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Rate Acceleration in Olefin Metathesis through a Fluorine−Ruthenium Interaction

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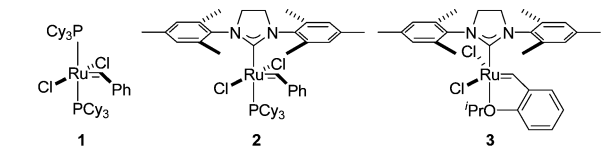
Ruthenium complexes **1**,[1] **2**,[2] and **3**[3] (Chart 1) are common catalysts for a variety of different olefin metathesis transformations.[4] In this communication, we describe the synthesis, structure, and performance of new ruthenium-based olefin metathesis catalysts featuring fluorinated N-heterocyclic carbene ligands. The introduction of ortho halogen atoms profoundly alters the catalytic metathesis performance. Structural investigation suggested that an uncommon fluorine−ruthenium interaction is responsible for the significant rate enhancement. This is the first example of such an interaction resulting in increased catalytic activity.

The synthesis of the fluorinated complexes **5** and **6** commenced with formation of the dihydroimidazolium carbene precursor **4**, accomplished in three steps from commercially available 2,6-difluoroaniline (Scheme 1, eq 1). Deprotonation of **4** in the presence of ruthenium source **1** did not afford the desired complex **5**, presumably because of a short lifetime of the intermediate carbene.[5] The use of a carbene transfer agent, however, generated through the reaction of silver(I) oxide with **4**, furnished **5** in 60% yield after transmetalation (Scheme 1, eq 2, yield based on **1**).[6] The phosphine-free analogue **6** was prepared from **5** by olefin metathesis with *o*-isopropoxy-*β*-methylstyrene and obtained in 75% yield after crystallization (Scheme 1, eq 3). Compounds **5** and **6** are air stable complexes in the solid state and can be purified by chromatography on silica gel.

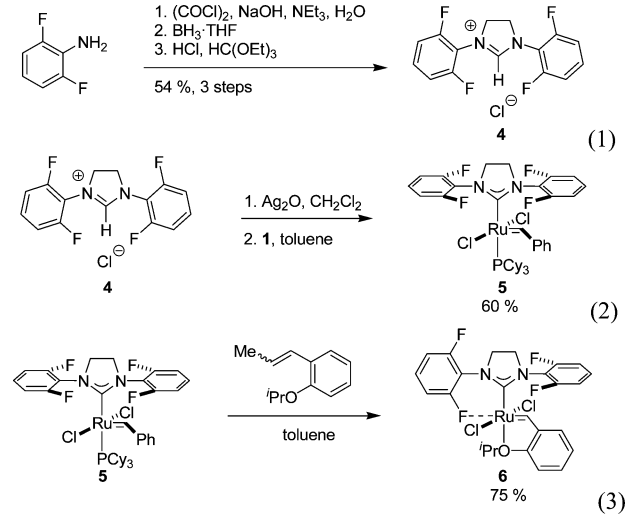
Figure 1 illustrates how catalysts **2**, **3**, **5**, and **6** perform in the ring-closing olefin metathesis of diethyldiallyl malonate under standard reaction conditions.[7] The phosphine-containing catalyst **5** shows a significantly increased reaction rate compared to the two standard second-generation catalysts **2** and **3**, which behave virtually identically. Interestingly, however, the phosphine-free analogue **6** catalyzes the reaction at a slower rate than **2** and **3**. The dissimilar behavior of **5** and **6** is intriguing, given the fact that the relative difference (exchange of a phosphine for a chelating ether ligand) between the two pairs of catalysts—**2** and **3** versus **5** and **6**— is the same. One would therefore expect a change of activity in identical directions for **5** and **6**, not in opposing directions. Recent theoretical investigations suggested the *σ*-withdrawing capacity of the electronegative fluorine atoms would lead to a decrease in catalyst activity,[8] but this is in contrast to what we observe with **5**. Moreover, if inductive effects were the single source of the reactivity enhancement in **5**, it should also be observed for **6**, but this is not the case.

To gain further insight into the unexpected difference in efficiency, crystals of **5** and **6** were grown (Figure 2). Crystallographic analysis revealed two significant differences in the structures. Complex **5** displays a distorted square pyramidal geometry similar to those observed with most other related complexes such as **2** and **3**. In particular, the plane of the NHC heterocycle bisects the Cl−Ru−Cl angle and the aryl substituents on the nitrogen atoms are perpendicular to the plane of the

Chart 1. Benchmark Olefin Metathesis Catalysts



Scheme 1



heterocycle. This arrangement is nicely illustrated by the top view of the catalysts given below the crystal structures in Figure 2. The phosphine-free complex **6**, however, shows a rotation of one of the two fluorinated aryls by 26° around the N−$C_{(aryl)}$ bond and a rotation of the entire NHC ligand around the Ru−C bond by 40° compared to **5**. These two structural differences in **6** position one of the fluorine atoms in close proximity to the ruthenium atom, and the complex might therefore be more correctly represented with a hexacoordinate ruthenium center in a distorted octahedral environment with an additional fluorine−ruthenium interaction. Although relatively weak in complex **6** (Ru−F distance = 3.2 Å) we have observed much stronger ruthenium−fluorine interactions (Ru−F distance = 2.5 Å) in related ruthenium benzylidene complexes, in which both phosphine ligands of **2** have been replaced by the fluorinated NHC ligands (for X-ray structures see Supporting Information (SI)). The Ru−F distances reported here are short compared to similar interactions in other complexes.[9] The absence of such an interaction in the solid state in **5** could be explained by steric congestion of the fluoroaryl substituent with the large tricyclohexylphosphine ligand upon fluorine coordination. The isopropoxy group in **6** is significantly smaller, leaving space for the fluorine atom to coordinate.

