Exploring the Formation of Copper-Ruthenium Bimetallic Complexes in Olefin Metathesis

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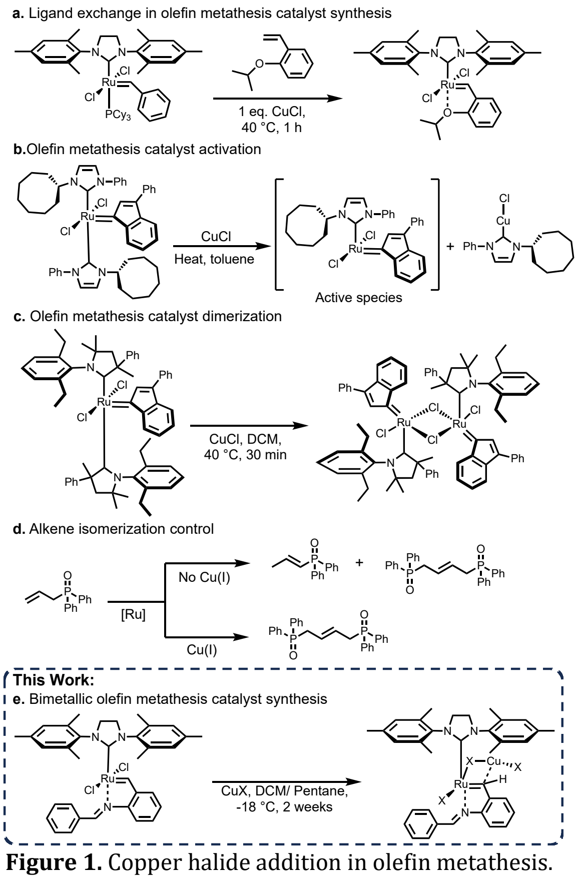
ABSTRACT: Copper(I) halides are often added to olefin metathesis reactions to inhibit catalyst degradation, control product isomerization, enhance catalyst activation, or facilitate catalyst dimerization. In each of these examples, the copper salt is presumed to operate as an independent species, separate from the ruthenium center. We have discovered, however, that certain copper salts can form complexes with the ruthenium catalyst itself, forming hetero-bimetallic copper-ruthenium olefin metathesis catalysts. We confirmed the formation of two complexes through single-crystal X-ray crystallography and NMR spectroscopy. The crystal structure revealed the presence of a four-member ring containing ruthenium, carbon, copper, and chlorine or bromine. The hetero-bimetallic catalyst displayed higher latency and lower activity in the ring-opening metathesis polymerization (ROMP) of norbornene compared to analogous monometallic catalysts. For example, norbornene polymerization catalyzed by the monometallic complex reached 80 % conversion after 4 h, but only 12% conversion when catalyzed by the hetero-bimetallic copper-ruthenium complex under the same conditions. Conversion increased to 63 % when the temperature increased to 50 °C for 1 h, indicating that the bimetallic complex retains activity but requires a higher temperature to activate. The formation of these copper-ruthenium bimetallic complexes suggests the possibility of multi-metallic olefin metathesis catalysts, potentially with different activity and properties than their traditional monometallic counterparts.

The development of well-defined ruthenium-based olefin metathesis catalysts has enabled synthetic access to a wide range of organic molecules and macromolecular structures.[1-5] Ongoing research on both catalyst modification and reaction condition optimization aims to improve catalyst stability, reactivity, and selectivity.[6] For ruthenium-based olefin metathesis catalysts, such modifications often begin with a phosphine-containing Grubbs-type catalyst, followed by a ligand exchange to replace the phosphine.[7] This phosphine exchange is often promoted by the addition of copper salts, which bind to the liberated phosphine ligand (**Figure 1a**).[8] This approach is quite common as nearly all syntheses of ruthenium-based olefin metathesis catalysts start from phosphine-containing catalysts.

