[1] J. F. Biard, S. Guyot, C. Roussakis, J. F. Verbist, J. Vercauteren, J. F. Weber, K. Boukef, *Tetrahedron Lett.* **1994**, *35*, 2691–2694.

[2] M. Jugé, N. Grimaud, J. F. Biard, M. P. Sauviat, M. Nabil, J. F. Verbist, J. Y. Petit, *Toxicon* **2001**, *39*, 1231–1237.

[3] a) K. M. Werner, J. M. de los Santos, S. M. Weinreb, *J. Org. Chem.* **1999**, *64*, 686–687; b) K. M. Werner, J. M. de los Santos, S. M. Weinreb, *J. Org. Chem.* **1999**, *64*, 4865–4873.

[4] a) W. H. Pearson, N. S. Barta, J. W. Kampf, *Tetrahedron Lett.* **1997**, *38*, 3369–3372; b) W. H. Pearson, Y. Ren, *J. Org. Chem.* **1999**, *64*, 688–689.

[5] a) H. Abe, S. Aoyagi, C. Kibayashi, *Tetrahedron Lett.* **2000**, *41*, 1205–1208; b) H. Abe, S. Aoyagi, C. Kibayashi, *J. Am. Chem. Soc.* **2000**, *122*, 4583–4592.

[6] P. Sun, C. Sun, S. M. Weinreb, *Org. Lett.* **2001**, *3*, 3507–3510.

[7] T. J. Greshock, R. L. Funk, *Org. Lett.* **2001**, *3*, 3511–3514.

[8] Many attempts at obtaining a crystalline derivative of natural lepadiformine (provided by Professor Biard as an oil) suitable for X-ray crystallography were unsuccessful (W. Pearson, personal communication).

[9] For reviews of the chemistry of N-acyliminium ions, see: a) W. N. Speckamp, H. Hiemstra, *Tetrahedron* **1985**, *41*, 4367–4416; b) H. Hiemstra, W. N. Speckamp in *The Alkaloids, Vol. 32* (Ed.: A. Brossi), Academic Press, San Diego, **1988**, pp. 271–339; c) H. Hiemstra, W. N. Speckamp in *Comprehensive Organic Synthesis, Vol. 2* (Eds.: B. M. Trost, I. Fleming, C. H. Heathcock), Pergamon, Oxford, **1991**, pp. 1047–1109; d) W. N. Speckamp, M. J. Moolenaar, *Tetrahedron* **2000**, *56*, 3817–3856.

[10] a) H. E. Schoemaker, W. N. Speckamp, *Tetrahedron Lett.* **1978**, 1515–1518; b) H. E. Schoemaker, W. N. Speckamp, *Tetrahedron Lett.* **1978**, 4841–4844; c) H. E. Schoemaker, W. N. Speckamp, *Tetrahedron* **1980**, 36, 951–958.

[11] D. A. Evans, E. W. Thomas, *Tetrahedron Lett.* **1979**, 411–414.

[12] a) T. Katoh, Y. Nagata, Y. Kobayashi, K. Arai, J. Minami, S. Terashima, *Tetrahedron Lett.* **1993**, *34*, 5743–5746; b) T. Katoh, Y. Nagata, Y. Kobayashi, K. Arai, J. Minami, S. Terashima, *Tetrahedron* **1994**, *50*, 6221–6238.

[13] For the organometallic ring-opening reaction of *N*-alkoxycarbonyl lactams, see: A. Giovannini, D. Savoia, A. Umani-Ronchi, *J. Org. Chem.* **1989**, *54*, 228–234.

[14] J. E. Baldwin, *J. Chem. Soc. Chem. Commun.* **1976**, 734–736.

[15] The diastereomeric mixture of the formate ester **7** gave a combined signal on a HPLC column. However, the alcohols **11a** and **11b** gave well-separated signals on the HPLC column, and thus the ratio was determined by HPLC integration.

