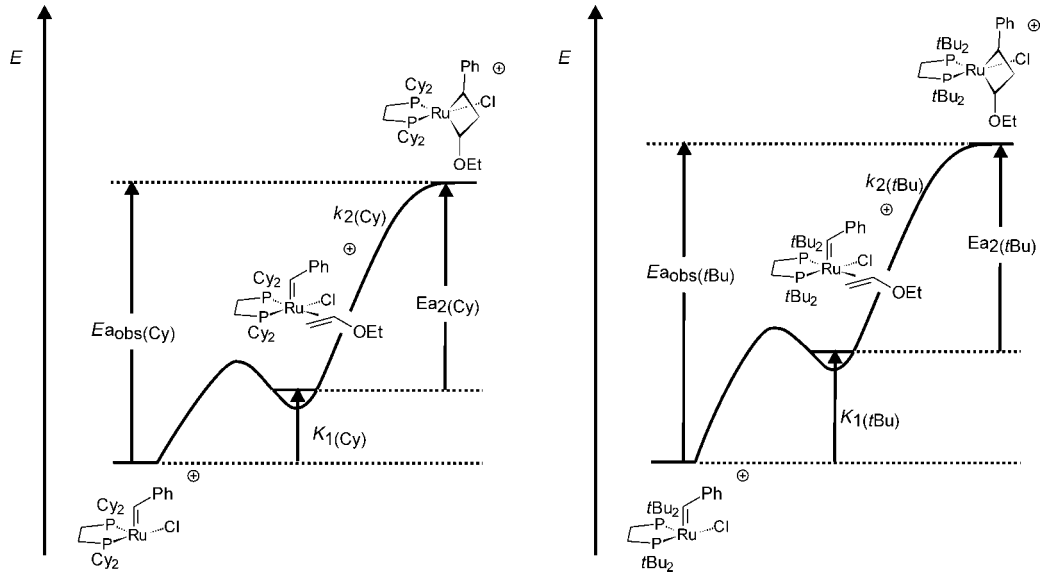


Figure 8. Preequilibrium constant K_1 is decisive for the difference of the overall rate olefin metathesis rate for [(dcpe-κ^2P)ClRu=CHPh]$^+$ and [(dtbpe-κ^2P)ClRu=CHPh]$^+$.

0947-6539/01/0721-4628 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 21

C for different P-Ru-P angles. Analogously, for [(dcpm-κ^2P)-ClRu=CHPh]$^+$ and [(dcpe-κ^2P)ClRu=CHPh]$^+$, the reaction rate decreases by a factor of ≈ 50, whereas π complexation decreases by a factor of ≈ 5. Through enlargement of the P-Ru-P angle from 74° to 86° the rate for the metathesis step **B** to **C** is decreased by a factor of 10 to 20.

Electronic effects, Hammett parameters, and isotope effects: Varying substituents R′ (R′ = OMe, Me, H, F, and CF_3) in the *para* position of the benzylidene moiety allows the direct assessment of electronic effects without steric influences. From Hammett plots, a positive ρ value of 0.23 ± 0.17 for [(dcpm-κ^2P)ClRu=CH(p-C_6H_4R′)]$^+$ and a ρ value of 0.69 ± 0.39 for [(dcpe-κ^2P)ClRu=CH(p-C_6H_4R′)]$^+$ are found. The faster dcpm systems with a lower activation barrier are influenced less by electronic effects than dcpe systems. This is consistent with an earlier transition state for the faster reaction according to Hammond postulate arguments. The positive ρ value indicates that electron-releasing groups slow down the reaction. The low-coordinate 14-electron complex **B** is stabilized more by electron-releasing groups than the metallacyclobutane **C**, in which the aryl group is no longer in direct conjugation to the ruthenium. This leads to a higher overall energy barrier and therefore lower rate. Furthermore the olefin π-complexation preequilibrium constant K_1 decreases for electron-releasing groups.

