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論文内容の要旨

C_3 Symmetry, threefold rotational symmetry, is one of the common elements found in natural and artificial objects as well as in science. In chemistry, a symmetrical element of molecules is one of the key terms to design a new molecule applied for asymmetric synthesis, molecular recognition, nanoarchitecture, and so on. Regarding to symmetry, C_2 symmetric compounds have been most widely and successfully applied especially in the field of asymmetric synthesis and catalyst. Due to the interest in the structural properties and the applications, C_3 symmetric compounds have been synthesized and many interesting compounds such as trialkyl methanes, trialkyl amines, substituted benzenens, cyclic peptides, and subporphirins have been reported. The utilities of C_3 symmetric compounds have recently emerged especially in the field of molecular recognition and nanoacrchitecture. Given the present less applications of C_3 symmetric compounds than the widespread applications of C_2 symmetric compounds, the potential utility of C_3 symmetric compounds is now under the progress.

C_3 symmetric *syn*-tris(bicycloalkeno)benzenes were originally introduced as a molecule possessing a significant bond alternation in the central benzene ring associated with the Mills-Nixon effect. *syn*-Tris(norborneno)benzenes among them possess a central benzene ring and three fused norbornene skeletons. Because of the unsymmetrical norbornene structure, they possess unsymmetrical concave and convex surfaces. The concave face forms a rigid cup-shaped structure that is suitable as a molecular pocket to encapsulate a guest molecule. Substituents with appropriate functional groups to interact with a guest molecule through hydrogen bonding or hydrophobic interaction, etc. can be incorporated on the rigid skeleton. Due to these superior properties, *syn*-tris(norborneno)benzenes have been extensively studied as cup-shaped C_3 symmetric host molecules in recent years. In addition, *syn*-tris(norbornadieno)benzenes have been applied to the syntheses of a C_3 symmetric bowl-shaped aromatic buckybowl, sumanene, and the derivatives as well. To explore the utilities, development for the efficient synthetic methodology has been widely studied. In general, tris(norborneno)benzenes have been synthesized through cyclotrimerization of norbornene derivatives. However, the tris(norborneno)benzenes are obtained as a mixture of *syn*- and *anti*-tris(norborneno)benzenes in the

reported examples, although only *syn*-tris(norborneno)benzenes are applicable as a cup-shaped host molecule. In this reason, development of a selective formation reaction of *syn*-tris(norborneno)benzenes is a very important issue in this research area.

Recently it has been found by the author's laboratory that a regioselective cyclotrimerization of enantiopure halonorbornene derivatives under palladium nanoclusters conditions affords only *syn*-tris(norborneno)benzene derivatives without formation of *anti*-tris(norborneno)benzenes. This novel palladium-catalyzed *syn*-selective cyclotrimerization reaction can be applicable to the syntheses of both chiral and achiral C_3 symmetric *syn*-tris(norborneno)benzenes by employing the corresponding enantiopure halonorbornenes, respectively. *syn*-Tris(oxonorborneno)benzene **1** and *syn*-tris(dioxonorborneno)benzene **2** were chosen as synthetic targets because of the feasibility to the following derivatization for cup-shaped molecules and precursors for buckybowls. To synthesize a variety of C_3 symmetric cup-shaped molecules, it is efficient to attach substituents on the appropriate rigid cup-shaped common platform. In this sense, the C_3 symmetric homochiral *syn*-tris(oxonorborneno)benzene **1** and achiral *syn*-tris(dioxonorborneno)benzene **2** with three or six carbonyl groups on the norbornene skeletons are appropriate common intermediates as a useful platform for the preparation of diverse C_3 symmetric chiral and achiral cup-shaped molecules.