Copper halides may also be added to olefin metathesis reactions to enhance catalyst effecacy.[9, 10] For example, phosphine-containing ruthenium catalysts often enter a resting state in which the phosphine ligand (which dissociated during catalyst activation) coordinates to the active ruthenium methylidene, producing an inactive complex that is slow to re-enter the catalytic cycle.[11, 12] Furthermore, some degradation mechanisms involve the liberated phosphine ligand.[13, 14] Adding copper salts, which act as phosphine sponges, sequesters the phosphine, thereby inhibiting formation of the catalyst resting state or phosphine-induced degradation.[15]

Similarly, Dorcet and co-workers studied the activation of ruthenium-indenylidene catalysts containing two unsymmetrical unsaturated NHC ligands.[10] This catalyst showed


a. Ligand exchange in olefin metathesis catalyst synthesis

b. Olefin metathesis catalyst activation

c. Olefin metathesis catalyst dimerization

d. Alkene isomerization control

This Work:

e. Bimetallic olefin metathesis catalyst synthesis

Figure 1. Copper halide addition in olefin metathesis.

high stability and low reactivity in ring-opening metathesis polymerization (ROMP), even at 80 °C, but becomes highly active at 30 °C with the addition of copper(I) chloride (CuCl). The copper salt traps the NHC ligand to release the active ruthenium species through a trans-metalation process (**Figure 1b**).[10] CuCl has also been shown to promote dimerization of a ruthenium-indenylidene complex, forming two bridging chloride donors (**Figure 1c**).[16] The dimerized complex initiates 250 times faster than the parent catalyst.[16] Finally, Thuo and co-workers studied the effects of copper(I) halide addition on olefin metathesis reactions in polar protic solvents with phosphine-based Grubbs catalysts.[9] In cross-metathesis reactions with copper halides present, product isomerization is reduced or eliminated, and the reaction selectively produces the cross-metathesis product (**Figure 1d**).[9]

While synthesizing a series of latent olefin metathesis catalysts with a chelating imine on the benzylidene ligand, we observed the formation of a ruthenium-copper complex during these ligand exchange reactions. Surprised by this finding, we investigated the effect of treating imine-chelated ruthenium olefin metathesis catalysts with different copper(I) salts (**Figure 1e**). The catalyst we investigated has a five-member chelating imine ring and was originally synthesized without the addition of copper halide.[17] It showed high stability in the presence of olefins at room temperature but was activated upon heating.[17] Here, we synthesized this complex with the addition of copper(I) chloride, bromide, and iodide.

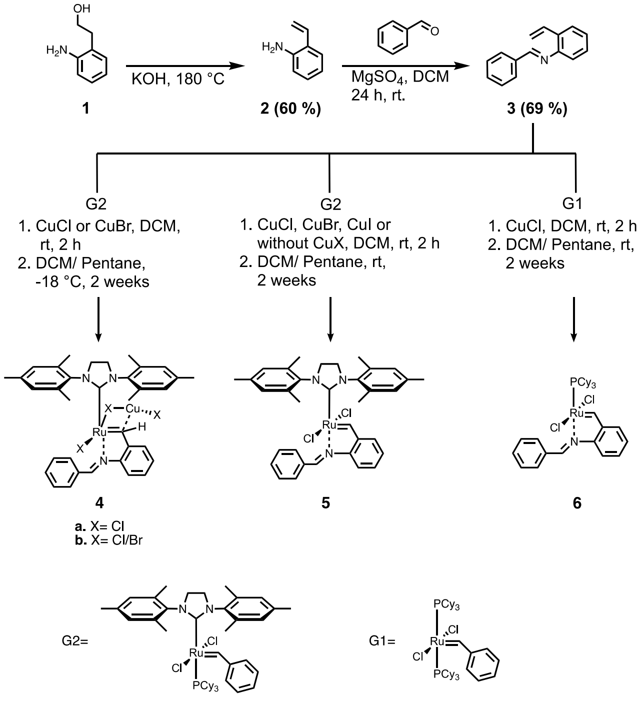


Figure 2. Conditions used to synthesize bimetallic cata-

The imine benzylidene ligand **3** was synthesized following a literature procedure (**Figure 2**),[17] and underwent an alkylidene exchange reaction with first- or second-generation Grubbs catalysts (G1 and G2) with the addition of copper(I) halide. Formation of the catalyst was indicated by a color change of the solution from red to green, and the product was precipitated in pentane.