Inverse secondary kinetic isotope effects are found for both [(dcpm-κ^2P)ClRu=CDC_6D_5]$^+$ with $k_H/k_D = 0.92 \pm 0.02$ and [(dcpe-κ^2P)ClRu=CDC_6D_5]$^+$ with $k_H/k_D = 0.68 \pm 0.08$ when reacting with ethyl vinyl ether. This is—according to an admittedly simple model—consistent with a rate-determining step in which the hybridization of a carbon is changed from sp^2 to sp^3, which means that formation of the metallacyclobutane **C** is the rate-determining step.[8, 33] The smaller inverse secondary kinetic isotope effects for the faster reaction is again consistent with an earlier transition state.

Backbiting: In ROMP with Grubbs-type catalysts, intramolecular π complexation of the growing polymer chain competes with propagation, which was deduced in solution phase[14] and observed for gas phase by a faster initiation than propagation ($k_{init,rel} = 1.00$; $k_{prop,rel} = 0.011$).[9] In the Hofmann dtbpm system on the other hand, initiation and propagation rates in the gas phase are the same ($k_{init,rel} = 1.00$; $k_{prop,rel} = 1.06$). From these results we can deduce that, in this type of catalyst, intramolecular π complexation of the growing polymer chain does not compete significantly with propagation (Scheme 3).

This interpretation is consistent with large PDIs (polydispersity index) of norbornene ROM polymers[12, 39] obtained by using [{(dtbpm-κ^2P)ClRu=CH−CH=CMe_2}$_2$][OTf]$_2$. Along these lines, this catalyst is not well suited for RCM in solution phase[12, 39] due to lack of backbiting, which is the prerequisite for RCM.

Notably, in the gas phase, the sterically less demanding [(dcpm-κ^2P)ClRu=CHPh]$^+$, though reacting at a very high rate in the first step in comparison to that of [(dtbpm-κ^2P)-ClRu=CH−CMe_2]$^+$, shows no second insertion of norbornene (Figure 9).

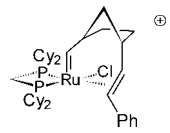
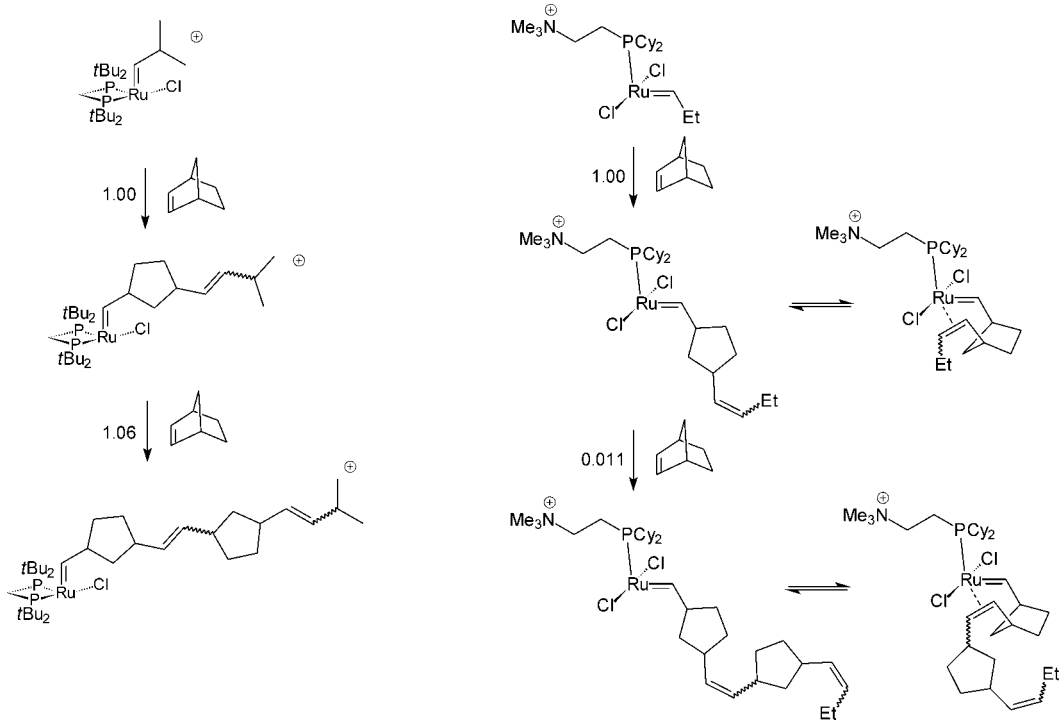


Figure 9. Backbiting of the growing polymer chain in the dcpm system.



