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Reactivation of a Ruthenium-Based Olefin Metathesis Catalyst

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Abstract

1st Generation Hoveyda-Grubbs olefin metathesis catalyst was purposely decomposed in the presence of ethylene yielding inorganic species that are inactive in the ring-closing metathesis (RCM) of benchmark substrate diethyldiallyl malonate (DEDAM). The decomposed catalyst was treated with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (**3**) to generate an olefin metathesis active ruthenium indenylidene-ether complex in 43 % yield. This complex was also prepared independently by reacting RuCl₂(*p*-cymene)(PCy₃) with organic precursor **3**. The activity of the isolated reactivated catalyst in the RCM of DEDAM is similar to that of the independently prepared complex.

Keywords

Olefin metathesis; catalyst reactivation; ruthenium indenylidene; RCM

Olefin metathesis is a powerful reaction that finds an impressive array of applications in organic and polymer synthesis.¹ Among the different complexes capable of promoting olefin metathesis, the ruthenium-based catalysts are the most attractive, because they combine high activity with excellent tolerance to functional groups.² The most popular ruthenium-based olefin metathesis promoters are the seminal systems discovered by Grubbs and the highly robust catalysts introduced by Hoveyda.³ Despite tremendous advances in catalyst design in recent years,⁴ there remain some limitations to this technology including catalyst decomposition, high catalyst costs, and ruthenium contamination of the organic products. Much understanding regarding catalyst decomposition⁵ has been gained and used to develop more stable systems,⁶ while the issue of high catalyst costs has motivated studies to substantially decrease catalyst loadings.⁷ Other recent efforts have been directed at developing supported catalysts in order to limit catalyst decomposition and product contamination.⁸ Nevertheless, deactivated homogeneous or supported catalysts cannot be reused as there is no direct method to reactivate them. Therefore, the only ruthenium recycling option to date is to recover the precious metal from the inorganic residue of metathesis processes. As the number and scale of industrial processes utilizing Grubbs-type catalysts continue to grow, a simple and direct method for catalyst reactivation becomes increasingly attractive.

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Author Contributions

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Supporting Information. Experimental details for the decomposition of **1**, the reactivation procedure, the preparation of **4**, and the RCM reactions. CIF files for the X-ray structure of **4**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

We have recently reported a convenient one-step method for the in-situ generation of an olefin metathesis catalyst involving the reaction of $\text{RuCl}_2(p\text{-cymene})(\text{PCy}_3)$ and 1-(3,5-dimethoxyphenyl)-1-phenylprop-2-yn-1-ol.⁹ A similar method based on reacting an analogous organic precursor with $\text{RuCl}_2(\text{PPh}_3)_3$ was independently developed by Bruneau and coworkers.¹⁰ We became interested in testing whether these types of 1,1-diphenylprop-2-yn-1-ol derivatives could also be used to reactivate decomposed olefin metathesis catalysts. Herein, we describe that a related organic precursor can indeed be used to turn the products of decomposition of the 1st generation Hoveyda-Grubbs catalyst into active catalytic species.

Grubbs benzylidene complexes are known to decompose primarily by a bimolecular process giving stilbenes as organic byproducts.^{5a,11} Grubbs methylidene complexes—the resting states in ring-closing metatheses (RCM) and cross metatheses (CM) of terminal olefins—degrade predominantly by a unimolecular pathway involving the attack of a dissociated tricyclohexylphosphine on the methylidene fragment ultimately liberating methyltricyclohexylphosphonium chloride.^{5a,5d,5e,11–12} Notwithstanding, a secondary bimolecular decomposition pathway for methylidene complexes is conceivable.^{5a,13} The inorganic species produced from catalyst decomposition have been characterized in the case of the second-generation Grubbs methylidene,^{5d} but not for the first-generation methylidene or alkylidene complexes. Conversely, very little is known regarding the decomposition of Hoveyda-Grubbs catalysts. While second-generation Hoveyda-Grubbs complexes were shown to produce intractable ruthenium hydride species upon degradation in the presence of ethylene,^{5e} the decomposition of their first-generation analogues are very poorly understood. Considering that the absence of a dissociating phosphine ligand on Hoveyda-Grubbs catalysts rules out the aforementioned unimolecular decomposition pathway, we hypothesized that the decomposition of first-generation Hoveyda-Grubbs complexes in the presence of ethylene may involve a bimolecular pathway and may generate oligomers such as $[\text{RuCl}_2(\text{PCy}_3)]_n$ ¹⁴ and $[\text{RuCl}_2(\text{PCy}_3)(\text{CH}_2=\text{CH}_2)_m]_n$. Furthermore, we theorized that these decomposition species may react with a 1-(3,5-dialkoxyphenyl)-1-phenylprop-2-yn-1-ol to yield an active olefin metathesis catalyst much in the same way that $\text{RuCl}_2(p\text{-cymene})(\text{PCy}_3)$ does.

