

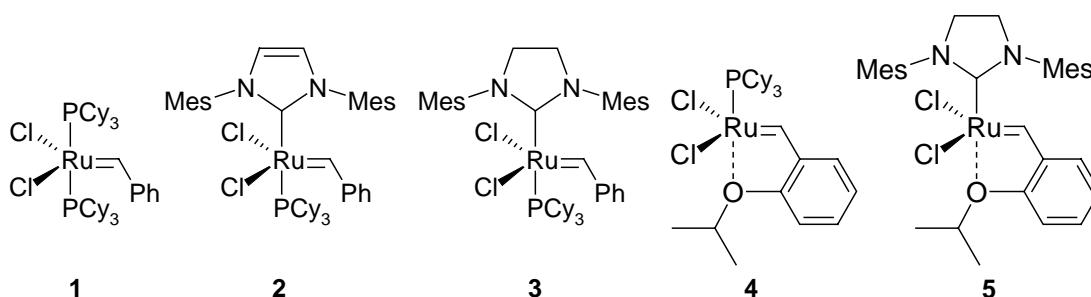
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“Immobilisation of Ru-Based Metathesis Catalysts
and Related Aspects of Olefin Metathesis”

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Summary

In the past decade impressive development of olefin metathesis catalysts and their applications has taken place. Especially, the discovery of ruthenium carbene complexes of the general formula $\text{Ru}(=\text{CHR})\text{Cl}_2(\text{PR}'_3)_2$ (e.g. $\text{R} = \text{Ph}$; $\text{R}' = \text{Ph}$ or Cy (**1**)) by Grubbs and co-workers, has had a profound impact on the field. A wide variety of ligands have since been used for the preparation of new analogues of this type of catalyst. Some of these ligands, e.g. *N*-heterocyclic carbenes (NHCs) and 2-isopropoxybenzylidene, produce more active and versatile catalysts, e.g. **2** – **5**, for alkene metathesis.

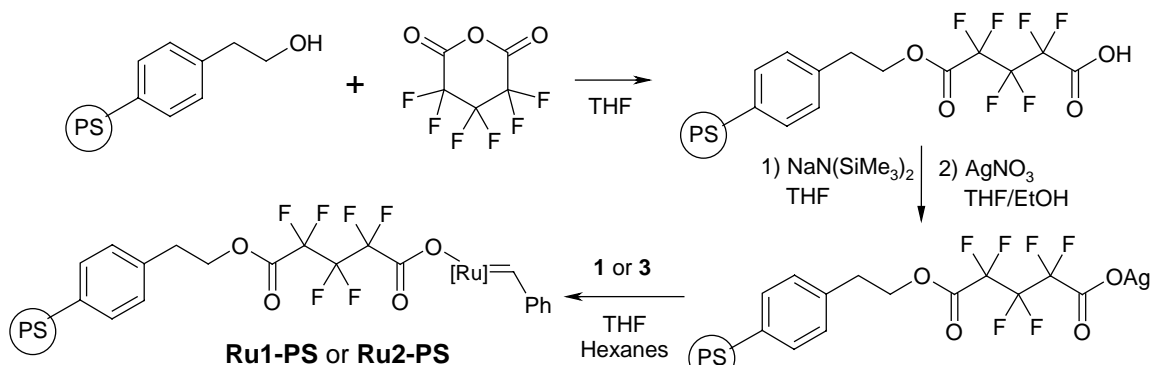


The well-defined homogeneous metathesis catalysts are now a formidable tool in the hands of an organic chemist due to their high catalytic activity, chemical robustness and functional group tolerance. The combination of these properties with the features of the heterogeneous catalytic systems, that are ease of handling, separation, and reusability, would be advantageous.

In Chapter 2 we have reported a new simple approach for permanent immobilisation of ruthenium carbene complexes on a polymeric support using carboxylate ligands as the linking groups.¹ The supported first generation Ru carbene catalyst performed well in the self-metathesis of internal alkenes and ring closing metathesis (RCM). It was easily separated from the metathesis products and reused without the addition of any stabilising agents, although some leaching and deterioration of the catalyst was observed.

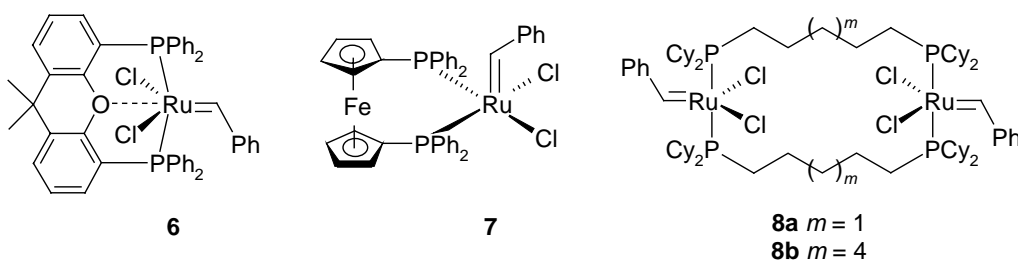
¹ P. Nieczypor, W. Buchowicz, W. J. N. Meester, F. P. J. T. Rutjes, J. C. Mol, *Tetrahedron Lett.* **2001**, 42, 7103.

Exploring the scope of the procedure, resin-immobilised ruthenium carbenes **Ru1-PS** and **Ru2-PS** of the 1st and 2nd generation catalysts, respectively, were prepared using the original or modified protocol with metal loading on the support varying from 0.35 to 2.90 wt% of ruthenium.



