Chelated Ruthenium Catalysts for Z-Selective Olefin Metathesis

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Abstract

We report the development of ruthenium-based metathesis catalysts with chelating N-heterocyclic carbene (NHC) ligands which catalyze highly Z-selective olefin metathesis. A very simple and convenient synthetic procedure of such a catalyst has been developed. An intramolecular C-H bond activation of the NHC ligand, which is promoted by anion ligand substitution, forms the appropriate chelate for stereo-controlled olefin metathesis.

Based on the continued development of well-defined catalysts, olefin metathesis has emerged as a valuable synthetic method for the formation of carbon-carbon double bonds. Among the frontiers of catalyst development has been the quest for Z-selective olefin metathesis catalysts which would enable access to complex natural products and stereo-regular unique polymers. Specifically, the use of Z-selective catalysts in olefin cross-metathesis (CM) represents a promising and useful methodology in organic chemistry. However, due to the thermodynamic nature of metathesis, most catalysts give a higher proportion of the thermodynamically favored E olefin isomer. This fundamental aspect of olefin metathesis has limited its applications in some areas of chemistry.

Recently, some ruthenium-based catalysts which showed enhanced Z-selectivity have been reported, however, their selectivity is still not satisfactory for precisely stereo-controlled syntheses. On the other hand, recently developed molybdenum- and tungsten-based catalysts have shown outstanding Z-selectivity in CM and metathesis homocoupling of terminal olefins. In particular, a bulky arylxide substituted molybdenum catalyst afforded the cross-coupled product of enol ether and allylbenzene with 98% of the Z isomer. As has been demonstrated in the past, the ruthenium- and molybdenum-based systems show significant differences in selectivities and utility.

For general use, metathesis catalysts should be not only tolerant towards various functional groups and impurities in reaction media, but also readily synthesized from common reagents by simple reaction steps. Here, we report chelated ruthenium catalysts, which catalyze highly Z-selective olefin metathesis, and their facile synthetic preparation.

We chose [H2IMes2]RuCl2=[CH-o-(OiPr)C6H4] (1a, H2I = imidazolidinylidene, Mes = mesityl) and the bulkier [H2IMesAdm]-RuCl2=[CH-o-(OiPr)C6H4] (1b, Adm = 1-adamantyl) as precursors. 1b was readily synthesized from commercially available 2 in excellent yield (Scheme 1).
decomposed immediately when exposed to oxygen in solution, meaning that degassing of syntheses and polymer syntheses without strict reaction conditions. However, metathesis reactions. This feature enables easy use of the catalyst in common organic tolerant towards water in organic solvent. Thus, dry solvent is not necessary for implied not only that water can be used to optimize reaction conditions but also that led to higher conversions and selectivity for the ethylene which was generated during the course of reaction. Unexpectedly, addition of water excellent

isomer). The conversion to for ruthenium-based olefin metathesis catalysts. In addition to this, the homocoupled and 7). The coupled product (entry 1 and 2) compared to their parent non-chelate catalysts (entry 6 and 7). The E/Z ratio of 0.12 (90% Z isomer) achieved by 4b is among the lowest reported for ruthenium-based olefin metathesis catalysts. In addition to this, the homocoupled product (12) afforded by 4b also showed significantly low E/Z ratio (E/Z = 0.06, 95% Z isomer). The conversion to 11 was improved under THF reflux condition maintaining excellent Z-selectivity (entry 3). This was probably a result of more efficient removal of ethylene which was generated during the course of reaction. Unexpectedly, addition of water led to higher conversions and selectivity for the Z olefin products (entry 4). This result implies not only that water can be used to optimize reaction conditions but also that 4b is tolerant towards water in organic solvent. Thus, dry solvent is not necessary for 4b in olefin metathesis reactions. This feature enables easy use of the catalyst in common organic syntheses and polymer syntheses without strict reaction conditions. However, 4b decomposed immediately when exposed to oxygen in solution, meaning that degassing of

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solvent is required to achieve high conversion. Notably, the reaction was reproducible on a synthetic scale (mmol scale, entry 5).

In summary, we have demonstrated the utility of chelated ruthenium catalyst for $Z$-selective olefin cross-metathesis reactions. The $Z$-selectivity achieved by 4b is the best among reported ruthenium-based catalysts and comparable to the molybdenum- and tungsten-based catalysts. Notably, this is the first time that $Z$-selectivity in the cross-metathesis of two different olefins has been demonstrated using a ruthenium-based catalyst. The ruthenium catalyst is readily synthesized from common reagents via simple reaction steps and is stable in the presence of water which should promote its application in precisely stereo-controlled organic and polymer syntheses.

**Supplementary Material**

Refer to Web version on PubMed Central for supplementary material.

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**References**


9. 3a was detected by $^1$H NMR and FD-MS. See details in the Supporting Information.


12. For X-ray crystal structure and selected bond length of 1b, see the Supporting Information.
15. The RCM data was referred to ref. 14.
16. For the reaction conditions and results, see the Supporting Information.
Figure 1.
Plausible transition states of the intramolecular C-H bond activation in 3a.
Figure 2.
X-ray crystal structure and selected bond length of 4a are shown. Displacement ellipsoids are drawn at 50% probability. For clarity, hydrogen atoms have been omitted.
Figure 3.
X-ray crystal structure and selected bond length of 4b are shown. Displacement ellipsoids are drawn at 50% probability. For clarity, hydrogen atoms have been omitted.
Figure 4.
Plot of conversion versus time for the RCM of 5. Reaction conditions were as follows: 1a: 1.0 mol % catalyst, 0.1 M substrate, 30 °C, CD$_2$Cl$_2$; 4a: 1.0 mol % catalyst, 0.1 M substrate, 30 °C, C$_6$D$_6$; 4b: 5.0 mol % catalyst, 0.1 M substrate, 70 °C, C$_6$D$_6$. 
Scheme 1.
Synthesis of 1b
Scheme 2.
Synthesis of 4a
Scheme 3.
Synthesis of 4b
### Table 1

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<th>entry</th>
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<th>11 conversion&lt;sup&gt;c&lt;/sup&gt; %</th>
<th>E/Z&lt;sup&gt;d&lt;/sup&gt;</th>
<th>12 conversion&lt;sup&gt;c&lt;/sup&gt; %</th>
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<sup>a</sup>All reactions unless otherwise stated were carried out using 0.20 mmol of 9, 0.40 mmol of 10 and 0.10 mmol of tridecane (internal standard for GC analysis) in 1.0 ml of solvent.

<sup>b</sup>Based on 9.

<sup>c</sup>Conversion of 9 to the product determined by GC analysis.

<sup>d</sup>Molar ratio of E isomer and Z isomer of the product determined by GC analysis.

<sup>e</sup>THF : H<sub>2</sub>O = 1 : 1 (by volume).

<sup>f</sup>The reaction was carried out using 1.0 mmol of 9, 2.0 mmol of 10 and 0.050 mmol of catalyst in 5.0 ml of solvent.

<sup>g</sup>Isolated yield.

<sup>h</sup>12 was obtained with impurities.

<sup>i</sup>GC signal of 12 was too small to quantify.