First-generation Hoveyda-Grubbs catalyst (**1**) was purposely decomposed by subjecting it to an atmosphere of ethylene (120 psi) in dichloromethane at 55 °C for 4 hours (Scheme 1). ¹H NMR spectroscopy suggests that >97 % of complex **1** was consumed as no alkylidene signal can be detected around 17 ppm.¹⁵ In order to confirm the decomposition of complex **1**, the residual inorganic species (**2**) was isolated and tested in the RCM of diethyl diallylmalonate (DEDAM). According to ¹H NMR spectroscopy, a 0.1 M solution of DEDAM in CD_2Cl_2 treated with the inorganic residue **2** (1 mol % Ru, assuming that the decomposition species are $[\text{RuCl}_2(\text{PCy}_3)]_n$) showed less than 3 % conversion after 1 hour at 40 °C (compared to 96 % conversion for the RCM of DEDAM catalyzed by **1** after 45 minutes at 30 °C under similar conditions¹⁶). The fact that there is some RCM activity is likely due to a very small amount of remaining Hoveyda-Grubbs catalyst.

Decomposition species **2** were then treated with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (**3**) in THF-*d*₈. The dark dirt-brown mixture of **2** and **3** was heated in a sealed NMR tube at 70 °C for 18 hours to give a bright orange-brown solution (Scheme 2a). The ³¹P NMR spectrum of this solution features a singlet resonance at 67.5 ppm as the most prominent peak and mass spectrometry (HRMS-FAB) shows a peak at *m/z* 758.2397, consistent with the presence of ruthenium indenylidene-ether complex **4**.

Complex **4** was independently generated in situ by reacting $\text{RuCl}_2(p\text{-cymene})(\text{PCy}_3)$ with organic precursor **3** in refluxing THF for 13 hours (Scheme 2b).¹⁷ The ³¹P NMR spectrum

of the reaction mixture features a singlet at 67.5 ppm for the major product. Complex **4** was isolated by crystallization from a dichloromethane/hexanes mixture at $-15\text{ }^{\circ}\text{C}$ and single-crystals were obtained by layering a chloroform solution of **4** with heptane. X-ray diffraction analysis shows that complex **4** adopts a distorted square pyramidal geometry similar to that of a related Hoveyda-Grubbs compound^{3d} and essentially identical to those of different ruthenium indenylidene-ether complexes (Figure 1).^{10a,10b} The ether ligand is positioned *trans* to the tricyclohexylphosphine with a P–Ru–O angle of $178.33(5)^{\circ}$. The Ru–C_α and Ru–O bond lengths ($1.852(2)\text{ \AA}$ and $2.4349(18)\text{ \AA}$, respectively) are very close to those found in other ruthenium indenylidene-ether complexes.

The solution of in-situ reactivated catalyst—generated by treating the inactive decomposition species **2** with organic precursor **3** as shown in scheme 2a—was found to promote the RCM of DEDAM (Figure 2). Indeed, the in-situ reactivated catalyst ($\sim 1\text{ mol \% total/Ru}$) converted 90 % of DEDAM to its RCM product in 2 hours under standard conditions. Complex **4** prepared in situ from $\text{RuCl}_2(p\text{-cymene})(\text{PCy}_3)$ achieves $\sim 94\text{ \%}$ conversion within 1 hour in the same RCM while the isolated complex **4** reaches $\sim 97\text{ \%}$ conversion (the same as catalyst **1**) at the 1 hour time point (Figure 2). The in-situ reactivated catalyst is clearly slower than isolated complex **4**. In order to shed some light on this activity difference and determine the yield of catalyst reactivation, the reactivation procedure was repeated on a preparative scale and the reactivated catalyst was isolated by silica gel chromatography. Using ^1H NMR spectroscopy and 9-methylantracene as an internal standard, it was determined that 43 % of the initial Hoveyda-Grubbs catalyst was reactivated. The RCM activity of this isolated reactivated catalyst is comparable to that of isolated complex **4** (Figure 2). Interestingly, the RCM kinetics of the in-situ reactivated catalyst ($\sim 1\text{ mol \% total/Ru}$) are even slower than those using $0.33\text{ mol \%}$ of isolated complex **4** (Figure 2). Thus, the explanation for the lower activity of the in-situ reactivated catalyst may be twofold. Only 43 % of the ruthenium species in the solution of in-situ reactivated catalyst are complex **4** and the other products present in the solution may include catalyst inhibitors.

