

Organometallic Chemistry Laboratory (2022)

Chief Scientist: Zhaomin Hou (D.Eng.)



(0) Research fields

CPR Subcommittee: Chemistry

Keywords: asymmetric catalysis, C-H functionalization, carbon dioxide fixation, Dinitrogen Activation, Olefin Polymerization

(1) Long-term goal of laboratory and research background

"New Catalysts, New Reactions, New Materials" -this is the main research theme at the Organometallic Chemistry Laboratory. The discovery of novel catalysts can lead to the development of unprecedented chemical reactions and the creation of innovative functional materials that cannot be synthesized by traditional methods. Our research interests cover broad areas of organometallic chemistry, which include the synthesis of new organometallic complexes having novel structures, the development of more efficient, selective catalysts for olefin polymerization and organic synthesis, and the activation and efficient utilization of small molecules. Much of our work lies at the interfaces between inorganic, organic, polymer, and materials chemistry, with an emphasis being placed on the development of our original catalysts for applications in efficient, selective chemical synthesis.

(2) Current research activities (FY2022) and plan

(A) Regio-, stereospecific polymerization by organo rare-earth catalysts

Aiming towards the creation of novel high-performance polymer materials, a part of our research programs focuses on developing highly active and selective polymerization catalysts based on the unique characteristics of rare-earth metal complexes. We found that polyisoprenes having an appropriate mixture (ca. 70/30) of 3,4- and *cis*-1,4-microstructures synthesized by using a half-sandwich scandium catalyst could act as excellent self-healing elastomers without any external intervention (Fig.1). The unprecedented self-healability could be ascribed to nanoscale heterogeneities formed by microphase separation of the relatively hard 3,4-segments from a flexible *cis*-1,4-segment matrix. The hydrogenated polyisoprenes (without C=C bonds) with the analogous microstructures also exhibited excellent mechanical and self-healing properties, further demonstrating that even simple polyolefins can be made self-healable if the microstructures are appropriately regulated.

In future, we will continue to design and synthesize new organo rare-earth alkyl complexes bearing various types of monoanionic ancillary ligands and develop new regio-, stereoselective transformations for the synthesis of novel functional polymers.

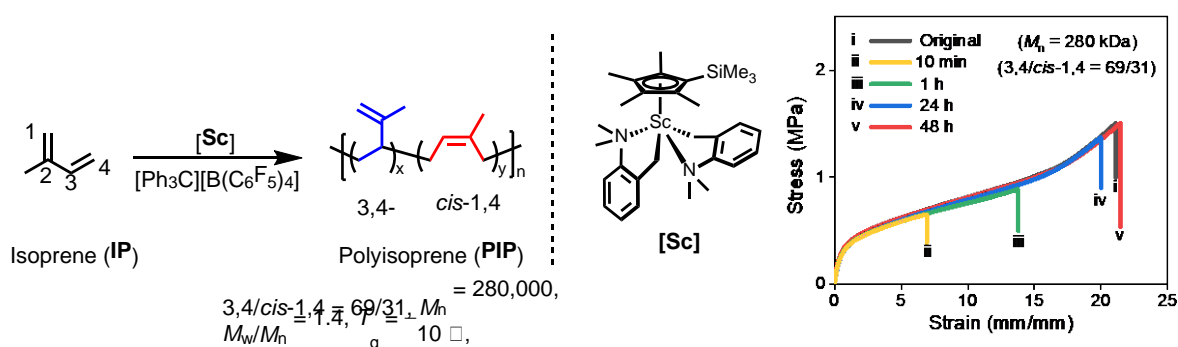


Fig. 1 Synthesis and self-healing property of polyisoprene

(B) Novel chemical transformations via C-H activation catalyzed by organo rare-earth catalysts

Benzo-fused carbocycles such as indanes and tetralins, especially those bearing an all-carbon quaternary stereocenter, are important structural motifs frequently found in natural products, bioactive molecules, and functional materials. By using the half-sandwich Sc and Y catalysts, we have achieved for the first time the *exo*-selective, regiospecific intramolecular annulation of a wide range of functionalized aromatic substrates with 1,1-disubstituted alkenes via C(sp²)-H and benzylic C(sp³)-H activation (Fig.2). Alkoxy-, phenoxy-, dimethylamino-, pyridyl-, and quinolinyl-functionalized aromatics, including heterocycles such as indole and carbazole substrates, are all suitable for this transformation. This protocol constitutes a straightforward and atom-efficient route for the synthesis of a new family of indane and tetralin derivatives with an all-carbon

quaternary stereocenter which were difficult to access previously by other catalysts.