Asymmetric synthesis of C_3 symmetric chiral (-)-(2*S*,4*S*,5*S*,8*S*,9*S*,12*S*)-*syn*-tris(oxonorborneno)benzene **1** started from enantiopure (1*S*,2*R*,4*S*,5*R*)-norbornan-2,5-diol. Enantiopure (1*S*,2*R*,4*S*,5*R*)-norbornan-2,5-diol was easily prepared from norbornadiene by catalytic asymmetric hydrosilylation and following Tamao oxidation. The preparation of the precursor for cyclotrimerization, (1*S*,4*S*)-5-iodonorborn-5-en-2-one, was thoroughly investigated and optimized to establish the short efficient route featuring a regioselective formation of enol phosphate and an iodonation reaction. (-)-*syn*-**1** was synthesized by the cyclotrimerization of (1*S*,4*S*)-5-iodonorborn-5-en-2-one in palladium nanoclusters conditions ($Pd(OAc)_2$, PPh_3, Bu_4NOAc, Na_2CO_3, MS 4Å, 1,4-dioxane). The addition of Bu_4NOAc was crucial for this cyclotrimerization reaction and the yield was improved by increasing the amount of Bu_4NOAc. Concerning to the mechanism, these results indicate

that the palladium nanoclusters generated in situ may play an important role. The appearance and the transmission electron microscopy measurement of the reaction mixtures revealed that the well-dispersed palladium nanoclusters in high concentration are stabilized by the excess amount of Bu_4NOAc, giving better yield of (-)-*syn*-**1**. The actual catalytic species is proposed to be monomeric palladium atoms leaching from the palladium nanoclusters.

Synthesis of C_{3v} symmetric achiral *syn*-tris(dihydroxynorborneno)benzene triacetonide **3**, a precursor of *syn*-tris(dioxonorborneno)benzene **2**, was achieved through the palladium-catalyzed cyclotrimerization as well. (1*R*,4*R*,5*R*,6*S*)-5,6-Dihydroxynorbornan-2-one acetonide was prepared from norbornadiene through dihydroxylation, protection by acetonide, asymmetric hydrosilylation, Tamao oxidation, and oxidation of hydroxy group. The following conversion of the carbonyl group to alkenyl iodide afforded the precursor for the cyclotrimerization, (1*R*,4*R*,5*R*,6*S*)-2-iodo-5,6-dihydroxynorborn-2-ene acetonide. Cyclotrimerization of (1*R*,4*R*,5*R*,6*S*)-2-iodo-5,6-dihydroxynorborn-2-ene acetonide in the palladium nanoclusters conditions affords *syn*-tris(dihydroxynorborneno)benzene triacetonide **3**. The following deprotection of acetonide and oxidation of hydroxy groups would give *syn*-tris(dioxonorborneno)benzene **2**. The wide applicability and feasibility of the developed palladium-catalyzed cyclotrimerization for chiral and achiral *syn*-tris(norborneno)benzenes were well demonstrated in these syntheses.

Thus-prepared C_3 symmetric chiral (-)-*syn*-tris(oxonorborneno)benzene **1** and C_{3v} symmetric achiral *syn*-tris(dioxonorborneno)benzene **2** can be a versatile common intermediate for synthesis of C_3 or C_{3v} symmetric buckybowls or cup-shaped molecules. The X-ray crystallographic structure of (-)-*syn*-**1** shows that the three carbonyl groups of (-)-*syn*-**1** are fixed in a helical form on the rigid cup-shaped norbornene skeleton. By introduction of substituents, (-)-*syn*-**1** can be derivatized into C_3 symmetric homochiral cup-shaped molecules with a helical arrangement of the substituents. The C_3 symmetric homochiral helical structure offers the utility for asymmetric chiral recognition of chiral molecules as well. Introduction of several types of substituents was demonstrated through palladium-catalyzed coupling reactions with the corresponding trisphosphate and tristrifluoromethanesulfonate of

(-)-*syn*-**1**. (-)-*syn*-Tris(methylnorbornadieno)benzene and (-)-*syn*-tris(phenylnorbornadieno)benzene were prepared by palladium-catalyzed Kumada-Tamao type coupling reactions from the trisphosphate and tristrifluoromethanesulfonate. (-)-*syn*-Tris(methylnorbornadieno)benzene was used as a synthetic intermediate for the synthesis of homochiral trimethylsumanene. *syn*-Tris(ethenylnorbornadieno)benzenes with Me_3Si, Ph, ferrocenyl groups were obtained by palladium-catalyzed Sonogashira coupling reactions from the tristrifluoromethanesulfonate. Cyano groups were also introduced by a palladium-catalyzed coupling reaction to afford *syn*-tris(cyanonorbornadieno)benzene. From these derivatizations, the wide applicability of *syn*-**1** for C_3 symmetric chiral molecules were well demonstrated.

