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Coming Back to the Starting Position of Carbons Traveling in Organic Molecules on Titanium: Merry-Go-Round Reaction

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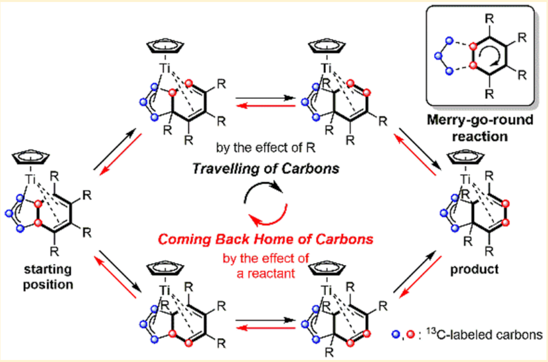
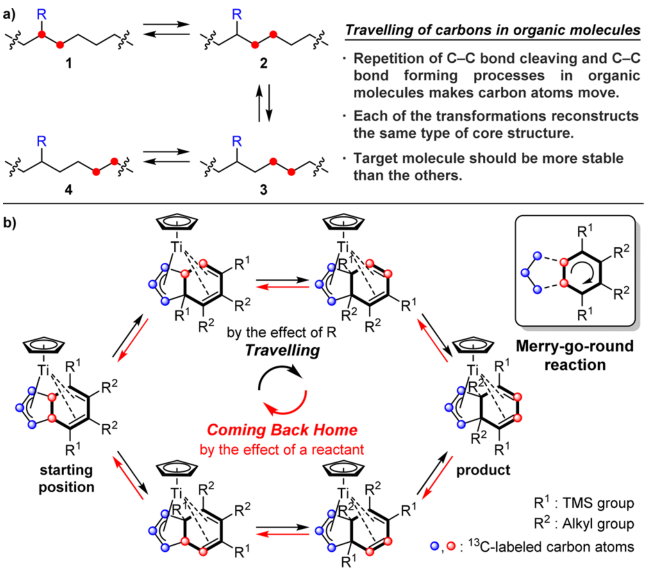
Supporting Information

ABSTRACT: Traveling of carbon atoms in organic molecules was successfully achieved. The six-membered ring of dihydroindenyl moiety on titanium rotated based on the five-membered ring like a merry-go-round. Two carbons at the bridgehead of the dihydroindenyl moiety and the other three carbons of the five-membered ring were monitored by ^{13}C-labeled experiments. The two carbons at the bridgehead moved to the farthest positions with the rotation of the six-membered ring. The intermediate where the two carbons were located at the farthest positions was isolated and fully characterized. Treatment of the intermediate with azobenzene made the two carbons come back to the starting positions. There is another viewpoint on this reaction. When the six-membered ring is fixed and the movement of three carbons of the five-membered ring of the dihydroindenyl moiety on titanium is focused, it was found that those three carbons moved around the six-membered ring and came back to the starting points.



Traveling of carbon atoms in organic molecules is a new challenge in organic chemistry. The general scheme of the reaction is shown in Scheme 1a. The position of carbons is changed step-by-step in an organic molecule as in compounds **1**−**4**. To achieve this challenge, each transformation consists of carbon−carbon bond-cleaving and carbon−carbon bond-forming processes. Although C−C bond cleavage has been well studied over the past three decades, there is no report on the traveling and coming back to the starting point of carbon atoms in the same type of carbon skeleton to the best of our knowledge.[1−21] When compounds **1**−**4** are in equilibrium, a target molecule should be designed as the most stable compound among **1**−**4**. In other words, traveling of carbons in organic molecules is controlled by the stability of the molecules.

Scheme 1. Traveling of Carbon Atoms in Organic Molecules[a]



Travelling of carbons in organic molecules

- Repetition of C−C bond cleaving and C−C bond forming processes in organic molecules makes carbon atoms move.
- Each of the transformations reconstructs the same type of core structure.
- Target molecule should be more stable than the others.

R^1 : TMS group
R^2 : Alkyl group
^{13}C-labeled carbon atoms

[a] (a) General scheme of traveling of carbon atoms in organic molecules. (b) Traveling of two carbons along with a rotation of the six-membered ring in dihydroindenyl moiety on titanium (merry-go-round reaction).

Herein we report a rotation of a six-membered ring of dihydroindenyl moiety on titanium based on the five-membered ring like a merry-go-round (Scheme 1b). Two carbons at bridgehead and three carbons of the five-membered ring were monitored by ^{13}C-labeled experiments. We focused on two carbons at the bridgehead positions of the dihydroindenyl moiety on titanium. These two carbons moved to the farthest positions with the rotation of the six-membered ring by the effect of substituents (R) and came back to the starting positions by the effect of a reactant. The intermediate where the two carbons moved to the farthest positions was isolated and fully characterized.