In summary, 1st generation Hoveyda-Grubbs catalyst (**1**) was degraded by reaction with ethylene. The products of decomposition, which proved inactive in the ring-closing metathesis of diethyldiallyl malonate, were transformed into an olefin-metathesis active species by treatment with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (**3**) in 43 % yield. These results constitute the first reactivation of a decomposed ruthenium-based olefin metathesis catalyst and may serve as the foundation for the development of practical reactivation methods for industrial olefin metathesis processes. Preliminary attempts to reactivate decomposed 1st and 2nd generation Grubbs as well as 2nd generation Hoveyda-Grubbs catalysts indicate that this reactivation method may be specific to 1st generation Hoveyda-Grubbs catalysts. Ongoing work includes further probing of this question and developments aimed at improving the efficiency of the reactivation method.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- (a) Chauvin Y. *Angew Chem Int Ed Engl.* 2006; 45:3740. [PubMed: 16724296] (b) Grubbs RH. *Angew Chem, Int Ed.* 2006; 45:3760.(c) Schrock RR. *Angew Chem, Int Ed.* 2006; 45:3748.(d) Grubbs, RH. *Handbook of Metathesis.* Wiley-VCH; Weinheim, Germany: 2003. (e) Trnka TM, Grubbs RH. *Acc Chem Res.* 2001; 34:18. [PubMed: 11170353] (f) Hoveyda AH, Zhugralin AR. *Nature (London, U K).* 2007; 450:243. [PubMed: 17994091] (g) Schrock RR, Czekelius C. *Adv Synth Catal.* 2007; 349:55.(h) Dragutan I, Dragutan V, Mitran C, Vosloo HCM, Delaude L, Demonceau A. *Beilstein J Org Chem.* 2011; 7:699. [PubMed: 21804866] (i) Leitgeb A, Wappel J, Slugovc C. *Polymer.* 2010; 51:2927.
- (a) Schrodi Y, Pederson RL. *Aldrichimica Acta.* 2007; 40:45.(b) Vougioukalakis GC, Grubbs RH. *Chem Rev.* 2010; 110:1746. [PubMed: 20000700]
- (a) Schwab P, France MB, Ziller JW, Grubbs RH. *Angew Chem, Int Ed Engl.* 1995; 34:2039.(b) Schwab P, Grubbs RH, Ziller JW. *J Am Chem Soc.* 1996; 118:100.(c) Scholl M, Ding S, Lee CW, Grubbs RH. *Org Lett.* 1999; 1:953. [PubMed: 10823227] (d) Kingsbury JS, Harrity JPA, Bonitatebus PJ Jr, Hoveyda AH. *J Am Chem Soc.* 1999; 121:791.(e) Garber SB, Kingsbury JS, Gray BL, Hoveyda AH. *J Am Chem Soc.* 2000; 122:8168.
- (a) Colacino E, Martinez J, Lamaty F. *Coord Chem Rev.* 2007; 251:726.(b) Stewart IC, Ung T, Pletnev AA, Berlin JM, Grubbs RH, Schrodi Y. *Org Lett.* 2007; 9:1589. [PubMed: 17378575] (c) Bieniek M, Michrowska A, Usanov DL, Grela K. *Chem--Eur J.* 2008; 14:806. [PubMed: 18064624] (d) Hoveyda AH, Malcolmson SJ, Meek SJ, Zhugralin AR. *Angew Chem, Int Ed.* 2010; 49:34.(e) Stenne B, Timperio J, Savoie J, Dudding T, Collins SK. *Org Lett.* 2010; 12:2032. [PubMed: 20337494] (f) Tiede S, Berger A, Schlesiger D, Rost D, Luehl A, Blechert S. *Angew Chem, Int Ed.* 2010; 49:3972.(g) Kannenberg A, Rost D, Eibauer S, Tiede S, Blechert S. *Angew Chem Int Ed Engl.* 2011; 50:3299. [PubMed: 21432955] (h) Bieniek M, Samojlowicz C, Sashuk V, Bujok R, Sledz P, Lugan N, Lavigne G, Arlt D, Grela K. *Organometallics.* 2011; 30:4144.(i) Keitz BK, Endo K, Herbert MB, Grubbs RH. *J Am Chem Soc.* 2011; 133:9686. [PubMed: 21649443]
- (a) Ulman M, Grubbs RH. *J Org Chem.* 1999; 64:7202.(b) Amoroso D, Snelgrove JL, Conrad JC, Drouin SD, Yap GPA, Fogg DE. *Adv Synth Catal.* 2002; 344:757.(c) van RWJ, Steynberg PJ, Meyer WH, Kirk MM, Forman GS. *J Am Chem Soc.* 2004; 126:14332. [PubMed: 15521734] (d) Hong SH, Day MW, Grubbs RH. *J Am Chem Soc.* 2004; 126:7414. [PubMed: 15198568] (e) Hong SH, Wenzel AG, Salguero TT, Day MW, Grubbs RH. *J Am Chem Soc.* 2007; 129:7961. [PubMed: 17547403] (f) Hong SH, Chlenov A, Day MW, Grubbs RH. *Angew Chem, Int Ed.* 2007; 46:5148. (g) Mathew J, Koga N, Suresh CH. *Organometallics.* 2008; 27:4666.(h) Poater A, Cavallo L. *J Mol Catal A: Chem.* 2010; 324:75.(i) Herbert MB, Lan Y, Keitz BK, Liu P, Endo K, Day MW, Houk KN, Grubbs RH. *J Am Chem Soc.* 2012; 134:7861. [PubMed: 22500642]
- (a) Chung CK, Grubbs RH. *Org Lett.* 2008; 10:2693. [PubMed: 18510331] (b) Kuhn KM, Bourg JB, Chung CK, Virgil SC, Grubbs RH. *J Am Chem Soc.* 2009; 131:5313. [PubMed: 19351207] (c) Savoie J, Stenne B, Collins SK. *Adv Synth Catal.* 2009; 351:1826.(d) Vieille-Petit L, Luan X, Gatti M, Blumentritt S, Linden A, Clavier H, Nolan SP, Dorta R. *Chem Commun (Cambridge, U K).* 2009:3783.(e) Vieille-Petit L, Clavier H, Linden A, Blumentritt S, Nolan SP, Dorta R. *Organometallics.* 2010; 29:775.(f) Poater A, Bahri-Laleh N, Cavallo L. *Chem Commun (Cambridge, U K).* 2011; 47:6674.
- (a) Dinger MB, Mol JC. *Adv Synth Catal.* 2002; 344:671.(b) Anderson DR, Ung T, Mkrtumyan G, Bertrand G, Grubbs RH, Schrodi Y. *Organometallics.* 2008; 27:563. [PubMed: 18584055] (c) Kuhn KM, Champagne TM, Hong SH, Wei WH, Nickel A, Lee CW, Virgil SC, Grubbs RH, Pederson RL. *Org Lett.* 2010; 12:984. [PubMed: 20141172] (d) Nickel A, Ung T, Mkrtumyan G, Uy J, Lee CW, Stoianova D, Papazian J, Wei WH, Mallari A, Schrodi Y, Pederson RL. *Top Catal.* 2012; 55:518.