X-ray crystal structures of the catalysts revealed the formation of different complexes based on the crystallization conditions and copper halides used. Reaction of the benzylidene ligand **3** with G2 and copper chloride or bromide followed by crystallization from dichloromethane (DCM)/pentane at −18 °C yielded hetero-bimetallic copper-ruthenium complexes **4a** and **4b** (**Figure 2**). The crystal structures of the catalysts grown at room temperature showed only formation of monometallic catalyst **5** (**Figure 2**). Attempts to grow crystals with the addition of CuI at room temperature and −18 °C were unsuccessful, possibly due to the large size of the iodine atoms.

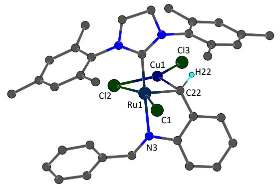
In the crystal structure of **4a**, the occupancy of the Cu site was refined to give the copper-ruthenium complex 93.3% of the time, while the other 6.7% was the complex without copper. In the crystal structure of **4b** (synthesized with CuBr), the Cu is modeled as fully occupied. The catalyst underwent halide exchange and Cl/Br disorder was modeled at all three halogen sites with relative occupancies that refined to 0.717(3)/0.283(3) for Cl1/Br1, 0.626(3)/0.374(3) for Cl2/Br2, and 0.420(3)/0.580(3) for Cl3/Br3 (**Figure 3**).

NMR spectroscopy confirmed both the synthesis of the bimetallic catalysts and the halide exchange reaction of **4b**. The alkylidene and imine peaks became broader, presumably as a result of the copper addition. Additionally, ^{1}H NMR of **4b** showed multiple peaks corresponding to the alkylidene proton at 17.02, 16.95, and 16.86 ppm (ratio of 53:39:8), and imine proton at 9.40, 9.37, and 9.33 ppm (ratio of 7:39:54) (Figure S3), which may reflect the presence of a mixture of halides on these catalysts and/or a mixture of **4b** and **5**. To investigate if **5** is present in the sample, we added **5** to the **4b** NMR sample. ^{1}H NMR showed that the alkylidene peak of **5** overlapped with the alkylidene peak at 17.02 ppm and the imine peak overlapped with the peak at 9.33 ppm (Figure S4). Consequently, the ^{1}H NMR of **4b** showed a mixture of (53:37) **5**:**4b**. ^{13}C NMR also showed a mixture of **4b** and **5** peaks (Figure S6).

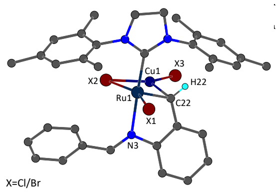
We further characterized crystals of **4b** by ^{1}H NMR at −20 °C to assess if the presence of **5** in **4b** was a result of a reversible reaction leading to CuX release at room temperature. However, even at −20 °C, **5** is present in the sample with the same ratio (53:37) (Figure S3). The ratio between **4b** and **5** remained constant even after keeping the sample for two days at room temperature. We also did a variable temperature (VT) ^{1}H NMR experiment to assess **4b** stability. In this experiment, we raised the temperature to 70 °C and monitored the alkylidene peaks (Figure S7). We did not observe a significant difference at elevated temperature, even after the sample was kept at 70 °C for 30 min. The fact that the ratio between the alkylidene peaks did not change suggests relatively high stability for both **4b** and **5**.

To investigate if Cu-Ru complexes would form with other catalysts, we treated the Hoveyda–Grubbs second-generation catalyst with copper(I) chloride under identical crystallization conditions; however, no Cu-Ru complex formation was observed. Hypothesizing that the chelating imine ligand might be critical to the formation of these heterobimetallic complexes, we synthesized a novel catalyst featuring both the chelating imine ligand and a PCy3 ligand instead of the NHC to form a first-generation analogue of this imine-containing catalyst. We isolated the novel complex **6** with the phosphine ligand; however, crystals grown at room temperature and at −18 °C showed only monometallic catalysts without copper halide coordination.