[16] R. Noyori, I. Tomino, Y. Tanimoto, *J. Am. Chem. Soc.* **1979**, *101*, 3129–3131.

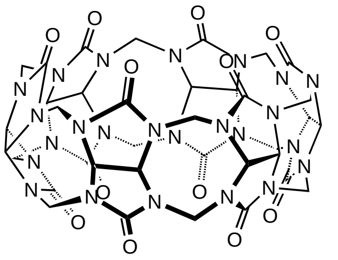
[17] For inhibition of hydrogenolysis of benzyl ether groups with Pd–C in the presence of ammonia and amines, see: H. Sajiki, *Tetrahedron Lett.* **1995**, *36*, 3465–3468.

"Molecular" Molecular Sieves: Lid-Free Decamethylcucurbit[5]uril Absorbs and Desorbs Gases Selectively[**]

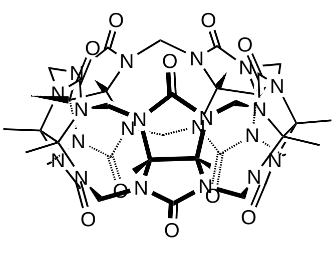
Yuji Miyahara,[*] Kazuaki Abe, and Takahiko Inazu

Several types of inorganic crystalline materials and organic polymers function as molecular sieves, the most common of which are numerous types of zeolites.[1] While some organic host molecules encapsulate small molecules in solution,[2] practical applications have never been attempted because of their inaccessibility. Here we report that the title compound, which can be readily synthesized from simple starting materials, shows potential for use as molecular sieves in the solid state by utilizing its molecular cavity.

In 1981 Mock and co-workers reported[3] that the compound which Behrend prepared from glycoluril and formalin in 1905[4] has a beautiful barrel-like macrocyclic structure composed of six glycoluril units; they named it cucurbituril (Cuc6). Since then extensive studies have been conducted on this unique host compound.[5]



Cuc6



MeCuc5

In 1982, in his PhD thesis on cucurbituril, Shih also described a compound, assumed to have a pentameric structure, which was obtained by heating dimethylglycoluril under reflux with formalin in dilute HCl;[6] Shih and Mock did not study the compound further because of its inactivity as a host molecule.[3b] In 1992, Stoddart and co-workers confirmed its basic structure by X-ray structure analysis of a crystal grown in dilute HNO_3 and named it decamethylcucurbit[5]uril (MeCuc5).[7] At the time when the paper by Stoddart and co-workers appeared we had already found that the product obtained under the reaction conditions contained two NH_4Cl

---

[*] Dr. Y. Miyahara, K. Abe, Prof. Emer. Dr. T. Inazu
Department of Chemistry, Faculty of Sciences
Kyushu University
6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581 (Japan)
Fax: (+81) 92-642-2607
E-mail: miyahscc@mbox.nc.kyushu-u.ac.jp

[**] This work was supported in part by a Grant-in-Aid for COE Research "Design and Control of Advanced Molecular Assembly Systems" from the Ministry of Education, Science, Sports, and Culture, Japan (#08CE2005). The authors also thank Prof. T. Shinmyozu of the Institute for Fundamental Organic Chemistry in Kyushu University for use of a Rigaku RAPID X-ray instrument.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

units resulting from decomposition of dimethylglycoluril,[8] but we were unable to disclose our results because of its curious properties as described below. Since then, several groups have published papers on properties of MeCuc5 without knowing the true composition of the product.[9–11] We have now unequivocally confirmed the structure of the product as the bis-NH_4Cl salt adduct by X-ray structural analysis on a crystal grown under a He atmosphere (Figure 1).[12,14]