Scheme 3. Backbiting of the growing polymer chain in the Grubbs system slows down insertion of additional norbornene, whereas backbiting seems to be absent in the Hofmann dtbpm systems.

This may be due to higher tendency for backbiting, which is underlined by the extremely high complexation constant K_1 for 1-butene (Table 3).

ROMP activity in solution—Grubbs versus Hofmann carbenes: The Grubbs complex is a less active ROMP catalyst in solution compared to the dtbpm carbenes. The overall solution phase rate is mainly governed by three factors: 1) concentration of the active species, 2) backbiting of the growing polymer chain, and 3) intrinsic reactivity of the active species.

1) In the Hofmann system formation of the catalytically active monomer by dissociation of the dinuclear dicationic dtbpm complexes is more facile than formation of the catalytically active complex $[(PCy_3)Cl_2Ru{=}CHPh]$ by loss of one PCy_3 in the Grubbs system.[27] Therefore the concentration of the active species is presumably higher in the dtbpm system.
2) As shown previously for the Grubbs system, the propagation rate is reduced by a factor of 90 relative to the initiation rate due to backbiting. In the dtbpm systems, on the other hand, backbiting is absent.
3) The intrinsic reactivity of the active species of the Grubbs system is higher than for the Hofmann system (k_{rel} is $\approx 40{:}1$ for $[\{Cy_2P(CH_2)_2NMe_3\}Cl_2Ru{=}CH{-}CH{=}CMe_2]^+$ and $[(\text{dtbpm-}\kappa^2P)ClRu{=}CH{-}CH{=}CMe_2]^+$).[27]

All three factors enter into the observed solution-phase reactivity, with the net result that, although the active species of the Grubbs system is intrinsically more reactive in the gas phase than the active species of the Hofmann system, the higher concentration of active species and lack of backbiting in the latter system makes it the more potent ROMP catalyst in solution.

It should be emphasized that the overall metathesis rate of the Hofmann carbenes in solution is proportional to the dimer/monomer preequilibrium ($K_{d/m}$) as well as to the olefin-binding preequilibrium K_1. Given that k_2 is rate determining, the overall metathesis rate in solution is described by Equation (2) (cf. Scheme 1).

$$d[P]/dt = k_2[\text{adduct}] = (k_2)K_1[\text{monomer}][\text{olefin}] = k_2K_1K_{d/m}[\text{dimer}]^{1/2}[\text{olefin}] \quad (2)$$

As a consequence, further ROMP catalyst development also has to focus on shifting the preequilibrium $K_{d/m}$ towards the monomer; this should also lead to a narrower PDI. Enhanced olefin binding, for example, by reduction in steric demand of the phosphane ligand, although increasing the rate by enlarging K_1, will decrease the ROMP rate, since the second insertion is hampered by backbiting. Evidently, reduction of the energy barrier of the rate-determining step, for example, by decreasing the P-Ru-P chelating angle, leads to a larger rate due to an increased k_2. From these results, one can predict that the broad PDI of ROM polymers made with $[\{(t\text{Bu}_2PCH_2Pt\text{Bu}_2\text{-}\kappa^2P)ClRu{=}CH{-}CH{=}C(CH_3)_2\}_2][OTf]_2$ can be narrowed by using a more electron-deficient initial carbene for which the initiation, but not the subsequent propagation, would be accelerated.

Conclusion

In situ synthesis of complexes combined with an assay by electrospray ionization tandem mass spectrometry, excluding solvent effects and solution-phase preequilibria, was used to systematically investigate the influence of four structural features of catalysts $[\{R_2P(CH_2)_nPR_2\text{-}\kappa^2P\}XRu{=}CHR']^+$, that is, the halogen ligand, the diphosphane bite-angle, the steric bulk of the phosphane, and carbene ligand, as well as the variation of the metathesis substrate. Moreover, we were able to establish that the reactivity trends determined in the gas phase parallel solution-phase reactivity. Chloride as the anionic ligand X, a small chelating angle ($n = 1$), and reduced steric demand of the substituents R (Cy versus *t*Bu) lead to the most reactive complex in acyclic olefin metathesis, whereas variation of the carbene moiety CHR′ has only modest influence. The overall rate for the monocations in the gas phase depends on the π-complex preequilibrium and metallacyclobutane formation, which was found to be the rate-determining step. In ROMP reactions backbiting has a profound influence on the overall rate. The overall rate in solution is also determined by a favorable dimer/monomer preequilibrium, which provides a high concentration of active monocations from dicationic precursors.