We have previously reported traveling of two carbons from the starting complex **5** to **6** and finally to complex **7** by the effect of a ligand, as shown in Scheme 2.[22−24] Complexes **5** and **6** have

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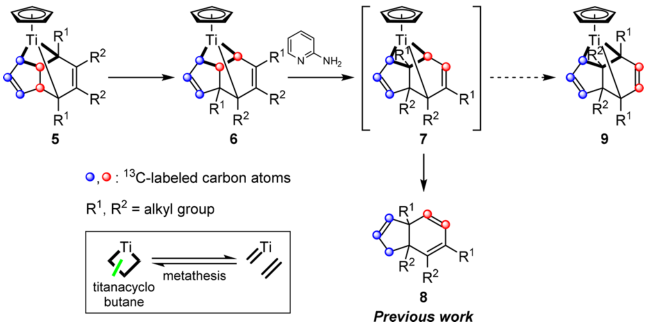
Scheme 2. Traveling of Two Carbons in Dihydroindenyl Molecules on Titanium through Titanacyclobutane Rings



been reported and isolated from titanacyclopentadienes by Rosenthal et al. as a pioneer work.[17,25] In the reaction from complex **6** to complex **7**, aminopyridine stabilized complex **7** through its coordination to titanium, and the following protonolysis with NH_2 group provided dihydroindene **8**. To continue further traveling of the carbons in organic molecules, the undesired protonation step to remove titanium should be avoided. In addition, a more stable titanium complex should be designed to the destination of the two carbons.

We have previously proposed a reaction mechanism for the traveling of two carbons from complex **5** to **6** (Supporting Information (SI), page S32).[22,23] Key steps for the traveling are the metathesis-type carbon−carbon bond cleavage and reformation in the same type of the core structure, dihydroindenyl moiety, through the titanacyclobutane ring. As we have already reported, complexes **5** and **6** were in equilibrium.[23] Because complex **6** was more stable than complex **5** because of the less substituted diene coordinated to titanium compared with complex **5**, the equilibrium lay to the side of complex **6**.

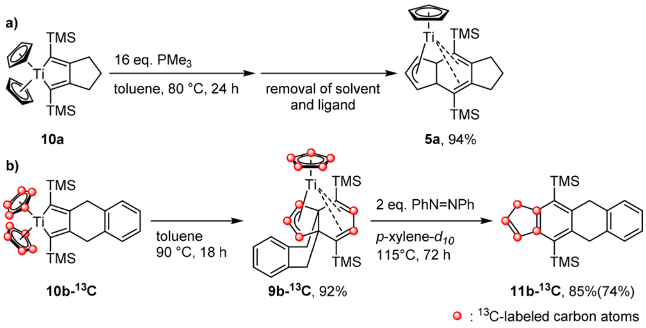
As with complex **5**, complex **6** also has the titanacyclobutane moiety. Therefore, complex **6** is further converted to complex **7** if complex **7** is more stable than complex **6**. The reaction shown in Scheme 2 demonstrates the existence of complex **7**; however, aminopyridine not only stabilized complex **7** but also protonated complex **7** to give the organic compound **8**, which did not have the titanium. Because there was no titanacyclobutane moiety in **8**, the traveling of two carbon atoms in the organic molecule stopped at this position. If the protonation does not occur for complex **7**, then further transformation can be expected because complex **7** also has the titanacyclobutane moiety.

If our mechanism (SI, page S32) is correct, then we can expect the formation of complex **9**, where the two carbons move to the longest distance from the starting position of complex **5** (Scheme 2). Because the mechanism is metathesis-like, complex **9** is also in equilibrium with other complexes **5**−**7**. To make the traveling of two carbons to the farthest positions, complex **9** must be more stable than complexes **5**−**7**.

There are two possible methods to control the stability of such dihydroindenyltitanium complexes. One is control by ligands. The other is control by substituents. As shown in Scheme 2, aminopyridine acted as a ligand but unfortunately removed titanium from complex **7** by the protonation with its NH_2 group. Although substituted aminopyridine, which had no hydrogen atom on nitrogen, was used to avoid the protonolysis, the reaction did not afford complex **7**. Therefore, the substituent control had to be chosen to move the two carbons to the longest distance position as in complex **9**. To make complex **9** more stable than complexes **5**−**7**, we focused on substituents R^1, which occupied the bridgehead positions in complexes **6** and **7** (Scheme 2). When R^1 is a bulky substituent such as a trimethylsilyl group, it enhances its steric hindrance on the quaternary carbon atom and destabilizes complexes **6** and **7** as compared with **5** and **9**. When complex **9** is compared with complex **5**, its diene moiety coordinating titanium is disubstituted diene in complex **9**, whereas it is tetrasubstituted diene in complex **5**. Hence, it is presumed that complex **9** is the most stable among complexes **5**−**7** and **9**. Moreover, the trimethylsilyl group stabilizes the α position of organotitanium complexes. Then, we designed the titanacyclopentadienes **10a** and **10b** having trimethylsilyl groups on α-carbons for providing dihydroindenyltitanium complexes **9**.