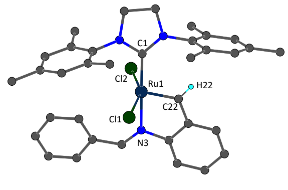
Figure 3 presents the catalyst crystal structures and selected bond lengths and angles for the synthesized complexes. Although these complexes showed similar bond lengths and angles around the ruthenium center, Ru=C and Ru–N distances are systematically longer with CuX (**4a** and **b**) than without (**5** and **6**). The Cu-Ru distances are 2.6049(6) Å (**4a**) and 2.6110(6) Å (**4b**), indicating significant Cu/Ru orbital overlap as these distances are lower than the sum of the Cu and Ru covalent radii (2.78 Å).[18] The Cl2-Ru1-C22 angle in **5** is wider than Cl2-Ru1-C19 in **6** by 8°. This wider angle may explain the ability of copper to form a complex with **5** but not **6**. After copper addition, the Cl2-Ru1-C22 and Br1-Ru1-C22 angle decreased to 103.04(6) and 103.78(10) in **4a** and **4b** respectively, but these angles are still wider than the corresponding angle in **6** (100.90(5) º). This result suggests that **6** may be sterically prohibited from undergoing copper coordination, even with crystallization at a lower temperature.



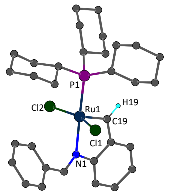
4a			
Bond Lengths [Å]		Bond Angles [°]	
Cu-C22	2.0588(18)	Cl2-Ru1-C22	103.04(6)
Ru1-N3	2.1997(15)	Cl1-Ru1-Cl2	154.906(17)
Ru1-C22	1.8791(18)	C22-Cu1-Cl2	103.27(5)



4b			
Bond Lengths [Å]		Bond Angles [°]	
Cu-C22	2.061(3)	X2-Ru1-C22	103.78(10)
Ru1-N3	2.202(3)	X1-Ru1-X2	154.26(2)
Ru1-C22	1.890(3)	C22-Cu1-X2	104.86(9)



5			
Bond Lengths [Å]		Bond Angles [°]	
Ru1-N3	2.174(4)	Cl2-Ru1-C22	108.06(14)
Ru1-C22	1.846(5)	Cl1-Ru1-Cl2	152.53(4)



6			
Bond Lengths [Å]		Bond Angles [°]	
Ru1-N1	2.1488(15)	C19-Ru1-Cl2	100.90(5)
Ru1-C19	1.8365(18)	Cl1-Ru1-Cl2	157.388(15)

Figure 3. Catalyst crystal structures and selected bond lengths and angles. For **4a** and **4b** (X=Cl or Br), the alkylidene H-atom was located from the difference electron density map and refined independently. In **5** and **6**, the diffraction data was not of sufficient quality to locate the alkylidene H-atom and idealized positions were used.

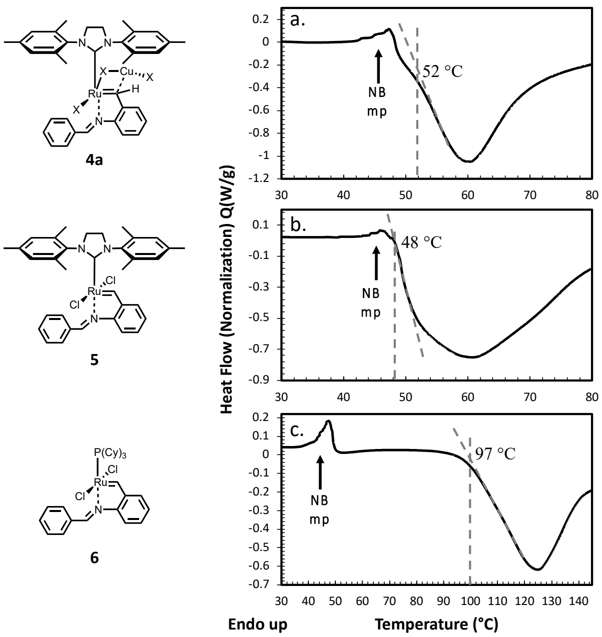
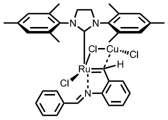
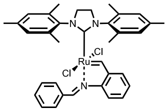


Figure 4. Activation temperatures of a) **4a**, b) **5**, and c) **6** were measured by DSC. Norbornene melting was observed at ~44–48 °C.