The [2+2] cycloaddition of allenes with alkenes is of much interest and importance as a straightforward route for the construction of four-membered carbocycles. We have achieved for the first time the intermolecular regio- and diastereoselective formal [2+2] cycloaddition of a wide range of allenes with amino-functionalized alkenes via allene C(sp²)-H activation by using half-sandwich rare-earth catalysts (Fig.3). The reaction with terminal allenes as the substrate selectively affords four-membered cyclization products with exomethylene structures, while the reaction with 1,3-disubstituted allenes selectively affords four-membered cyclization products with internal double bonds. This protocol offers a unique and efficient route for the synthesis of a new family of cyclobutane and cyclobutene derivatives which were difficult to access previously. Furthermore, in FY2022, the benzylic C-H aluminination reaction of 2-methylpyridine derivatives has been developed by using a half-sandwich yttrium catalyst.

In future, we will continue to develop regio-, stereoselective and atom-efficient reactions based on our original rare-earth catalysts by making use of the unique activity of rare-earth alkyl species toward C-H activation and C=X insertion (X = C, O, N, S, etc.) together with the unique interaction between rare-earth metal and heteroatom.

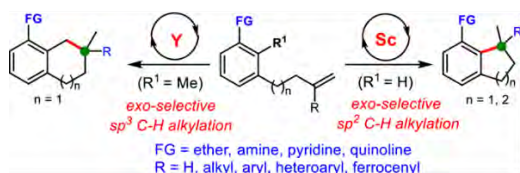


Fig. 2 Exo-Selective Intramolecular C-H Alkylation

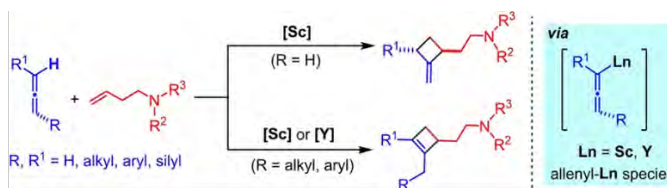


Fig. 3 [2+2] Cycloaddition of Allenes with Amino-Functionalized Alkenes

(C) Activation and transformation of CO₂ by organometallic catalysts

The *trans*-selective terminal C(sp²)-H bond carboxylation of styrene derivatives with CO₂ has been achieved in the presence of a diboron compound and LiOtBu using a bidentate-phosphine-ligated copper catalyst (Fig.4). This reaction is the first example of the C(sp²)-H carboxylation of alkenes bearing no directing group that promotes C-H bond activation process. In this reaction, copper alkoxide species is a key active species and acts as the catalyst in two catalytic cycles to afford the desired carboxylation products; the first one is C-H borylation of the styrenes, and the second one is carboxylation of the resulting alkenyl boranes with CO₂. In the former C-H borylation process, a β-hydride elimination occurs to provide a copper hydride species that may cause side reactions. However, in the current system, the copper hydride automatically reacts with CO₂ and LiOtBu to regenerate copper alkoxide species to enable the desired tandem catalytic pathways selectively. In this reaction, functional group tolerance is high, and various acrylic acid derivatives can be efficiently synthesized.

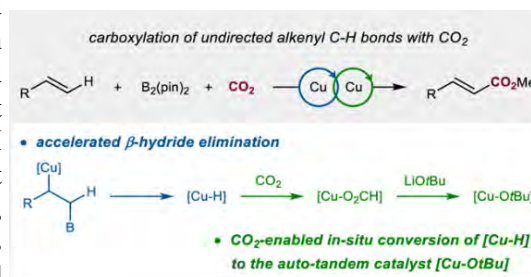


Fig. 4 C-H Carboxylation of Styrenes with CO₂

In future plan, we will continue to develop CO₂ fixation reactions that enable the synthesis of a wide variety of value-added compounds.