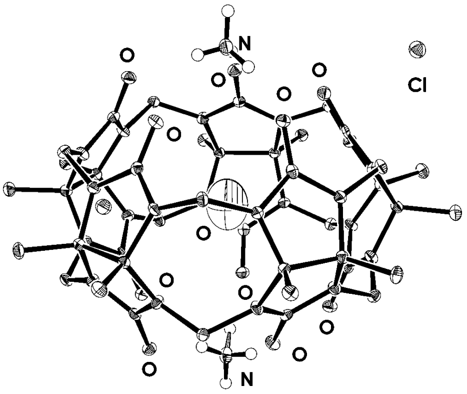
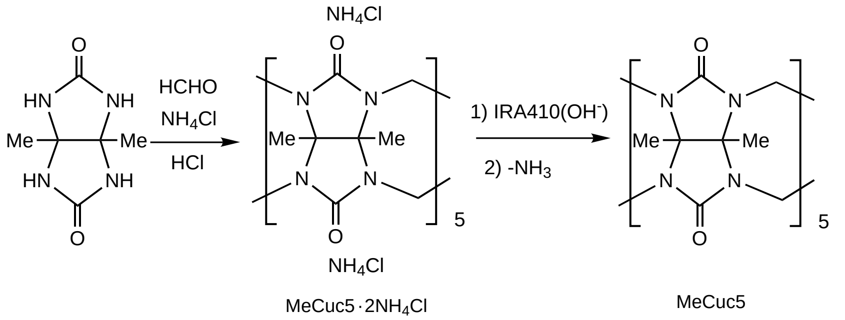


Figure 1. Crystal structure of $MeCuc5{\cdot}2NH_4Cl{\cdot}4H_2O$. The O atom of the cavity water molecule has an occupancy of 0.47. One of the external water molecules (not shown) has an occupancy of 0.28; with these values the structure converged to give $R_1 = 0.044$.

Once the product was confirmed to be the bis-NH_4Cl adduct, the yield could be raised from 14%[7] to 36% by addition of excess NH_4Cl to the reaction mixture (Scheme 1). The higher yield is caused by the low solubility of the NH_4Cl adduct in concentrated HCl solution, because little difference was noticed either when NH_4Cl was added before or after the reaction.

The NH_4Cl was removed quantitatively by converting it into the corresponding hydroxide using Amberlite IRA410 ion-exchange resin, OH^- form, and then heating in vacuo to expel NH_3 (Scheme 1).

While complexes of MeCuc5 with NH_4^+ or metal cations demonstrate gas encapsulation in solution,[11] they were inactive in the solid state. Once the lids (the NH_4^+ ions or metal cations) are removed, however, MeCuc5 behaves as a molecular sieve in the solid state.



Scheme 1. Synthesis of MeCuc5 from dimethylglycoluril.

The crystals of MeCuc5, large transparent plates formed from an aqueous solution, lost the water of crystallization slowly at room temperature and rapidly on heating at 80 °C to give a white powder (m.p. > 370 °C). The powder rapidly gained in weight on cooling in air and gave copious air bubbles on dissolving in water. We determined the absorption capacities of the powder for a variety of gases. After circulating a gas through a powder of MeCuc5 to cause gas absorption, the volume of the gas released on heating (110 °C) was measured by means of a gas burette. At the same time, the composition and identity of the released gas was analyzed by GC–MS.

Gases of small kinetic diameters such as He, Ne, and H_2 (260, 289, and 275 pm, respectively),[1] which can move freely in and out of the portals (320 pm in diameter), were not released in appreciable amounts on heating. On the other hand, Kr, Xe, and CH_4, with larger diameters (360, 396, and 380 pm, respectively)[1] were not absorbed significantly. The gases of intermediate sizes (N_2, O_2, Ar, N_2O, NO, CO, and CO_2) were absorbed and released repeatedly. The most efficient absorption–release process was observed with N_2O, with the capacity of MeCuc5 for this gas as high as 40 mL g^{-1}, followed by CO_2 (26 mL g^{-1}). The capacities for the others fall in the range of 11–16 mL g^{-1}. The absorption of acetylene is so strong that the capacity for this gas could not be measured.