As shown in Scheme 3a, when a toluene solution of complex **10a**, which was prepared from 1,7-bis(trimethylsilyl)-1,6-heptadiyne, Mg, and Cp_2TiCl_2, was heated to 80 °C in the presence of trimethylphosphine, the starting complex **5a** was obtained in 94% yield by a coupling reaction of a Cp ligand and the diene moiety. The structure of **5a** was verified by X-ray analysis (SI, page S13). In this reaction, the desired complex **9** was not formed because the five-membered side ring made the structure very rigid for the rearrangement.

Scheme 3[a]



[a](a) Synthesis of the starting complex **5a** from complex **10a**. (b) ^{13}C-labeling experiments: Traveling and coming back to the starting position of two carbons in dihydroindenyl moiety on titanium.

When a more flexible six-membered side ring was used instead of the five-membered ring, our expected complex **9b** was obtained in high yield (Scheme 3b). Complex **9b** afforded single crystals suitable for X-ray analysis. The crystal structure of **9b** (SI, page S15) indicated that two carbons originating from a Cp ligand traveled to the longest distance positions (C(7) and C(8) positions in the ORTEP drawing) of the dihydroindenyl moiety.

To confirm the positions of the traveling two carbons, a ^{13}C-labeled experiment was carried out (Scheme 3b). The ^{13}C NMR spectrum of complex **9b-^{13}C** revealed that two ^{13}C-labeled carbons were located at the opposite side of the five-membered ring in the dihydroindenyl moiety. This result clearly showed that two ^{13}C-labeled carbons moved to the farthest position from the starting position in complex **5**.

Now two carbons traveled to the longest distance destination from the starting point in the dihydroindenyl moiety on titanium, as shown above. The next question is, "Can the two carbons, which already traveled to the longest distance position in the organic molecule, come back to the starting point?".

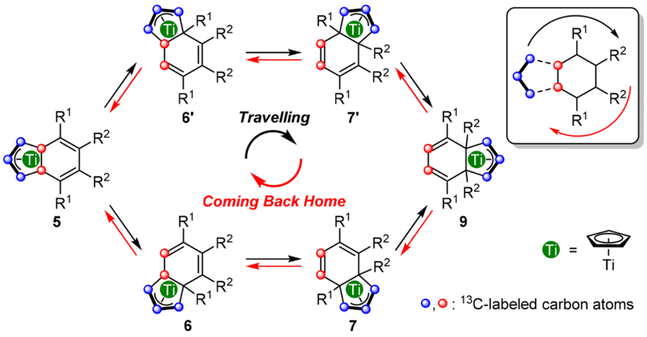
Possessing a titanacyclobutane moiety, complex **9** is also in equilibrium with other complexes **5**−**7** and has the potential for the traveling of carbons from its position. The results shown in

Scheme 3b revealed that complex **9b** was the most stable among complexes **5b**–**7b** and **9b** by the effect of silyl substituents. This means that to move the two carbons back to the starting point in complex **5**, it is necessary that complex **5** should step out of the equilibrium irreversibly by derivatization. Two hydrogen atoms at the bridgehead carbons of complex **5** can be abstracted by azobenzene to give an indene derivative **11**.[26] Because complexes **6**, **7**, and **9** do not have the two hydrogen atoms capable of being abstracted, we expected that the reaction of complex **9** with azobenzene gave indene derivative **11** through the formation of complex **5**.

A ^{13}C-labeling experiment of complex **9b-^{13}C** with azobenzene provided indene derivative **11b-^{13}C** in a good yield, as we expected (Scheme 3b). The ^{13}C NMR study demonstrated that three carbons in the five-membered ring and traveling two carbons were in the same five-membered ring in indene derivative **11b-^{13}C**. This result clearly showed that complex **9** was converted into complex **5** and then the two hydrogen atoms of **5** were eliminated by azobenzene to produce indene derivative **11**. The two carbons, once moved to the farthest positions as in complex **9** with the rotation of the six-membered ring, came back to the starting point of complex **5**.

The above results are summarized in Scheme 1b. The two carbons starting from complex **5** traveled to the longest distance position in complex **9** via complexes **6** and **7** because **9** was the most stable complex among complexes **5**–**7** and **9** by the substituent effect. The carbons that once moved to the longest distance position, in turn, moved back to the starting position in complex **5** with the effect of azobenzene. The hydrogen elimination from complex **5** gave indene derivative **11**, which clearly showed that the two carbons came back to the starting point. A different chemical drawing, as shown in Scheme 4, provides another viewpoint on the reaction where the three carbons traveled around the six-membered ring and came back home instead of the two carbons. This dual aspects are important for the concept of "traveling of carbon atoms in organic molecules: merry-go-round reaction".

Scheme 4. Another Viewpoint on the Reaction: Traveling of *Three* Carbons around the Six-Membered Ring and Coming Back Home



■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.8b00876.

Materials, methods, NMR, HRMS, and X-ray crystallographic analysis (PDF)

Accession Codes

CCDC 1879710–1879711 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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(26) Reaction of complex **5a** with azobenzene gave indene derivative **11a** (see page S8 in the SI for details). The indene derivatives **11** were also obtained when titanacyclopentadienes **10** was heated in the presence of azobenzene (see page S8 in the SI for details).