8. (a) Allen DP, Van Wingerden MM, Grubbs RH. *Org Lett*. 2009; 11:1261. [PubMed: 19239246] (b) Buchmeiser MR. *Chem Rev*. 2009; 109:303. [PubMed: 18980343] (c) Hobbs C, Yang YC, Ling J, Nicola S, Su HL, Bazzi HS, Bergbreiter DE. *Org Lett*. 2011; 13:3904. [PubMed: 21707117] (d) Keraani A, Fischmeister C, Renouard T, Le FM, Baudry A, Bruneau C, Rabiller-Baudry M. *J Mol Catal A: Chem*. 2012; 357:73. (e) Vougioukalakis GC. *Chem–Eur J*. 2012; 18:8868. [PubMed: 22689268]
9. (a) Jimenez LR, Gallon BJ, Schrodi Y. *Organometallics*. 2010; 29:3471. (b) Jimenez LR, Tolentino DR, Gallon BJ, Schrodi Y. *Molecules*. 2012; 17:5675. [PubMed: 22580400]
10. (a) Kabro A, Roisnel T, Fischmeister C, Bruneau C. *Chem–Eur J*. 2010; 16:12255. [PubMed: 20839190] (b) Kabro A, Ghattas G, Roisnel T, Fischmeister C, Bruneau C. *Dalton Trans*. 2012; 41:3695. [PubMed: 22344398]
11. (a) Sanford MS, Love JA, Grubbs RH. *J Am Chem Soc*. 2001; 123:6543. [PubMed: 11439041] (b) Wang H, Metzger JO. *Organometallics*. 2008; 27:2761.
12. Nelson RC, Miller JT. *Catal Sci Technol*. 2012; 2:461.
13. Dias EL, Grubbs RH. *Organometallics*. 1998; 17:2758.
14. Solari E, Gauthier S, Scopelliti R, Severin K. *Organometallics*. 2009; 28:4519.
15. See supporting information.
16. Ritter T, Hejl A, Wenzel AG, Funk TW, Grubbs RH. *Organometallics*. 2006; 25:5740.
17. Complex **4** was previously prepared by an alternative method by Bruneau and coworkers: see reference 10b.

Figure 1.
Representation of complex **4** with thermal ellipsoids drawn at the 50 % probability level.
Hydrogen atoms have been omitted for clarity.

Figure 2.
RCM of diethyl diallylmalonate.

Scheme 1. Decomposition of 1st generation Hoveyda-Grubbs catalyst **1** under ethylene.

Scheme 2.

Preparation of ruthenium indenylidene-ether complex **4** from decomposition species **2** (a) and from $\text{RuCl}_2(p\text{-cymene})(\text{PCy}_3)$ (b).