These gases are encapsulated in the molecular cavity and not in the lattice space as in zeolites (see Figure 2). In contrast to the absorption behavior in the solid state, MeCuc5 in aqueous solution absorbed the whole range of gases studied. A gas was bubbled into the solution by use of a syringe pump and the progress of inclusion of the gas into the molecular cavity was monitored by the intensities of newly appearing NMR signals for the CH_2 protons and for the C=O, CH_2, and even the remote CH_3 carbon atoms. Of special interest are: 1) when paramagnetic O_2 was included, the NMR signals, in particular that of the CO carbon atoms, became very broad, 2) in the case of CH_4, new signals for the included CH_4 appeared at $\delta = -0.87$ ppm (^{1}H NMR spectrum) and at -4.81 ppm (^{13}C NMR spectrum), 3) although CO_2-saturated D_2O showed a barely discernible signal at $\delta = 127.41$ ppm in the ^{13}C NMR spectrum, CO_2 in the cavity gave rise to a readily recognizable signal at 127.12 ppm, and 4) acetylene, insoluble in water, gave rise to new signals at $\delta = 1.02$ ppm (^{1}H NMR spectrum) and at $\delta = 73.64$ ppm (^{13}C NMR spectrum; usually 1.80 and 71.9 ppm, respectively[13]).

Most of the gases were encapsulated by bubbling them through a solution of MeCuc5 at room temperature; crystals were deposited when the MeCuc5 was saturated with gas (4×10^{-3} mol L^{-1}). However, large gases (CH_4, Kr, and Xe) required heating at 80 °C to cause them to be included. Because concomitant release of the included gas occurs at higher temperatures, the optimal conditions were difficult to find. In monitoring the extent of encapsulation by comparing the intensities of the signals caused by the carbonyl C atoms in the ^{13}C NMR spectrum, we