The rapid assay of a variety of structural effects on metathesis rate, combined with mechanistic analysis, leads to predictions for optimized catalysts for given applications. As was already shown, the experimental assay for backbiting leads to the rapid determination of catalysts suitable for ROMP or RCM. Optimizations of a given catalyst structure for a given reaction ordinarily requires independent synthesis of each individual candidate complex, followed by testing. Given that, for typical organometallic complexes in homogeneous catalysis, the synthesis consumes the greatest fraction of expended time, the methodology described here—screening before synthesis—offers great savings in time and effort.

Experimental Section

Instrumental: Gas-phase experiments with norbornene and with 1-butene were performed on a slightly modified Finnigan MAT TSQ-7000 tandem mass spectrometer. In case of ethyl vinyl ether, propyl vinyl ether, and cyclopentene a modified Finnigan MAT TSQ-700 tandem mass spectrometer equipped with an electrospray ionization source as described previously was used.[8–11] Typically 10^{-5} M solutions of the complex in CH_2Cl_2 were electrosprayed at a flow-rate of 5 μL min^{-1} with nitrogen as sheath gas at 5 kV and a capillary temperature of 423 K. The tube lens potential was varied between 70 V and 190 V depending on the complex. In a typical collision experiment, the principal isotope peak of a cationic complex was thermalized to 343 K in the atmospheric pressure ionization (API) octopole (O1) (or API 24-pole in TSQ-700), then mass-selected with the first quadrupole (Q1) and collided with the reactants at a nominal kinetic energy of 1 eV (laboratory frame) in an octopole (O2) collision cell. The width of the energy distribution of the ions after mass selection in Q1 was approximately 1 – 2 eV. The pressure in the collision cell was taken with a Pirani gauge without further correction and maintained constant for each series of experiments to within 5 %. The products were mass-analyzed with the second quadrupole (Q2) and detected with an electron multiplier at 1400 V (TSQ-7000) or 1100 V (TSQ-700). Every spectrum consists of 60 averaged scans of 1 s to give a signal to noise ratio of more than 10000 to 1. The product distributions were taken from the integrated peak intensities without further intensity correction depending on the mass.

0947-6539/01/0721-4630 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 21

From previous Monte Carlo simulations we know that the ions in the collision cell at a pressure in the mTorr range undergo a total of up to ≈5000 collisions.[8] We assume that under these multiple-collision conditions, all reactants and intermediates are approximately thermalized and that fast preequilibria are reached, in contrast to typical gas phase experiments under single collision conditions.[40]

Each experiment was repeated 10 times. Error bounds on the relative rates were determined from a *t* distribution by standard statistical methods and represent 95 % confidence limit. Rates were calculated from Equation (3) and equilibrium constants from Equation (4).

$$r = p^2/p(\mathrm{av})^2\,([\mathrm{prod}] - \mathrm{baseline})/([\mathrm{prod}] + [\mathrm{reactant}] + [\mathrm{adduct}] - \mathrm{baseline}) \quad (3)$$

$$K_{eq} = p/p(\mathrm{av})\,([\mathrm{adduct}] - \mathrm{baseline})/([\mathrm{reactant}] - \mathrm{baseline}) \quad (4)$$

For each given reactant, equilibrium constants were linearly normalized to one pressure. For each given reactant, pseudo-first-order reaction rates were normalized by the square of the pressure, because the rates depend linearly on the concentration (pressure) of the reactant, and at low conversion linearly on reaction time in O2 ($t \propto \kappa^{-1}$ and $\kappa \propto p^{-1} \Rightarrow t \propto p$; $\kappa =$ diffusion coefficient; these assumptions agree with our Monte Carlo simulations[8]). Baseline resolved spectra of several reactants were taken on a Finnigan LCQ DECA ion trap.

