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Reactivation of a Ruthenium-Based Olefin Metathesis Catalyst

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Supporting Information

ABSTRACT: First-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 the benchmark substrate diethyl diallylmalonate (DEDAM). The decomposed catalyst was treated with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2yn-1-ol (3) to generate an olefin metathesis active ruthenium



indenylidene-ether complex in 43% yield. This complex was also prepared independently by reacting $RuCl_2(p$ -cymene)(PCy₃) with the organic precursor 3. The activity of the isolated reactivated catalyst in the RCM of DEDAM is similar to that of the independently prepared complex.

lefin 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.

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 co-workers.¹⁰ We became interested in testing whether these types of 1,1diphenylprop-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 first-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, d, e, 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,^{Se} the decomposition of their first-generation analogues is 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 $[\operatorname{RuCl}_2(\operatorname{PCy}_3)]_n^{1_{14}}$ and $[\operatorname{RuCl}_2(\operatorname{PCy}_3)(\operatorname{CH}_2=\operatorname{CH}_2)_m]_n$. Furthermore, we theorized that these decomposition species may react with a 1-(3,5-dialkoxyphenyl)-1-phenylprop-2-yn-1ol to yield an active olefin metathesis catalyst in much the same way that $\operatorname{RuCl}_2(p$ -cymene)(PCy₃) does.

First-generation Hoveyda–Grubbs catalyst (1) was purposely decomposed by subjecting it to an atmosphere of

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ethylene (120 psi) in dichloromethane at 55 $^\circ C$ for 4 h (Scheme 1). $^1 H$ NMR spectroscopy suggests that >97% of

Scheme 1. Decomposition of First-Generation Hoveyda– Grubbs Catalyst 1 under Ethylene



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 $[RuCl_2(PCy_3)]_n$) showed less than 3% conversion after 1 h at 40 °C (compared to 96% conversion for the RCM of DEDAM catalyzed by 1 after 45 min 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-(3,5diisopropoxyphenyl)-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 h to give a bright orange-brown solution (Scheme 2a). The ³¹P NMR spectrum of this solution

Scheme 2. Preparation of Ruthenium Indenylidene-Ether Complex 4 from Decomposition Species 2 (a) and from RuCl₂(*p*-cymene)(PCy₃) (b)



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 $\operatorname{RuCl}_2(p\text{-cymene})(\operatorname{PCy}_3)$ with the organic precursor 3 in refluxing THF for 13 h (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 °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 with those of different ruthenium indenylidene-ether complexes (Figure 1).^{10a,b} The ether ligand is positioned trans to the tricyclohexylphosphine with a P–Ru–O angle of 178.33(5)°. The Ru–C_a and Ru–O bond lengths (1.852(2))



C17

C14

- 16

C31

C30

C8

C5

C11 (

C12

C21

C19

🖤 c20

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

and 2.4349(18) Å, 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 (~1 mol % total Ru) converted 90% of DEDAM to its RCM product in 2 h under standard conditions. Complex 4 prepared in situ from $RuCl_2(p$ -cymene)(PCy₃) achieves ~94% conversion within 1 h under the same RCM conditions, while the isolated complex 4 reaches \sim 97% conversion (the same as catalyst 1) at the 1 h 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-methylanthracene 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 (~1 mol % total Ru) are even slower than those using 0.33 mol % of isolated complex 4 (Figure 2). Thus, the explanation for the lower activity of the in situ reactivated catalyst may be 2-fold. 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, first-generation Hoveyda–Grubbs catalyst (1) was degraded by reaction with ethylene. The products of decomposition, which proved inactive in the ring-closing metathesis of diethyl diallylmalonate, were transformed into



Figure 2. RCM of diethyl diallylmalonate.

an olefin-metathesis-active species by treatment with 1-(3,5diisopropoxyphenyl)-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 first- and second-generation Grubbs as well as second-generation Hoveyda–Grubbs catalysts indicate that this reactivation method may be specific to first-generation Hoveyda–Grubbs catalysts. Ongoing work includes further probing of this question and developments aimed at improving the efficiency of the reactivation method.

ASSOCIATED CONTENT

S Supporting Information

Text, figures, and a CIF file giving experimental details for the decomposition of 1, the reactivation procedure, the preparation of 4, RCM reactions, and the X-ray structure of 4. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

[†]The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. These authors contributed equally.

Notes

The authors declare no competing financial interest.

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