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Rational synthesis of benzimidazole[3]arenes by Cu^{II}-catalyzed post-macrocyclization transformation

A new series of calix[n]arene analogues, benzimidazole[3]arenes, was rationally synthesized by Cu^{II}-catalyzed post-macrocyclization transformation of a tris(o-phenylenediamine) macrocycle, and fully characterized by NMR, MS, and single-crystal X-ray diffraction analyses. The resulting syn- and anti-benzimidazole[3]arenes have a bowl-shaped and a warped structure, respectively, in their crystalline states, and both display a dynamic inversion behavior in solution. This modification resulted in strong fluorescence due to the generated benzimidazole moieties. The mechanistic study of the post-macrocyclization transformation was also conducted to reveal the formation of triimine intermediates.

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Introduction

Since the discovery of calix[4]arene and its analogues such as cyclotriveratrylene, pyrogallol[*n*]arenes, and resorcin[*n*]arenes,¹ macrocyclic compounds with several aromatic rings circularly arranged through methylene linkers have attracted much attention in both fundamental and applied chemistry. Significant efforts have been devoted to the synthesis of their new series including pillar[*n*]arenes,^{2*a*} pillar[*n*]quinones,^{2*b*} asar[*n*] arenes,^{2*c*} biphen[*n*]arenes,^{2*a*} oxatub[*n*]anrenes,^{2*e*} and others.^{2*f*-*i*} These macrocycles have a well-defined hydrophobic cavity enclosed by a relatively flexible ring framework due to the presence of methylene linkers. It is also worth noting that some macrocycles are chiral when they have a circumferentially and axially anisotropic three-dimensional structure.³ Their structure and function depend heavily on the type and sequence feature of the building unit of the macrocycles.

N-Heterocycles are typical building blocks of macrocycles, as N-heterocycle-based calix[*n*]arene analogues such as calix[*n*] pyrroles,^{4a} calix[*n*]imidazolium,^{4b} calix[*n*]pyridines or pyridine [*n*]arenes,^{4c-e} ExBox,^{4f} Texas-sized box,^{4g} and others^{4h-j} exhibit strong fluorescence and ion recognition ability through non-

Rational synthesis of benzimidazole[3]arenes by Cu^{II}-catalyzed post-macrocyclization transformation[†]‡

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A new series of calix[*n*]arene analogues, benzimidazole[3]arenes, was rationally synthesized by Cu^{II}catalyzed post-macrocyclization transformation of a tris(*o*-phenylenediamine) macrocycle, and fully characterized by NMR, MS, and single-crystal X-ray diffraction (XRD) analyses. The resulting *syn*- and *anti*-benzimidazole[3]arenes have a bowl-shaped and a warped structure, respectively, in their crystalline states, and both display a dynamic inversion behavior in solution. This modification resulted in strong fluorescence due to the generated benzimidazole moieties. The mechanistic study of the postmacrocyclization transformation demonstrated that the formation of both benzimidazole[3]arenes was catalyzed, *via* triimine intermediates, by Cu^{II} ions in air through oxidation and cyclization of the tris(*o*phenylenediamine) macrocycle.

> covalent interactions. However, as far as we know, benzimidazole-based calix[n]arenes^{5,6} have not been reported so far due to the lack of rational synthetic strategies to circularly arrange benzimidazole moieties in macrocyclic skeletons, despite the fact that benzimidazole is known to show strong fluorescence, bioactivity, metal binding and ion recognition abilities.⁷ Here we report the Cu^{II}-catalyzed facile synthesis, structures, and properties of two isomeric *syn-* and *anti-*benzimidazole[3]arenes (*syn-*2 and *anti-*3) with C_3 - and C_1 -symmetry, respectively, based on the different permutations of three benzimidazole units. The molecular structures and their dynamic inversion behaviors were evaluated by single-crystal Xray diffraction (XRD) and variable-temperature (VT) NMR analyses. We also found that three benzimidazole moieties in the macrocycle led to strong fluorescence.

> A key step in the synthesis of syn-2 and anti-3 is postmacrocyclization transformation of macrocyclic tris(o-phenylenediamine) (1), which can be easily prepared from o-phenylenediamine and terephthalaldehyde in two steps of macrocyclization and hydrogenation.8a As in our previous report,⁸ macrocycle 1 reacted with Pd^{II} ions to form a trinuclear Pd^{II}-macrocycle. However, we found that a reaction with Cu^{II} ions produced not trinuclear Cu^{II}-macrocycles of 1, but two isomeric syn- and anti-benzimidazole[3]arenes (syn-2 and anti-3) through a Cu^{II} -catalyzed transformation reaction (Fig. 1). In general, calix[n]arene and its analogues can be synthesized by simple macrocyclization of each building block.1,2 However, it is not always suitable to apply this direct macrocyclization to an unsymmetrical arrangement of building blocks for lowersymmetry macrocycles. In contrast, post-macrocyclization transformation⁹ is a powerful tool to prepare lower-symmetry macrocycles as proven by the intensive synthetic studies of



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Department of Chemistry, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. E-mail: shionoya@chem.s.u-tokyo.ac.jp † Dedicated to the late Mr Akihiro Mizoguchi for his contribution to the development of this study.