0044-8249/02/4116-3021 $ 20.00+.50/0

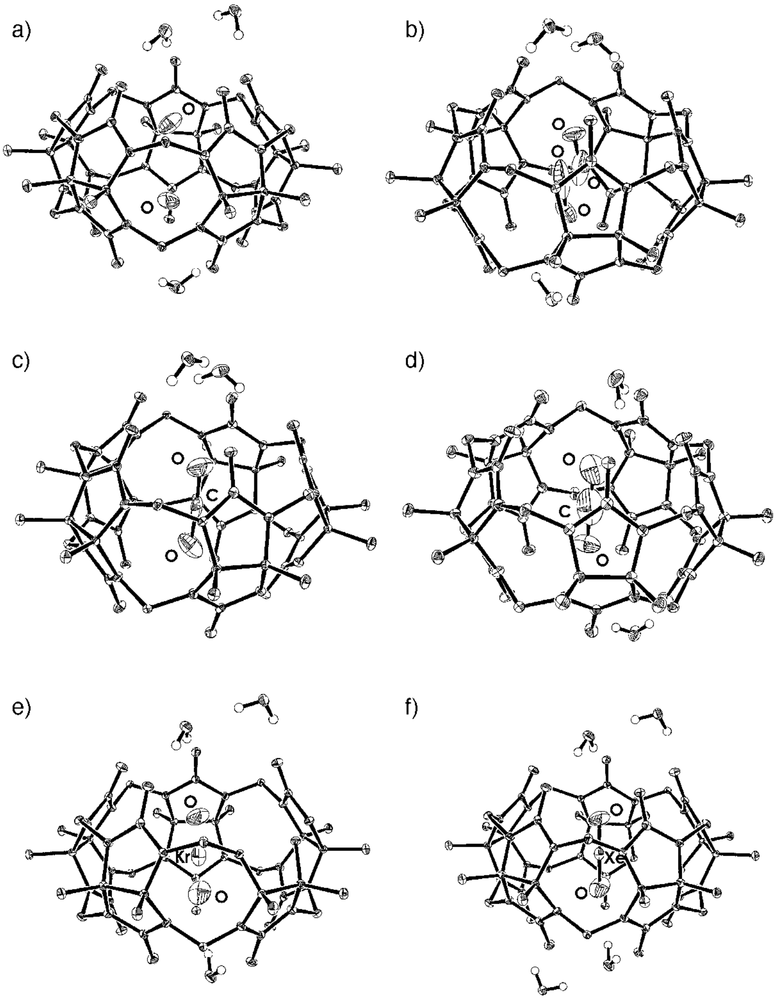


Figure 2. Crystal structures of gas-inclusion complexes of MeCuc5. The external water molecules (six in total, in all cases) are not shown except for those which are hydrogen bonded to carbonyl groups and not as the lids (occupancies of atoms in the cavity, convergence index): a) He complex (He not treated, O = 0.83, $R_1 = 0.047$), b) O_2 complex (O = 0.34 and $O_{central} = 0.12$, $R_1 = 0.044$, c) CO_2 complex (C = O = 0.76, $R_1 = 0.040$), d) CH_4 complex (C = 0.49, O = 0.64, $R_1 = 0.049$), e) Kr complex (Kr = −0.42, O = 0.47, $R_1 = 0.045$), f) Xe complex (Xe = 0.52, O = 0.34, $R_1 = 0.033$).

observed fluctuation of the signal positions of the gas-included species beyond instrumental error.

A clue to understanding this puzzling behavior in the ^{13}C NMR spectra came from X-ray crystal structure determination (Figure 2).[14] Although the diffraction data were collected at −180 °C on crystals freshly formed in gas-saturated solutions, the occupancies of the gases were considerably less than unity in all cases. There are also some water molecules inside the cavity, near the C=O carbon atoms. The cavity is large enough to accommodate both a Xe atom and water molecules. The fluctuation of signal positions in the ^{13}C NMR spectra appears to indicate that the amount of water included depends upon the bubbling conditions.

As expected, gas absorption in the solid state was also strongly influenced by the residual included water molecules. While the water molecules in the lattice and those at the portals are readily removed by heating in air, those in the cavity stay even after prolonged heating in vacuo. For a large, weakly interacting gas, removal of the residual water is a rather high hurdle to clear. For example, when Ar was absorbed into a MeCuc5 powder conditioned to the maximum capacity for N_2 (16 mL g^{-1}), only 4 mL g^{-1} was initially absorbed. After several absorption–desorption cycles, however, the capacity reached 15 mL g^{-1}. On the other hand, strongly interacting gases such as N_2O readily expelled the internal water. Then, after a rapid release of the gas on heating, a gradual decrease in volume of the gas was observed by absorption of the water vapor in the gas into the water in the gas burette.

Therefore, while the MeCuc5 powder shows selective gas inclusion, even Xe atoms and CH_4 molecules can be encapsulated in aqueous solution. In view of the presence of water molecules or metal ions as lids, as well as the cavity water molecules, this is remarkable. Because enlargement of the portals by heating is unlikely, when the rigidity of the cage is considered, the gas molecules may be pushed into the cavity by colliding water molecules.

Preliminary studies on MeCuc5 demonstrate its potential in practical applications. For example, a rather high level of CO_2 in air (5 %) was decreased to 0.01 % (0.035 % in fresh air) in 1 h by circulating the air through a powder of MeCuc5. While MeCuc5 has a lower capacity and activity than 5 Å molecular sieves (MS), its lower regeneration temperature (110 °C as compared to 350 °C) and low affinity for water (prior drying necessary for 5 Å MS) may be of great advantage in controlling the amounts of CO_2 in air. MeCuc5 may also be used to decrease the amount of NOx in air, because it has a high absorption capacity for N_2O and NO, and can be quantitatively regenerated by recrystallization.

Received: March 28, 2002
Revised: May 31, 2002 [Z19000]

---

[1] D. W. Breck, *Zeolite Molecular Sieves*, Wiley-Interscience, New York, **1974**.

[2] For example, N. Brenda, R. M. Grotzfeld, C. Valdés, J. Rebek, Jr., *J. Am. Chem. Soc.* **1995**, *117*, 85–88.