Organometallic complex chemistry: The CH_2Cl_2 was dried over CaH_2 and saturated with argon prior to use. All reactions were carried out in a dry box ($H_2O < 1$ ppm and $O_2 < 1$ ppm). The cationic ruthenium compounds used in this study were prepared as follows: cationic ruthenium carbene complexes with the *tert*-butyl-substituted phosphanes [i.e., bis(di-*tert*-butylphosphino)methane (dtbpm)[41] and bis(di-*tert*-butylphosphino)-ethane (dtbpe)][42] were prepared according to literature procedures[12] and electrosprayed from a 10^{-5} M solution of the triflate salts in CH_2Cl_2. To study the halogen substituent effect, chloride was exchanged in situ by treatment of complex [{(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)ClRu=CH−CH=C(CH$_3$)$_2$}$_2$][OTf]$_2$ with an excess of [Bu$_4$N][Br] or [Bu$_4$N][I] in CH_2Cl_2. Complexes with cyclohexyl-substituted phosphane ligands [LCl$_2$Ru=CHPh] or [LCl$_2$Ru=CH−CH=C(CH$_3$)$_2$], with L = bis(dicyclohexylphosphino)methane (dcpm),[43a] bis(dicyclohexylphosphino)ethane (dcpe),[43b] and bis(dicyclohexylphosphino)propane (dcpp),[43c] were prepared in situ by adding a 10^{-5} M CH_2Cl_2 solution of the corresponding ligand to a 10^{-5} M solution of commercially available [(PCy$_3$)$_2$Cl$_2$Ru=CHPh][43d] or [(PCy$_3$)$_2$Cl$_2$Ru=CH−CH=C(CH$_3$)$_2$],[44] respectively, in CH_2Cl_2 (reaction conditions: r.t., 15 min). The derivatives [LCl$_2$Ru=CHAr] ([LCl$_2$Ru=CDC$_6$D$_5$]) were also prepared in situ by adding an excess of the substituted styrene H$_2$C=CHAr (D$_2$C=CDC$_6$D$_5$) to a 10^{-5} M solution of [(PCy$_3$)$_2$Cl$_2$Ru=CHPh] in CH_2Cl_2 (r.t., 30 min) and subsequent treatment with the ligand L (r.t., 15 min). All corresponding cations [LClRu=CHR]$^+$ ([LClRu=CDC$_6$D$_5$]$^+$) were formed under electrospray conditions.

Attempted in situ preparation of [(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)Cl$_2$Ru=CHPh] by addition of dtbpm to [(PCy$_3$)$_2$Cl$_2$Ru=CHPh] in CH_2Cl_2 in order to generate the desired [(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)ClRu=CHPh]$^+$ ion did not show the desired product peak in ESI-MS. As reported, a dinuclear ylide rather than the cationic carbene complex [(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)ClRu=CHPh]$^+$ is formed for this *t*Bu-substituted diphosphinomethane ligand under these conditions.[12a]

The cyclooctene (> 99.5 % (GC)) for the NMR ROMP kinetics in CD_2Cl_2 was obtained from Fluka, degassed and used without further purification. NMR spectra were recorded on a Bruker DRX 500 spectrometer.

Acknowledgement

This work has been generously supported by Fonds der Chemischen Industrie and Studienstiftung des deutschen Volkes (Fellowships to M.A.O.V.), the Forschungskommission der Eidgenössischen Technischen Hochschule, and the Kommission für Technologie und Innovation des Bundesamts für Berufsbildung und Technologie.