We then investigated the activation temperature of these complexes in ROMP of norbornene using differential scanning calorimetry (DSC), which detects an exothermic peak associated with polymerization upon catalyst activation. A mixture of norbornene and **4a**, **5**, or **6** was added to a high-volume DSC pan and heated (3 °C/ min). The DSC measurements of **4a** and **5** showed the norbornene melting point (mp) at 44–48 °C and activation temperatures of 52 and 48 °C, respectively (**Figure 4**). Complex **6** exhibited a significantly higher activation temperature of 97 °C, probably due to the phosphine ligand, which tends to increase catalyst stability.

To further investigate the effect of forming this copper-ruthenium complex on the catalyst activity, we conducted a solution phase polymerization of norbornene in CD_2Cl_2 catalyzed by **4a** or **5** (**Table 1**). ^{1}H NMR spectroscopy showed no polymer peaks after 30 min at 27 °C but polymer peaks slowly increased over 240 min to 12% in the polymerization of norbornene using **4a** as a catalyst. Under the same conditions, the polymerization went faster using **5** with 80% monomer conversion within 240 min. This result suggests that the copper addition stabilizes the catalyst under these conditions, enhancing latency. We then increased the polymerization temperature to 50 °C to increase the catalyst activity. ^{1}H NMR spectroscopy showed an increase in monomer conversion from 12% to 63% within one hour for the polymerization at 50 °C using **4a**. The ^{1}H NMR study confirmed the effect of copper addition in increasing the catalyst stability. However, the catalyst activity can be increased by increasing the temperature, as is expected. While we did not observe any peaks in the NMR spectra that correspond to **5** in these experiments, it is challenging to rule out the possibility that the observed catalytic activity is due to the presence of small amounts of **5** rather than to the copper-coordinated complex.

Catalyst		 **4a**	 **5**
Temperature (°C)	**Time (min)**	**Norbornene conversion (%)**[a]	
27	30	0	25
27	60	2	33
27	240	12	80
50	60	63	-

[a] Determined by ^{1}H NMR spectroscopy

Table 1. Polymerization of norbornene using **4a** and **5** as a catalyst

In conclusion, we have synthesized novel olefin metathesis catalysts featuring a copper-ruthenium bimetallic four-member ring using CuCl and CuBr. X-ray crystallography analysis confirmed the copper coordination. However, an analogous catalyst with a PCy_3 ligand did not show any copper addition. We found that the hetero-bimetallic catalyst showed higher latency compared to the monometallic complex in polymerizing norbornene. The successful synthesis of these complexes presents an opportunity to explore new olefin metathesis catalysts with bimetallic structures.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website. X-ray crystallographic data in tabular format for the structures of compounds: **4a** and **b**, **5** and **6**. CIFs have been deposited as CCDC 2278619-2278622 at the Cambridge Crystallographic Data Centre (www.ccdc.cam.ac.uk/data_request/cif). Experimental section, NMR spectroscopy of the benzylidene ligand **3** and catalysts, and crystallographic data.

General characterization (PDF)

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Notes

The authors declare no competing financial interests.

