Renat Kadyrov

Olefin metathesis ruthenium catalysts with unsaturated NHC

RENAT KADYROV*, ANNA ROSIAK
*Corresponding author
Evonik Degussa GmbH, Rodenbacher Chaussee 4, Hanau-Wolfgang, 63457, Germany

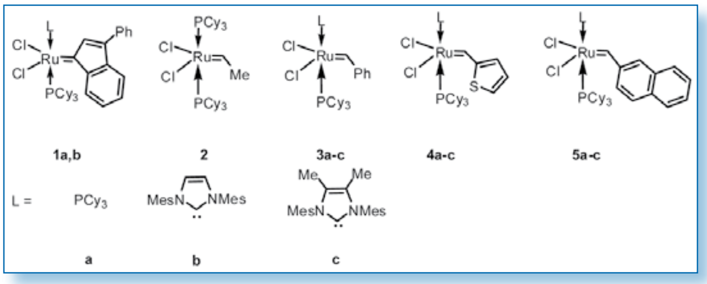
ABSTRACT *"Second-generation" Ru-carbene complexes bearing one unsaturated nucleophilic imidazolin-2-ylidene ligand with broad variation of the alkylidene fragment are available via ethylidene complex RuCl2(=CH-Me)(PCy3)2 under very mild conditions. The synthesis and the first applications of new ruthenium complexes containing new aromatic and heteroaromatic units attached to the alkylidene bond are described. It is shown that improvements in activity of the ruthenium carbene complexes can be achieved by incorporation of methyl groups in 4,5-position of imidazol-2-ylidene moiety independent from alkylidene fragment.*

INTRODUCTION

Olefin metathesis has emerged over the last half century as a powerful tool in chemistry opening unique industrial routes to new petrochemical, polymers and specialty chemicals. Particularly metathesis reactions have found extensive uses in various organic syntheses. In the last decades, thanks to the intensive development of well-defined and stable ruthenium carbenes, there has been an explosion in the number of published syntheses using metathesis as a key step. Following significant breakthroughs in the ruthenium chemistry, a variety of ruthenium carbene catalysts have been prepared. Many research teams have used metathesis based on these complexes as a convenient strategy in the synthesis of various organic compounds. Among them, "second generation" catalysts bearing N-heterocyclic carbene (NHC) ligands exhibit improved activity, stability and an excellent application profile (1). Herein we describe an attractive synthesis of the ethylidene complex $RuCl_2(=CH\text{-}Me)(PCy_3)_2$ - an efficient precursor for the preparation of broad variety of alkylidene complexes under very mild conditions. Furthermore, on the examples of two metathesis reactions we show general tendencies in catalytic behaviour of Ru complexes with unsaturated N-heterocyclic carbenes.

RESULTS AND DISCUSSION

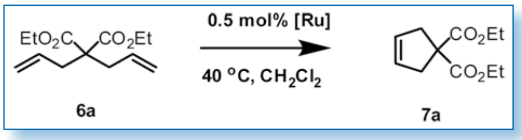
The key to active metathesis ruthenium initiators which can be prepared in industrial scale is the availability of ruthenium precursor containing the alkylidene moiety. The most popular precursors for the "second generation" catalysts bearing NHC ligands are the alkylidene ruthenium complexes coordinated with two phosphines. There are several synthetic routes for preparation of Ru alkylidene compounds. Among the known precursors the phenylindenylidene complex **1a** is the most attractive due to its convenient preparation using propargyl alcohol as the carbene source. The synthesis of this complex was first described by Hill et al. and was believed to provide the 3,3-diphenylallenylidene complex (2). More detailed studies, however, have shown that the stable product formed in this reaction is the phenylindenylidene ruthenium complex (3, 4). Simple ligand substitution allows to generate metathesis active initiator **1b** (5). This method allows access only to the indenylidene and allenylidene complexes. However, the indenylidene and allenylidene ligands in Ru activators are not very effective in the initiation step at ambient temperature. Therefore, we were interested in the alternative routes for the preparation of the ruthenium alkylidene complexes.