[1] A general review of screening for catalysts: B. Jandeleit, H. W. Turner, T. Uno, J. A. M. van Beck, W. H. Weinberg, *CATTECH* **1998**, *2*, 101.
[2] H. Burges, H. J. Lim, A. M. Porte, G. A. Sulikowski, *Angew. Chem.* **1996**, *108*, 192; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 220; S. M. Senkan, *Nature* **1998**, *394*, 350.
[3] S. Caravieilhes, C. de Bellefon, N. Tanchoux *Catal. Today* **2001**, *66*, 145.
[4] B. M. Cole, K. D. Shimizu, C. A. Krueger, J. P. A. Harrity, M. L. Snapper, A. H. Hoveyda, *Angew. Chem.* **1996**, *108*, 1776; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1668; T. R. Boussie, C. Coutard, H. Turner, V. Murphy, T. S. Powers, *Angew. Chem.* **1998**, *110*, 3472; *Angew. Chem. Int. Ed.* **1998**, *37*, 3272.
[5] A. Fürstner, L. Ackermann, B. Gabor, R. Goddard, C. W. Lehmann, R. Mynott, F. Stelzer, O. R. Thiel, *Chem. Eur. J.* **2001**, *7*, 3236; M. T. Reetz, M. H. Becker, M. Liebl, A. Fürstner, *Angew. Chem.* **2000**, *112*, 1294; *Angew. Chem. Int. Ed.* **2000**, *39*, 1236; S. J. Taylor, J. P. Morken, *Science* **1998**, *280*, 267; M. T. Reetz, M. H. Becker, K. M. Kühling, A. Holzwarth, *Angew. Chem.* **1998**, *110*, 2792; *Angew. Chem. Int. Ed.* **1998**, *37*, 2644.
[6] M. B. Francis, E. N. Jacobsen, *Angew. Chem.* **1999**, *111*, 987; *Angew. Chem. Int. Ed.* **1999**, *38*, 937; O. Löber, M. Kawatsura, J. F. Hartwig, *J. Am. Chem. Soc.* **2001**, *123*, 4366.
[7] K. Mikami, R. Angelaud, K. L. Ding, A. Ishii, A. Tanaka, N. Sawada, K. Kudo, M. Senda, *Chem. Eur. J.* **2001**, *7*, 730.
[8] C. Adlhart, C. Hinderling, H. Baumann, P. Chen, *J. Am. Chem. Soc.* **2000**, *122*, 8204.
[9] C. Hinderling, C. Adlhart, P. Chen, *Angew. Chem.* **1998**, *108*, 2831; *Angew. Chem. Int. Ed.* **1998**, *37*, 2685.
[10] C. Adlhart, P. Chen, *Helv. Chim. Acta* **2000**, *83*, 2192.
[11] C. Hinderling, D. A. Plattner, P. Chen, *Angew. Chem.* **1997**, *109*, 272; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 243; C. Hinderling, D. Feichtinger, D. A. Plattner, P. Chen, *J. Am. Chem. Soc.* **1997**, *119*, 10793; D. Feichtinger, D. A. Plattner, *Angew. Chem.* **1997**, *109*, 1796; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1718; D. Feichtinger, D. A. Plattner, P. Chen, *J. Am. Chem. Soc.* **1998**, *120*, 7175.