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REFERENCES

1. Bielawski, C. W.; Grubbs, R. H., Living ring-opening metathesis polymerization. *Prog. Polym. Sci.* **2007,** *32* (1), 1-29.
2. Blosch, S. E.; Scannelli, S. J.; Alaboalirat, M.; Matson, J. B., Complex Polymer Architectures Using Ring-Opening Metathesis Polymerization: Synthesis, Applications, and Practical Considerations. *Macromolecules* **2022,** *55* (11), 4200-4227.
3. Vougioukalakis, G. C.; Grubbs, R. H., Ruthenium-Based Heterocyclic Carbene-Coordinated Olefin Metathesis Catalysts. *Chem. Rev.* **2010,** *110* (3), 1746-1787.
4. Fürstner, A., Olefin Metathesis and Beyond. *Angew. Chem. Int. Ed.* **2000,** *39* (17), 3012-3043.
5. Cheng-Sánchez, I.; Sarabia, F., Recent Advances in Total Synthesis via Metathesis Reactions. *Synthesis* **2018,** *50* (19), 3749-3786.
6. Bano, T.; Zahoor, A. F.; Rasool, N.; Irfan, M.; Mansha, A., Recent trends in Grubbs catalysis toward the synthesis of natural products: a review. *J. Iran. Chem. Soc.* **2022,** *19* (6), 2131-2170.
7. Garber, S. B.; Kingsbury, J. S.; Gray, B. L.; Hoveyda, A. H., Efficient and Recyclable Monomeric and Dendritic Ru-Based Metathesis Catalysts. *J. Am. Chem. Soc.* **2000,** *122* (34), 8168-8179.
8. Garber, S. B.; Kingsbury, J. S.; Gray, B. L.; Hoveyda, A. H., Efficient and Recyclable Monomeric and Dendritic Ru-Based Metathesis Catalysts. *J. Am. Chem. Soc.* **2000,** *122* (34), 8168-8179.
9. Schulz, M. D.; Atkinson, M. B. J.; Elsey, R. J.; Thuo, M. M., Copper(I) halides inhibit olefin isomerized by-products from phosphine-based Grubbs' metathesis catalysts in polar protic solvents. *Transit. Met. Chem.* **2014,** *39* (7), 763-767.
10. Kamal, F.; Colombel-Rouen, S.; Dumas, A.; Guégan, J.-P.; Roisnel, T.; Dorcet, V.; Baslé, O.; Rouen, M.; Mauduit, M., Activation of olefin metathesis complexes containing unsymmetrical unsaturated N-heterocyclic carbenes by copper and gold transmetalation. *Chem. Commun.* **2019,** *55* (77), 11583-11586.
11. Sanford, M. S.; Love, J. A.; Grubbs, R. H., Mechanism and Activity of Ruthenium Olefin Metathesis Catalysts. *J. Am. Chem. Soc.* **2001,** *123* (27), 6543-6554.
12. Bates, J. M.; Lummiss, J. A. M.; Bailey, G. A.; Fogg, D. E., Operation of the Boomerang Mechanism in Olefin Metathesis Reactions Promoted by the Second-Generation Hoveyda Catalyst. *ACS Catalysis* **2014,** *4* (7), 2387-2394.
13. Hong, S. H.; Day, M. W.; Grubbs, R. H., Decomposition of a Key Intermediate in Ruthenium-Catalyzed Olefin Metathesis Reactions. *J. Am. Chem. Soc.* **2004,** *126* (24), 7414-7415.
14. McClennan, W. L.; Rufh, S. A.; Lummiss, J. A. M.; Fogg, D. E., A General Decomposition Pathway for Phosphine-Stabilized Metathesis Catalysts: Lewis Donors Accelerate Methylidene Abstraction. *J. Am. Chem. Soc.* **2016,** *138* (44), 14668-14677.
15. Ulman, M.; Grubbs, R. H., Ruthenium Carbene-Based Olefin Metathesis Initiators: Catalyst Decomposition and Longevity. *J. Org. Chem.* **1999,** *64* (19), 7202-7207.
16. Nascimento, D. L.; Gawin, A.; Gawin, R.; Guńka, P. A.; Zachara, J.; Skowerski, K.; Fogg, D. E., Integrating Activity with Accessibility in Olefin Metathesis: An Unprecedentedly Reactive Ruthenium-Indenylidene Catalyst. *J. Am. Chem. Soc.* **2019,** *141* (27), 10626-10631.
17. Slugovc, C.; Burtscher, D.; Stelzer, F.; Mereiter, K., Thermally Switchable Olefin Metathesis Initiators Bearing Chelating Carbenes: Influence of the Chelate's Ring Size. *Organometallics* **2005,** *24* (10), 2255-2258.
18. Cordero, B.; Gómez, V.; Platero-Prats, A. E.; Revés, M.; Echeverría, J.; Cremades, E.; Barragán, F.; Alvarez, S., Covalent radii revisited. *Dalton Trans.* **2008,** (21), 2832-2838.

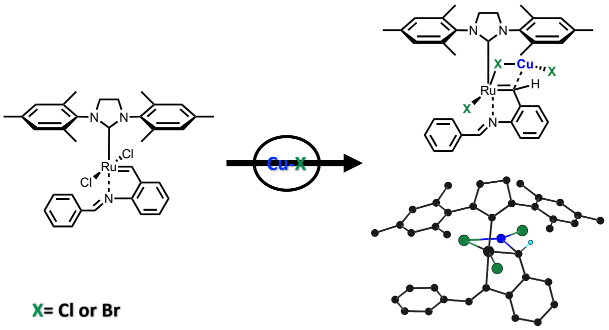

Table of Contents/Abstract Graphics.