(D) Activation and transformation of small molecules by hydride clusters

As part of our efforts towards dinitrogen functionalization by multimetallic hydrides, we have recently achieved the activation and functionalization of dinitrogen (N₂) with aromatic aldehydes (ArCHO) by the titanium hydride complex to form bibenzyls through hydrodeoxygenative coupling of aldehydes (Fig.5). Further reactions with the corresponding aldehydes afford hydrobenzamides. Both hydride and imide ligands play an important role for the reductive coupling, hydrogenation processes, as well as functionalization of the N₂-derived imide units without the need of sacrificial reagents. These results demonstrate that the tetranuclear titanium imide/hydride framework is not only applicable for N₂ activation and functionalization, but also providing a new platform for C-C bond formation using carbonyl compounds.

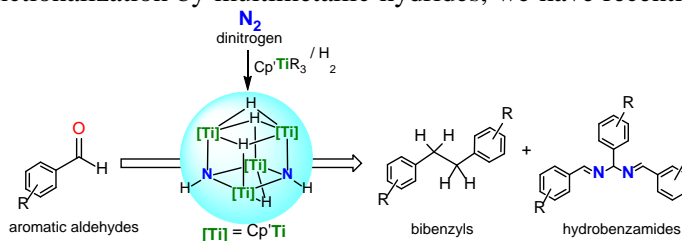


Fig.5 Hydrodeoxygenative coupling and transformation of aldehydes at an N₂-derived tetranuclear titanium imide/hydride framework

In future, we will continue to design and synthesize various multimetallic polyhydride complexes changing the metal combination (or nuclearity) and the steric and electronic properties of the ancillary

ligands and explore their potential for the activation and transformation of small molecules and inactive skeletons.

(3) Members

as of March, 2023

(Chief Scientist)

Zhaomin Hou

(Senior Research Scientist)

Masayoshi Nishiura, Takanori Shima, Masanori Takimoto, Liang Zhang, Satoshi Kamiguchi

(Postdoctoral Researcher)

Qingde Zhuo, Kun An

(Contract Researcher)

Xiaoxi Zhou

(Visiting Researcher)

Hao Wang

(Assistant)

Yuka Cowart

(Part-time Worker)

Akiko Karube, Keiko Nakamura

(4) Representative research achievements

1. "Auto-Tandem Copper-Catalyzed Carboxylation of Undirected Alkenyl C–H Bonds with CO₂ by Harnessing β -Hydride Elimination", H. Sahoo, L. Zhang, J. Cheng, M. Nishiura, Z. Hou, *J. Am. Chem. Soc.*, *144*, 23585-23594 (2022).
2. "Regioselective Benzylic C–H Almination and Further Functionalization of 2-Alkylpyridines by Yttrium Catalyst", M. Takimoto, M. Liu, M. Nishiura, Z. Hou, *ACS Catal.*, *12*, 13792-13804 (2022).
3. "Regio- and Diastereoselective Formal [2 + 2] Cycloaddition of Allenes with Amino-Functionalized Alkenes by Rare-Earth-Catalyzed C(sp²)–H Activation", W. Xu, X. Cong, K. An, S. Lou, Z. Li, M. Nishiura, T. Murahashi, Z. Hou, *Angew. Chem. Int. Ed.*, *61*, e2210624 (2022).
4. "Making Polyisoprene Self-Healable through Microstructure Regulation by Rare-Earth Catalysts", H. Wang, Y. Yang, M. Nishiura, Y. Hong, Y. Nishiyama, Y. Higaki, Z. Hou, *Angew. Chem. Int. Ed.*, *61*, e202210023 (2022).
5. "Dinitrogen Cleavage and Functionalization with Carbon Dioxide in a Ditungsten Dihydride Framework", Q. Zhuo, J. Yang, Z. Mo, X. Zhou, T. Shima, Y. Luo, Z. Hou, *J. Am. Chem. Soc.*, *144*, 6972-6980 (2022).

Supplementary

Laboratory Homepage

https://www.riken.jp/en/research/labs/chief/organometal_chem/index.html

<http://www2.riken.jp/lab-www/organometallic/HP2015e/index.html>