There are several routes accessing five-coordinated ruthenium(II) alkylidenes including diazo-transfer (6) and reaction of vinyl or propargyl halides with hydrido(dihydrogen)-Ru-complex generated from $[RuCl_2(COD)]$ and PCy_3 under hydrogen pressure (7). It should be noted that the method for the generation of such highly reactive hydrido(dihydrogen)-Ru-complexes was first developed by Werner and co-workers using two equivalents of $P(i\text{-}Pr)_3$ in 2-buthanol and hydrogen (8). This last attractive one-pot procedure without use of hydrogen was improved by Ciba-group (9). Werner and co-workers published one-pot synthesis of complex **2** by direct reduction of $RuCl_3$ with $Mg/ClCH_2CH_2Cl$ in THF in the presence of excess PCy_3 and hydrogen and consequent reaction with acetylene (10). We have further improved this procedure eliminating potentially explosive hydrogen and displacing acetylene by trimethylsilylacetylene afferding ethylidene complex **2** in good yield. Compound **2** is remarkably stable below room temperature and exchange readily ethylidene moiety by other alkenes. Thus the compound **2** is ideal precursor for a variety of other ruthenium alkylidenes. Further improvement was achieved by bypassing isolation step for the complex **2** and subsequent reaction with appropriate olefin $H_2C=CRR'$ generating alkylidene complex of the general formula $RuCl_2(=CRR')(PCy_3)_2$.

The Ru complexes with different alkylidene moieties routinely prepared in this way by alkylidene exchange in complex **2** showed that complexes with 2-thienyl and 2-naphthyl-residues **4a** and **5a** possesses remarkable stability in solution comparing just with benzylidene complex **3a**. In order to compare the activities of the "second generation" catalysts with different alkylidene fragments we have transformed phosphine complexes into the ruthenium carbene complexes bearing one unsaturated nucleophilic imidazolin-2-ylidene ligands. The modification of the NHC allows access to Ru catalysts suitable for appropriate metathesis application. Moreover, recently we have demonstrated that introducing of alkyl groups in 4,5-position of imidazol-2-ylidene moiety improved activity of the catalysts (11). Therefore we have prepared the new alkylidene complexes **3c**, **4b,c** and **5b,c** with both imidazolydenes.

The efficiency of the NHC containing catalysts **1b** and **3-5b,c** was examined in some metathesis transformations at identical conditions. Herein we discuss two representative examples of these investigations. As a benchmark reaction, the catalysts were tested in the ring closing metathesis of diethyl diallylmalonate **6a**. The selected examples of this transformation in dichloromethane at 40°C are summarized in Table 1. Almost complete conversion to product was reached by employing catalyst **5c** with two methyl groups in 4,5-position of NHC ligand. Surprisingly, the catalyst **3c** gave lower conversion compared with **3b**. Interestingly, indenylidene catalyst **1b** initiates only very slowly typical metathesis reactions when tested at 40°C.

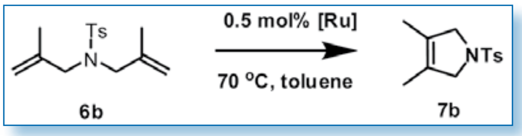


Time, h	1b	3b	3c	5b	5c
0,5	9	40	26	10	31
1	8	66	43	27	62
2	9	89	60	67	95
3	10	93	70	87	99

Table 1. GC-yields of 7a in RCM of 6a in dichloromethane at 40°C using 0.5 mol% of catalysts 1b, 3b, 3c, 5b and 5c.

The full analysis of the screening results for catalysts bearing unsaturated NHC indicate that the efficiency of most transformations studied frequently depended more on solvent, concentration and temperature effects rather than on the nature of alkylidene moiety and NHC ligand. In collaboration with group of K. Grela we have recently demonstrated that Ru-catalysts bearing NHC ligands exhibit generally higher activity in aromatic solvents (12). Furthermore, we have shown that increasing the degree of fluorination of the aromatic solvent generally leads to the higher yields (12b). This can be attributed to competing interactions of the N-aryl group and the fluorinated aromatic solvent reducing the stabilizing effect of the intramolecular π–π interaction with the benzylidene moiety. An alternative explanation might be a π–π interaction between the N-aryl group that is not coplanar with the benzylidene moiety and the aromatic solvent.

The formation of tetrasubstituted double bonds is one of the most challenging metathesis transformations with Ru catalysts. This transformation requires the application of "second-generation" catalysts at high loadings typically 5-10 mol%. We have optimized the reaction parameter achieving almost complete conversion in toluene at 80°C in 2-3 h using all NHC catalysts **1b** and **3-5b,c** at very low (0.5 mol%) loading. Interesting to consider the progress of the RCM of **6b** at lower temperature (70°C) using catalysts **4b** (u) **4c** (l) and **3c** (n) monitored by GC showed on the Figure 1. The plot reflects some differences in activities of initiating versus propagating species. While the activation of the thienylmethylidene complexes **4b,c** is somewhat slower compared to the benzylidene complex **3c**, the propagating species generated from the complexes **3c** and **4c** are the same, showing qualitatively similar slope at higher conversion. However, it can be clearly seen that the rate of RCM using **3c** and **4c** is obviously higher than that using complex **3b**. This demonstrate a strong increase in catalyst activity of propagating complex by using 4,5-dimethyl-imidazol-2-ylidene instead of unsubstituted NHC.