[3] a) W. A. Freeman, W. L. Mock, N.-Y. Shih, *J. Am. Chem. Soc.* **1981**, *103*, 7367–7368; b) W. L. Mock, *Top. Curr. Chem.* **1995**, *175*, 1–24.

[4] R. Behrend, E. Meyer, F. Rusche, *Justus Liebigs Ann. Chem.* **1905**, *339*, 1–37.

[5] K. Kim, *Chem. Soc. Rev.* **2002**, *31*, 96–107 and references therein.

[6] N.-Y. Shih, Ph.D. thesis, University of Chicago, **1981** [*Diss. Abst. Int.* **1982-B**, *42*, 4071].

[7] A. Flinn, G. C. Hough, J. F. Stoddart, D. J. Williams, *Angew. Chem.* **1992**, *104*, 1550–1552; *Angew. Chem. Int. Ed. Engl.* **1992**, *31*, 1475–1477.

[8] In a recent paper, it is noted that a considerable amount of NH_4^+ salts is present in Cuc6 synthesized under harsh conditions. A. Day, A. P. Arnold, R. J. Blanch, B. Snushall, *J. Org. Chem.* **2001**, *66*, 8094–8100.

[9] X. X. Zhang, K. E. Krakowiak, G. Xue, J. S. Bradshaw, R. M. Izatt, *Ind. Eng. Chem. Res.* **2000**, *39*, 3516–3520.

[10] K. Jansen, H.-J. Buschmann, A. Wego, D. Döpp, C. Mayer, H.-J. Drexler, H.-J. Holdt, E. Schollmeyer, *J. Inclusion Phenom. Macrocyclic Chem.* **2001**, *39*, 357–363.

[11] It has been reported that N_2 and O_2, as well as small organic molecules, can be encapsulated in the NH_4^+ salt of MeCuc5 in the gas phase. The authors added NH_4OAc intentionally without recognizing the presence of NH_4Cl in their samples. K. A. Kellersberger, J. D. Anderson, S. M. Ward, K. E. Krakowiak, D. V. Dearden, *J. Am. Chem. Soc.* **2001**, *123*, 11316–11317.

[12] The considerable discrepancies between the elemental analytical data for the reaction product and the expected formula have been noted. For example, H. J. Buschmann, E. Cleve, K. Jansen, E. Schollmeyer, *Anal. Chim. Acta.* **2001**, *437*, 157–163.a) The NH_4Cl salt of MeCuc5 from the reaction mixture gave an elemental analysis of C 41.99, H 5.75, N 26.63, which agrees well with the formula $C_{40}H_{50}N_{20}{\cdot}2\,NH_4Cl{\cdot}4\,H_2O$ (FW = 1150.00, calcd C 41.78, H 5.78, N 26.80). Recently, the parent Cuc5[a] and its tetramethylene derivative[b] have been synthesized in salt-free forms after complicated workup procedures: J. Kim, I.-S. Jung, S.-Y. Kim, E. Lee, J.-K. Kang, S. Sakamoto, K. Yamaguchi, K. Kim, *J. Am. Chem. Soc.* **2000**, *122*, 540–541; b) J. Zhao, H.-J. Kim, J. Oh, S.-Y. Kim, J. W. Lee, S. Sakamoto, K. Yamaguchi, K. Kim, *Angew. Chem.* **2001**, *113*, 4365–4369; *Angew. Chem. Int. Ed.* **2001**, *40*, 4233–4235.

[13] E. Pretsch, W. Simon, J. Seibl, T. Clerc, *Table of Spectral Data for Structure Determination of Organic Compounds*, Springer, Berlin, **1989**.