The supported catalyst of the second generation **Ru2-PS** showed unexpected diminished activity in RCM but was still a superior catalyst in cross metathesis (CM) of internal alkenes. With increasing ruthenium loading of the supported catalyst, inferior activity was observed due to formation of unidentified metathesis-inactive Ru complexes and clusters. The supported catalysts could be recycled, though upon recycling the activity decreased. In the first cycle this was caused by catalyst leaching and in the following cycles mainly by catalyst decomposition. Contamination with ruthenium residues was relatively low, facilitating the work-up and purification of the metathesis products. The ruthenium K edge EXAFS measurements were used to elucidate the binding mode of ruthenium to the support. In the first generation resins with a low metal loading the binding occurred via a chelating carboxylic group of one linker unit, which replaced a chlorine and a phosphine atom. In the case of immobilised second generation Ru carbene both chelating and monodentate tethers are needed to account for the experimental results.

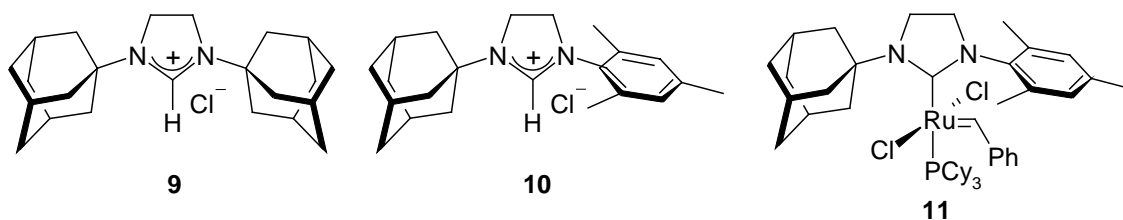
New aspects of homogeneous Ru carbene complexes are described in the two subsequent chapters. Ruthenium carbene complexes containing diphosphines could be synthesised by either phosphine substitution in the PPh_3 analogue of Grubbs catalyst or in a one-pot, two-step synthetic procedure starting from $\text{RuCl}_2(\text{PPh}_3)_3$, phenyldiazomethane and an appropriate diphosphine.²



² P. Nieczypor, P. W. N. M. van Leeuwen, J. C. Mol, M. Lutz, A. L. Spek, *J. Organomet. Chem.* **2001**, 625, 58.

Diphosphines with rigid backbones produced mononuclear complexes, e.g. **6** and **7**, whereas the ligands featuring flexible aliphatic chains gave dinuclear complexes e.g. **8a** and **8b**. These complexes are stable to air and moisture, but they showed lower activity in ring opening metathesis polymerisation ROMP of norbornene and RCM of diethyl diallylmalonate than Grubbs catalyst. The lower activity can be attributed to a detrimental effect of the chelating ligand and possible contributions from unfavourable steric effects. These observations are in general agreement with the postulated mechanism for the metathesis reaction.

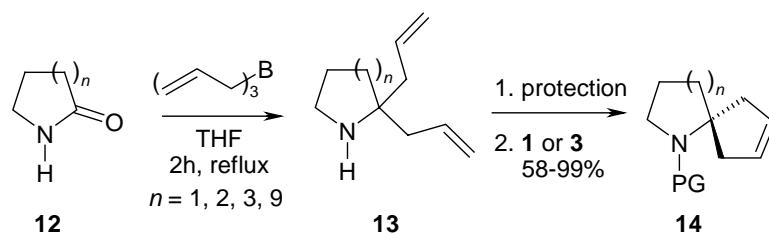
We also accomplished the synthesis of the NHC ligands H₂IAd (**9**) and H₂IAdMes (**10**) bearing the very bulky adamantyl substituent.³ Only H₂IAdMes reacted with Grubbs catalyst to give the expected product **11**. In light of this result, the apparent inability of H₂IAd to displace a PCy₃ ligand in Grubbs catalyst is primarily a consequence of the uncompromising steric bulk of H₂IAd ligand. The formation of only a single isomer of **11**, together with a space-filling model generated from its crystallographic coordinates, further support this notion. The crystal structure of a phosphine-free, dinuclear analogue shows a similar global spatial arrangement of ligands as found for the mononuclear carbene, although some additional peculiar features were also observed.



The catalytic behaviour of the new complex **11** clearly highlights the relevance of the NHC ligand employed when designing second generation Grubbs-type metathesis catalysts. In the present case, the H₂IAdMes ligand (**10**) imparted the resulting complex with only very limited metathesis activity, considerably lower than the parent complex. Indeed, complex **11** was incapable of initiating the metathesis of 1-octene in the absence of a phosphine scavenger (CuCl), and even then only very low turnover numbers could be obtained. The very low metathesis performance of **11** illustrates the importance of the steric bulk of the NHC fragment.

³ M. B. Dinger, P. Nieczyk, J. C. Mol, *Organometallics* **2003**, 22, 5291.

Finally, we have demonstrated that the combination of diallylboration of lactams **12** and the subsequent ring closing metathesis of the resulting 2,2-diallyl *N*-heterocyclic compounds (**13**) is an efficient route towards 6-azaspiro[4.*n*]alk-2-enes (**14**).⁴



Both steps of the procedure give the wanted products in high yields. Protection of the free amine with an appropriate group to neutralise the catalyst-deteriorating basicity of the nitrogen atom greatly facilitated the ring closing metathesis. A limitation of this procedure was that only the cyclopentene ring could be formed and the double bond was always β with respect to the spiro carbon atom.

⁴ P. Nieczypor, J. C. Mol, N. B. Bespalova, Y. N. Bubnov, *Eur. J. Org. Chem.* **2004**, 812.