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Theoretical Study of Ruthenium Catalyzed Enantioselective Asymmetric Dehydrative Cyclization of ω-Hydroxy Allyl Alcohol

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Abstract

In this study, we investigated the reaction mechanism of asymmetric dehydrative cyclization of ω-hydroxy allyl alcohol and elucidated the origin of the high enantioselectivity using DFT (ωB97XD/SDD-6-31G(d,p)-PCM(DMA solvent) calculations. The CpRu(II) catalyst models using (*R*)-Cl-Napthalene-PyridineCOOH ligand were studied. We have defined Ru_R and Ru_S diastereomers. The results indicated that the RDS step is the first step (Oxidative addition or Dehydration step) with the intrinsic activation energy, 20.6 and 20.8 kcal/mol for Ru_R and Ru_S, respectively. However, the intrinsic activation energy of both diastereomers gave similar values. Hence, we have calculated the apparent activation energy(δE) and the turnover frequency(TOF) using the energetic span model. Finally, our calculations results were consistent with the experimental data which revealed that this ligand gave an enantioenriched the *S*-product.

Introduction

Kitamura group have developed an axially chiral ligand (*R*)-Cl-naph-pyCOOH ligand with a Trost-type CpRu complex which achieved dehydrative intramolecular cyclization ω-hydroxy allyl alcohol with an excellent reactivity and high enantioselectivity.[1] In this work, we have investigated three possible reaction pathways (Ru_R/C(1)-π-σ-π, Ru_R/C(3)-π-σ-π, Ru_S/C(1)-π-σ-π routes) for this mechanism using the CpRu(II) catalyst models with (*R*)-Cl-naph-pyCOOH ligand of the diastereomers (Ru_R and Ru_S) as given in Fig.1 by DFT calculations.

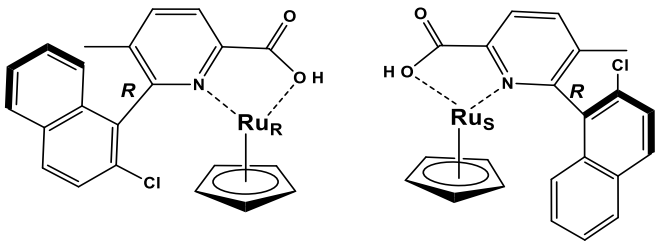

Fig. 1 The CpRu(II) catalyst models using (*R*)-Cl-naph-pyCOOH ligand
Diastereomers Ru_R (left) and Ru_S (right) were defined.

Moreover, we attempt to shed some light on the unclear mechanism of the π-σ-π isomerization step of this reaction Furthermore, the origin of high enantioselectivity was elucidated.

Computational Methods

Geometry optimizations and frequency calculations were performed with the ωB97XD/6-31G(d,p) and the Stuttgart-Dresden(SDD) basis set used for the Ru metal atom. Solvation effect of *N*,*N*-Dimethylacetamide(DMA) was evaluated with PCM model. Free energies are evaluated at 25^0C according to the method of Whiteside. [2] All calculations were carried out with Gaussian 09 (Rev. E.01) program.

Results and Discussion

The calculation results revealed that the RDS step is the first step (Oxidative addition or Dehydration step) with the intrinsic activation energy (E_a^{RDS}) 20.6 and 20.8 kcal/mol for Ru_R and Ru_S, respectively. However, the E_a^{RDS} of both diastereomers gave similar values. Hence, we have calculated the apparent activation energy (δE) and the turnover frequency (TOF) using the energetic span model [3]. The results indicated that the catalyst model of the Ru_R/C(1)-π-σ-π route is the most preferable pathway (see Fig. 2) provides an *S*-product with δE=20.6 kcal/mol and TOF=18 h^{-1}. While the Ru_R/C(3)-π-σ-π route is the second favored pathway (δE=22.6 kcal/mol and TOF=0.58 h^{-1}) provides an *R*-product. The Ru_S/C(1)-π-σ-π route is disfavored pathway provides an *R*-product with δE=23.6 kcal/mol and TOF=0.11 h^{-1}. Therefore, the ratios of calculated reaction rates are 96.3(*S*):3.1(*R*):0.6(*R*) which are in good agreement with the experimental data with an *S*/*R* enantiomeric ratio (e.r.) of 97:3 with 6-*exo*-trig selectivity. [4]

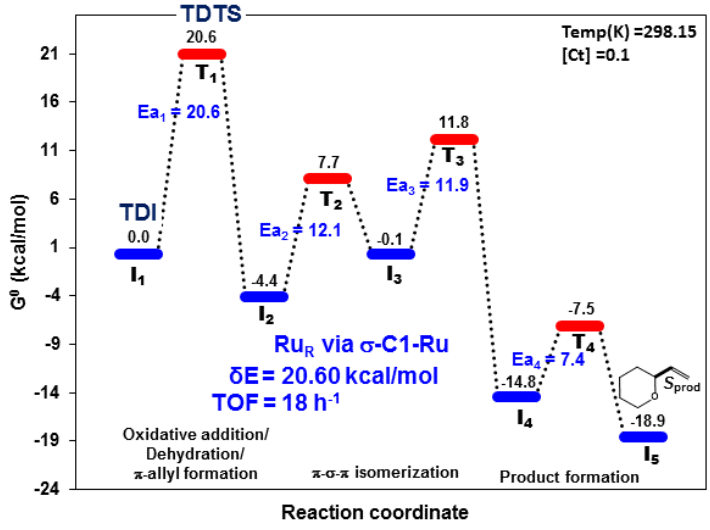

Fig. 2. Free energy profile of the most favorable pathway for *R*-Cl-Naph-PyCOOH–CpRu-catalyzed intramolecular O-allylation via Ru_R/C(1)-π-σ-π route using the energetic span model. [3]

References

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