[12] a) S. M. Hansen, F. Rominger, M. Metz, P. Hofmann, *Chem. Eur. J.* **1999**, *5*, 557; b) S. M. Hansen, M. A. O. Volland, F. Rominger, F. Eisenträger, P. Hofmann, *Angew. Chem.* **1999**, *111*, 1360; *Angew. Chem. Int. Ed.* **1999**, *38*, 1273; c) M. A. O. Volland, B. F. Straub, I. Gruber, F. Rominger, P. Hofmann, *J. Organomet. Chem.* **2001**, *617/618*, 288.
[13] J. S. Kingsbury, J. P. A. Harrity, P. J. Bonitatebus, Jr., A. H. Hoveyda, *J. Am. Chem. Soc.* **1999**, *121*, 791.
[14] P. Schwab, R. H. Grubbs, J. W. Ziller, *J. Am. Chem. Soc.* **1996**, *118*, 110.
[15] a) Z. Wu, S. T. Nguyen, R. H. Grubbs, J. W. Ziller, *J. Am. Chem. Soc.* **1995**, *117*, 5503; b) E. L. Dias, S. T. Nguyen, R. H. Grubbs, *J. Am. Chem. Soc.* **1997**, *119*, 3887.
[16] S. Chang, II, L. Jones C. Wang, L. M. Henling, R. H. Grubbs, *Organometallics* **1998**, *17*, 3460.
[17] a) A. Fürstner, K. Langemann, *J. Am. Chem. Soc.* **1997**, *119*, 9136; b) E. L. Dias, R. H. Grubbs, *Organometallics* **1998**, *17*, 2758.
[18] T. Weskamp, W. C. Schattenmann, M. Spiegler, W. A. Herrmann, *Angew. Chem.* **1998**, *110*, 2631; *Angew. Chem. Int. Ed.* **1998**, *37*, 2490 (Corrigendum: *Angew. Chem.* **1999**, *111*, 277; *Angew. Chem. Int. Ed.* **1998**, *38*, 262).
[19] a) J. Huang, E. D. Stevens, S. P. Nolan, J. L. Petersen, *J. Am. Chem. Soc.* **1999**, *121*, 2674; b) T. Weskamp, F. J. Kohl, W. Hieringer, D. Gleich, W. A. Herrmann, *Angew. Chem.* **1999**, *111*, 2573; *Angew. Chem. Int. Ed.* **1999**, *38*, 2416; c) M; Scholl, T. M. Trnka, J. P. Morgan, R. H. Grubbs, *Tetrahedron Lett.* **1999**, *40*, 2247; d) M. Scholl, S. Ding, C. W. Lee, R. H. Grubbs, *Org. Lett.* **1999**, *1*, 953.
[20] M. S. Sanford, M. Ulman, R. H. Grubbs, *J. Am. Chem. Soc.* **2001**, *123*, 749.
[21] T. M. Trnka, R. H. Grubbs, *Acc. Chem. Res.* **2001**, *34*, 18.
[22] For representative reviews see: T. J. Katz, *Adv. Organomet. Chem.* **1978**, *16*, 283; N. Calderon, J. P. Lawrence, E. A. Ofstead, *Adv. Organomet. Chem.* **1979**, *17*, 449; R. H. Grubbs, W. Tumas, *Science* **1989**, *243*, 907.
[23] a) A. Fürstner, in *Topics in Organometallic Chemistry*, *Vol. 1*, Springer, Berlin, **1998**; b) M. Schuster, S. Blechert, *Angew. Chem.* **1997**, *109*, 2124; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2037; c) A. Fürstner, *Angew. Chem.* **2000**, *112*, 3140; *Angew. Chem. Int. Ed.* **2000**, *39*, 3012.