As reported, *syn*-tris(norbornadieno)benzenes serves as a synthetic intermediate for sumanene and the derivatives. Toward a development of the versatile synthesis of substituted sumanenes, the reactivity of substituted benzonorbornene and *syn*-tris(norbornadieno)benzene derivatives for a ring-opening olefin metathesis reaction were investigated. Substituted benzonorbornenes and *syn*-tris(norbornadieno)benzenes with $B(OR)_2$, SiR_3, OSO_2CF_3, $OP(O)(OR)_2$, SPh, Ph groups were subjected to ring-opening olefin metathesis reactions with ruthenium catalysts, showing their less reactivity than non-substituted or methyl-substituted derivatives.

博士論文の審査結果の要旨

本論文は、C_3対称性を有するカップ型分子の合成研究について述べられており、以下の各章により構成されている。

第１章はC_3対称性を有する分子の機能や応用例について、さらにその中でもカップ型構造を有する*syn*-tris(norbornadieno)benzene骨格を有する化合物群についての現状、および合成面での問題点などについて述べられており、本論文の位置づけについての議論が行われている。

第２章では、カップ型分子合成における共通中間体となる*syn*-tris(oxonorborneno)benzene(*syn*-1)の高効率エナンチオマー合成の開発について述べている。(-)-*syn*-1の合成は、従来法では(1*S*, 2*R*, 4*S*, 5*R*)-norbornanediolより9段階、総収率14%で達成されていたが、多段階反応でかつ低効率であり、大量合成に不適な経路であったことから、合成経路の改良が必要であった。そこで、複数段階あるアルコール酸化の単段階化、保護／脱保護プロセスの省略化、またこれらを達成するために必要な、カルボニル化合物からヨウ化アルケンへの新しい変換反応の開発などを行っている。最後にパラジウムクラスター条件によるsyn選択的ハロアルケンの環化三量化反応を用いる事により、最終的に合成段階数を4段階に減らし、総収率20%となる新たな合成経路を確立している。この改良により比較的大量スケールでの*syn*-1のエナンチオマー調製が可能となった。

第３章では、様々なC_3対称ホモキラル*syn*-tris(norbornadieno)benzene化合物の合成について述べている。前章で合成法を確立した(-)-*syn*-1を出発とし、パラジウム触媒を用いたクロスカップリング反応に適用するために、対応するビニルトリフラート体を安定に単離する手法を開発し、さらに熊田-玉尾カップリング反応，園頭反応、シアノ化反応などの最適条件を見出すことによって、さまざまな官能基を有する化合物の合成法を確立するに至っている。

第４章では、２章で確立したC_3対称化合物合成法であるパラジウムクラスター条件による環化三量化反応を、C_{3v}対称カップ型化合物合成へ応用した例について述べている。*syn*-tris(dihydroxy- norborna)benzene diaceonide(*syn*-6)を標的分子として検討したところ、予期に反し、syn体だけではなく、anti体も副生成物として得られる事を見出している。この実験事実より、パラジウムクラスターを用いた環化三量化の反応機構において、これまで想定していなかったパラダサイクル化合物が中間体として生成している可能性について、議論をおこなっている。

第５章では、オレフィンメタセシス反応を用いた、カップ型化合物からボウル型化合物である置換スマネン誘導体への変換の試みについて述べている。これまで無置換、あるいはメチル基といった単純な置換基が導入されたカップ型化合物誘導体は、オレフィンメタセシス反応を適用する事により、スマネン誘導体へと変換できる事が報告されている。本手法をより一般的にするため、多岐にわたる置換基導入を可能とするヘテロ官能基を有する基質についての検討を行っている。はじめに銅錯体を用いた新たなホウ素化合物合成法の開発を行い、そのホウ素をはじめとする様々なヘテロ官能基を有する置換体のタンデムメタセシス反応を検討した結果、モデル化合物では反応が円滑に進行した系においても、

カップ型分子では反応が進行せず、カップ型分子の立体的影響がメタセシス触媒の反応性に大きく影響を及ぼしており、新たな触媒開発が必要であることを明らかにしている。

最後に６章では全体の総括を述べている。

以上、有機合成化学上未だに挑戦的分野であるカップ型化合物の構築法に関する研究について、膨大な実験量と的確な考察によって、当該分野の発展に非常に重要な知見を提供していることは高く評価できる。よって、本論文は博士（理学）の学位論文に値するものと認められる。