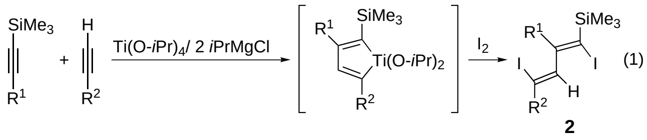
[14] See Supporting Information for the details of the X-ray analyses. CCDC-182123–182129 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

Efficient and General Synthetic Approach to Pentasubstituted Conjugated Dienes Using Site-Selective Coupling of Cuprates with 1,4-Diiodo-1,3-alkadienes as the Key Reaction**

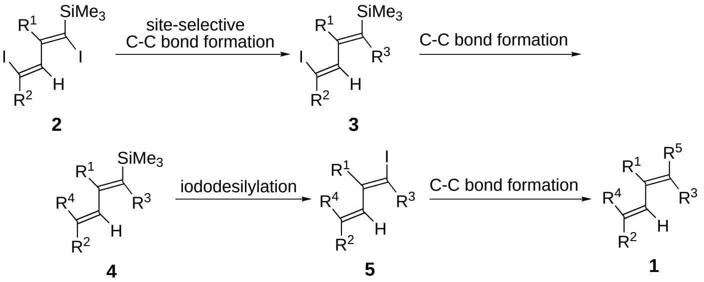
Ryota Nakajima, Christophe Delas, Yuuki Takayama, and Fumie Sato*

Selective preparation of polysubstituted conjugated dienes is an important transformation, because such dienes are useful intermediates and/or important structural constituents in natural product chemistry and materials science. When the regio- and stereoselective alignment of the substituents on the diene skeleton are considered, their synthesis is not necessarily an easy process, and the synthetic difficulty becomes more and more marked with an increase in the number of substituents. We report herein a general method for preparing 1,1,2,4,4-pentasubstituted 1,3-butadienes **1**.

Recently, we developed a highly efficient method for synthesizing titanacyclopentadienes by regioselective coupling of 1-trimethylsilyl-1-alkynes and terminal acetylenes, mediated by a divalent titanium reagent Ti(O-*i*Pr)$_4$/2 *i*PrMgCl.[1,2] Treatment of the titanacyclopentadienes thus generated in situ with iodine furnishes 1,4-diiodo-1,3-alkadienes **2** in high yields [Eq. (1)].[1,3]



With an efficient and practical entry to **2** in hand, we planned the preparation of **1** from **2**, according to the reaction pathway shown in Scheme 1. If the reaction proceeded as we expected, quite a number of dienes **1** with a variety of substituents could be prepared. For the success of our synthetic plan, the following two transformations hold the key, as other transformations were expected to occur readily by using established reactions. One transformation is the conversion of **2** into the monoiodides **3** by the site-selective carbon–carbon bond formation at one of the two vinyliodo moieties in **2**. The other transformation is the stereoselective conversion of **4** into **5** because, although there are many precedents for converting vinylsilanes into isomerically pure vinyl iodides, there are few reports for the conversion of dienylsilanes into dienyl iodides.



Scheme 1. Synthetic plan of 1,1,2,4,4-pentasubstituted 1,3-butadienes **1** from 1,4-diiodo-1,3-alkadienes **2**.

For the transformation of **2** into **3**, we anticipated that the reaction with organocuprates might occur selectively at the α-silyl vinyliodide moiety, because it was reported that the presence of a silyl group in the α position of vinyl bromides causes acceleration of their coupling reaction with organocuprates.[4] The reaction of **2a**, prepared from 1-trimethylsilyl-1-octyne and 1-octyne, with three equivalents of Me_2CuLi in diethyl ether at −50 °C for 3 h provided monomethylated product **3aa** exclusively in 90 % yield, as shown in Equation (2) (for R′ see Table 1).

It is noteworthy that no possible monomethylated and/or dimethylated product was produced in more than 1 % yield,

---

[*] Prof. Dr. F. Sato, R. Nakajima, Dr. C. Delas, Dr. Y. Takayama
Department of Biomolecular Engineering
Tokyo Institute of Technology
4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8501 (Japan)
Fax: (+81) 45-924-5826
E-mail: fsato@bio.titech.ac.jp

[**] C.D. would like to thank the Japan Society for the Promotion of Science (JSPS) for financial support.