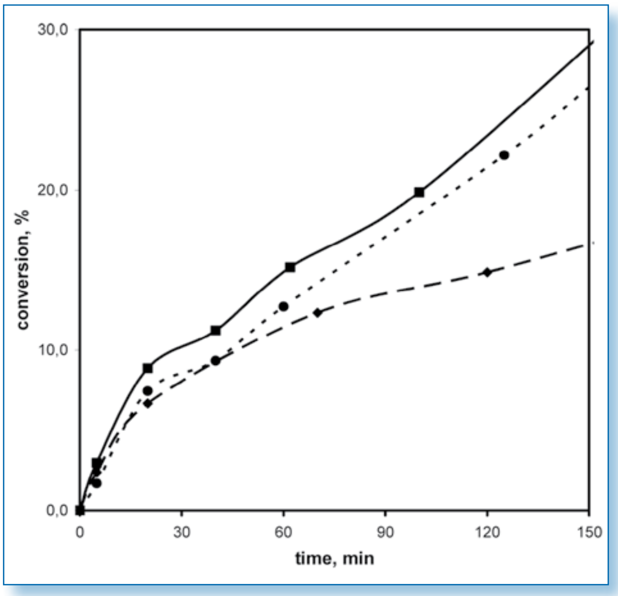


Figure 1. Progress of the RCM of 6b in toluene at 70°C using 0.5 mol% of catalysts 4b (♦) 4c (●) and 3c (■) monitored by GC.

In this contribution we describe large scale preparation of the ethylidene complex $RuCl_2(=CH\text{-}Me)(PCy_3)_2$ which is shown to be an efficient intermediate in the preparation of alkylidene complexes of the general type $RuCl_2(=CRR')(PCy_3)_2$. The alkylidene complexes with heteroaromatic or naphthyl residues R exhibit a remarkable stability in solution, are generated conveniently and in good yields via one pot synthesis from $[RuCl_2(COD)]$, tricyclohexylphosphine, trimethylsilylacetylene and corresponding alkene. The corresponding Ru complexes with unsaturated NHC are shown to be an efficient metathesis catalyst with remarkable stability and an excellent application profile (13).

REFERENCES AND NOTES

1. a) T. Weskamp, W.C. Schattenmann et al., *Angew. Chem. Int. Ed.*, **37**, pp. 2490-2493 (1998); b) T. Weskamp, F. Kohl et al., *Angew. Chem. Int. Ed.*, **38**, pp. 2416-2419 (1999); c) Fürstner, O. Guth et al., *J. Chem. Eur.*, **7**, pp. 4811-4820 (2001).
2. K. Harlow, A.F. Hill et al., *Dalton Trans.*, pp. 285-291 (1999).
3. L. Jafarpour, H.-J. Schanz et al., *Organometallics*, **18**, pp. 5416-5419 (1999).
4. A. Fürstner, O. Guth et al., *Chem. Eur. J.*, **7**, pp. 4811-4820 (2001).
5. R. Kadyrov, J. Almena et al., *Chemistry Today.*, **23**, pp. 14-15 (2005).
6. a) W.A. Herrmann, *Angew. Chem. Int. Ed.*, **17**, pp. 800-813 (1978); b) P. Schwab, R. H. Grubbs et al., *J. Am. Chem. Soc.*, **118**, pp. 100-110 (1996).
7. T.E. Wilhelm, T.R. Belderrain et al., *Organometallics*, **16**, pp. 3867-3869 (1997).
8. C. Grünwald, O. Gevert et al., *Organometallics*, **15**, pp. 1960-1962 (1996).
9. a) P.A. van der Schaaf, R. Kolly et al., *Chem. Commun.*, pp. 1045-1046 (2000); b) P.A. van der Schaaf, R. Kolly et al., *J. Organomet. Chem.*, **606**, pp. 65-74 (2000).
10. J. Wolf, W. Stüer et al., *Angew. Chem. Int. Ed.*, **37**, pp. 1124-1126 (1998).
11. R. Kadyrov, A. Rosiak et al., *Catalysis of Organic Reactions*, **123**, Ed. M. L. Prunier, CRC Press, pp. 217-222 (2009).
12. a) M. Bieniek, A. Michrowska et al., *Chem. Eur. J.*, **14**, pp. 806-818 (2008); b) C. Samojlowicz, M. Bieniek et al., *Chem. Commun.*, pp. 6282-6284 (2008).
13. The Ru complexes with unsaturated NHC are commercially available from Evonik Degussa GmbH under the trade name catMETium®.RF.