While ruthenium−fluorine interactions have been observed, they are rare and have, to the best of our knowledge, never been used

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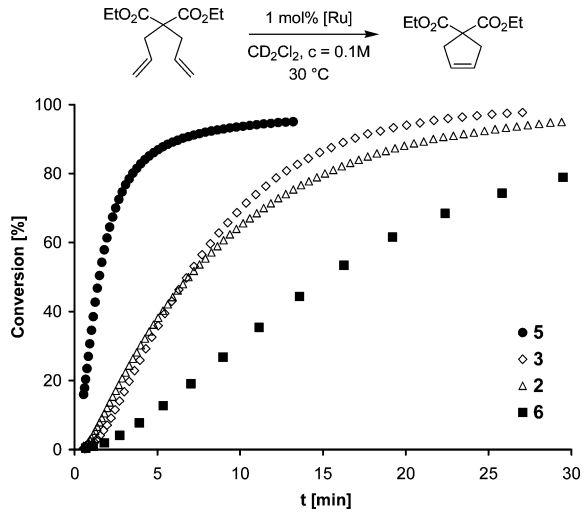


Figure 1. Relative activities of **2**, **3**, **5**, and **6** in RCM.

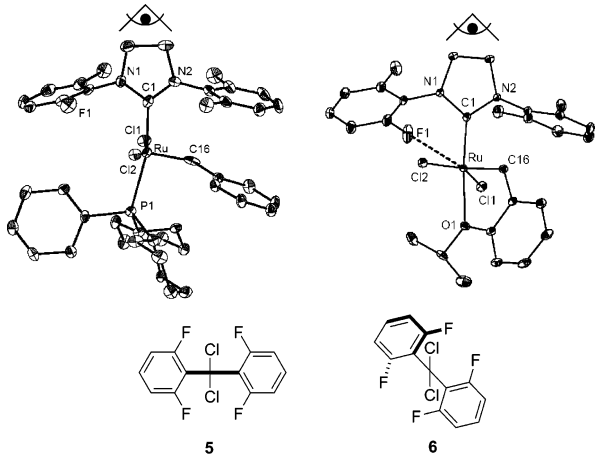
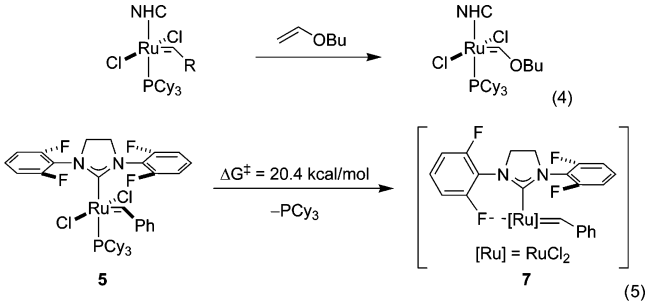


Figure 2. Structures of **5** and **6** with top-view of catalysts.

Scheme 2



to enhance catalytic activity as we present here.[10] We believe that a fluorine−ruthenium interaction accelerates the rate-limiting step in catalyst initiation and can explain the increased efficiency of **5**. To probe this hypothesis, we determined the activation parameters for catalyst initiation, known to be the rate-limiting phosphine dissociation for **2**.[11] This was accomplished by reaction of **5** with butyl vinyl ether, which irreversibly affords a Fischer carbene (Scheme 2, eq 4). Indeed, the free energy of activation of **5** ($\Delta G^{\ddagger 298}$ = 20.4 kcal·mol^{-1}) is ca. 2.6 kcal·mol^{-1} lower than for **2** ($\Delta G^{\ddagger 298}$ = 23.0 kcal·mol^{-1})[12] corresponding to a rate increase of roughly 2 orders of magnitude (Scheme 2, eq 5).[13] This enhancement can originate from a steric interaction of the fluoroaryl with the phosphine ligand upon fluorine coordination.

Chlorine atoms generally coordinate better to ruthenium than fluorine atoms.[10a] Therefore, analogues of **5** and **6**, in which fluorine has been replaced with chlorine, were prepared as well because the favorable halogen−ruthenium interaction in the chlorine case should lower the free energy of activation even further. As expected, the crystal structure of the chloro analogue of **6** shows a strong ruthenium−chlorine interaction (see SI). The chloro-substituted catalysts, however, were less stable than the corresponding fluoro-counterparts and are hence not as suitable for catalysis. A low quality crystal structure of a ruthenium(III) decomposition product in which both of the aryl substituents of the NHC are C-bound to ruthenium to form a tridentate ligand is in accord with C_{aryl}−Cl activation as a decomposition pathway.

In conclusion we have reported a ruthenium complex bearing a fluorinated NHC ligand. Its increased efficiency is attributed to an unusual fluorine−ruthenium interaction, which reduces the activation energy of rate-limiting phosphine dissociation and catalyst initiation. This is the first example of the use of such an interaction to enhance catalytic activity. We plan to use the beneficial effect of this interaction in related catalyst systems for olefin metathesis.

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Supporting Information Available: Experimental procedures and characterization for **4**, **5**, and **6**. Characterization for the chloro-substituted NHC-derived catalysts as well as two additional crystal structures illustrating strong ruthenium−fluorine interactions. This material is available free of charge via the Internet at http://pubs.acs.org.

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(13) The corresponding activation energies for **3** and **6** are $\Delta G^{\ddagger 298}$ = 20.7 kcal·mol^{-1} and $\Delta G^{\ddagger 298}$ = 21.4 kcal·mol^{-1}, respectively. In this case, however, conclusions about the rate cannot be made because the rate-determining step in catalyst initiation has not yet been investigated, but is likely not oxygen dissociation.

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