[24] a) S. T. Nguyen, L. K. Johnson, R. H. Grubbs, *J. Am. Chem. Soc.* **1992**, *114*, 3974; b) Z. Wu, A. D. Benedicto, R. H. Grubbs, *Macromolecules* **1993**, *26*, 4975; R. H. Grubbs, S. Chang, *Tetrahedron* **1998**, *54*, 4413.
[25] P. Hofmann, M. A. O. Volland, S. M. Hansen, F. Eisenträger, J. Gross, K. Stengel; *J. Organomet. Chem.* **2000**, *606*, 88.
[26] J-L. Hérisson, Y. Chauvin, *Makromol. Chem.* **1971**, *141*, 161.
[27] C. Adlhart, M. A. O. Volland, P. Hofmann, P. Chen, *Helv. Chim. Acta* **2000**, *83*, 3306.
[28] Normalization pressure for 1-butene: 15.2 mTorr; for norbornene: 16.3 mTorr; for ethyl vinyl ether: 6.2 mTorr; for propyl vinyl ether: 5.7 mTorr.
[29] Each relative rate k_{rel} (or relative adduct to reactant ratio K_{rel}) is the average of 10 measurements; the last representative digit at 95% confidence bounds based on a t distribution is given; value in parentheses: absolute rate k_{abs} (or absolute adduct to reactant ratio K_{abs}). Relative rates (or relative adduct to reactant ratios) are normalized to one species within the same column and are not comparable within rows.
[30] For the comparable neutral complex [(tBu$_2$PCH$_2$PtBu$_2$-κ^2P)(SO$_4$-κ^2O)Ru=CH−CH=C(CH$_3$)$_2$] this is found in the X-ray structure: P. Hofmann, M. A. O. Volland, unpublished results.
[31] Tolman cone angles: PCy$_3$: 170°, P(tBu)$_3$: 182°. (from: C. A. Tolman, *Chem. Rev.* **1977**, *77*, 313).
[32] J. March, *Advanced Organic Chemistry*, 4th ed., Wiley, New York, **1992**, p. 280.
[33] T. S. Lowry, K. S. Richardson, *Theory and Mechanism in Organic Chemistry*, 2nd ed., Harper Row, New York, **1981**, Chapter 2.
[34] It should be noted that a strict comparability of gas- and solution-phase results may be hampered, since solvent effects and solution-phase preequilibria are explicitly excluded in the gas phase, in which only the "naked" catalytically active species is investigated.
[35] Calculations (B3LYP/LANL2DZ) for isodesmic reactions on model systems confirm the exothermicity of the reaction of Hofmann carbenes with olefins such as ethyl vinyl ether: a) [(H$_2$PCH$_2$PH$_2$-κ^2P)ClRu=CH$_2$]$^+$ + H$_2$C=CHOH → [(H$_2$PCH$_2$PH$_2$-κ^2P)ClRu=CHOH]$^+$ + H$_2$C=CH$_2$; $\Delta E = -15.7$ kcal mol^{-1}; b) compare: [(H$_2$PCH$_2$PH$_2$-κ^2P)ClRu=CH$_2$]$^+$ + H$_2$C=CHCN → [(H$_2$PCH$_2$PH$_2$-κ^2P)ClRu=CHCN]$^+$ + H$_2$C=CH$_2$; $\Delta E = +6.8$ kcal mol^{-1}.[38]
[36] For the four- and five-membered chelate rings, the P-Ru-P angles of 74° and 86°, respectively, are obtained from X-ray structures (see ref. [12]). From fully geometry-optimzed structures (B3LYP/LANL2DZ) the analogous trend is obtained: the P-Ru-P angles in [{H$_2$P(CH$_2$)$_n$PH$_2$-κ^2P}ClRu=CH$_2$]$^+$ for $n = 1$, 2, and 3 are 74.0°, 84.6°, and 89.7°, respectively.[38]
[37] a) W. Stüer, J. Wolf, H. Werner, *Angew. Chem.* **1998**, *110*, 3603; *Angew. Chem. Int. Ed.* **1998**, *37*, 3421; b) P. Gonzáles-Herrero, B. Weberndörfer, K. Ilg, J. Wolf, H. Werner, *Angew. Chem.* **2000**, *112*, 3392; *Angew. Chem. Int. Ed.* **2000**, *39*, 3266.
[38] a) M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery Jr, R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, J. L. Andres, C. Gonzalez, M. Head-Gordon, E. S. Replogle, J. A. Pople, *Gaussian 98*, *Revision A.5*, Gaussian, Pittsburgh PA, **1998**; b) LANL2DZ Basis Set: P. J. Hay, W. R.Wadt, *J. Chem. Phys.* **1985**, *82*, 299; c) P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 284; d) Geometries were fully optimized and analyzed by frequency calculations: for all minima NIMAG = 0, for transition states NIMAG = 1).
[39] "Zur Komplexchemie und Metallorganik des Rutheniums: Der Weg zu neuen Katalysatoren für die Olefinmetathese": S. M. Hansen, Ph.D. Thesis, **1999**, Heidelberg.
[40] P. Liere, V. Steiner, K. R. Jennings, R. E. March, J. C. Tabet, *Int. J. Mass. Spectrom.* **1997**, *167*, 735.
[41] a) H. H. Karsch, *Z. Naturforsch. Teil B* **1983**, *38*, 1027; b) H. Heiss, P. Hofmann, (BASF AG) DE 41347772 A, **1992** [*Chem. Abstr.* **1992**, *117*, 171 685].
[42] K.-R. Pörschke, C. Pluta, B. Proft, F. Lutz, K. Krüger, *Z. Naturforsch. Teil B* **1993**, *48*, 608.
[43] a) Prepared according to standard literature procedures; ligand is also available from Sigma-Aldrich Fine Chemicals; b) Avocado Research Chemicals Ltd. c) Sigma-Aldrich Fine Chemicals; d) Strem Chemicals.
[44] T. E. Wilhelm, T. R. Belderrain, S. N. Brown, R. H. Grubbs, *Organometallics* **1997**, *16*, 3867.

Received: July 7, 2001 [F3412]

  0947-6539/01/0721-4632 $ 17.50+.50/0