[‡] Electronic supplementary information (ESI) available: Experimental details and characterization data. CCDC 1585798–1585799 and 1585801. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c8sc03086c

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Fig. 1 Schematic representation of the facile synthesis of benzimidazole[3]arenes through post-macrocyclization transformation.

diverse porphyrinoids, because a macrocyclic skeleton is asymmetrically folded by the macrocyclic transformation reaction.10

Results and discussion

Macrocycle 1 was reacted with an equimolar amount of $Cu(OAc)_2 \cdot H_2O$ in a mixed solvent of $CHCl_3/CH_3CN = 1/2$ (v/v) at 55 °C in air ([1] = 5.0 mM). The reaction mixture became brown after 15 min, and then turned green after one day. The ¹H NMR spectrum of the greenish reaction mixture showed broadened proton signals, indicating that Cu^{II} ions interacted with products. The ¹H NMR analysis of the crude product after removing Cu^{II} ions by a liquid separating operation indicated that 1 was completely consumed to form the target compounds, syn- and anti-benzimidazole[3]arenes (syn-2 and anti-3), in the molar ratio of ca. 1:10 (Fig. 2a and b). The mixture was separated by silica gel chromatography and then purified by recrystallization to afford syn-2 and anti-3 in 3.3% and 47% isolated yields, respectively (Fig. 2c and d). This selectivity is discussed later. The products were fully characterized by high-resolution electrospray ionization time-of-flight mass spectrometry (ESI-TOF MS) $(m/z = 619.2593 \text{ and } 619.2593 \text{ for } [syn-2 + H]^+ \text{ and } [anti-3]$

+ H]⁺, respectively), single-crystal X-ray diffraction (XRD), and NMR analyses as shown below.

The molecular structures of both compounds syn-2 and anti-3 have been determined by single-crystal XRD analyses. It was confirmed that both compounds are 21-membered macrocycles composed of three benzimidazole units. In the molecular structure of syn-2, three 2-phenylbenzimidazole moieties are symmetrically arranged in the same direction to form a C_3 symmetry structure in which all three methylene linkers are oriented toward the convex face of a folded bowl-shaped conformation (Fig. 3a). On the other hand, two benzimidazole moieties of anti-3 are directly connected to a p-phenylene moiety to form a 1,4-bis(benzimidazol-2-yl)benzene moiety with an extended conjugation system, which gives a warped C1symmetry structure (Fig. 3b) in combination with the rest of the structure containing a 2-phenylbenzimidazole and a benzene moiety. It is worth noting here that both structures are chiral, as evident from the fact that both (P)- and (M)-stereoisomers coexist in the ratio of 1 to 1 in each crystal of syn-2 and anti-3.11 For instance, two molecules of syn-2 formed a homochiral dimer sandwiching one CH₂Cl₂ molecule between two small cavities of syn-2, and the other enantiomeric dimers were lined up in parallel (Fig. 3c). For anti-3, (P)- or (M)-stereoisomers of anti-3 were stacked to form homochiral columns. The interstitial spaces formed between enantiomerically paired columns were occupied by CHCl₃ molecules (Fig. 3d).

We next evaluated the solution-state structures of syn-2 and anti-3 in CDCl₃ based on ¹H NMR spectroscopy (Fig. 2c and d). First, the signals of some *p*-phenylene protons next to methylene groups were observed in the range from 6.5 to 6.8 ppm, significantly upfield shifted from typical *p*-phenylene signals. These characteristic p-phenylene signals suggest that the folded conformations of syn-2 and anti-3 observed in the crystal state, in which the *p*-phenylene protons face benzimidazole moieties, are maintained also in CDCl₃. On the other hand, the ¹H NMR spectra of syn-2 and anti-3 in CDCl₃ indicate the formation of



Fig. 2 Reaction conditions of the post-macrocyclization transformation and ¹H NMR spectra (500 MHz, 300 K, CDCl₃ for (a) and (b) or CDCl₃/ $CD_3OD = 20/1$ for (c) and (d)) of (a) 1, (b) crude product, (c) syn-2 and (d) anti-3.



Fig. 3 Molecular structures of (a) *syn*-2 and (b) *anti*-3 (top and side views), and crystal packing structures of (c) *syn*-2 and (d) *anti*-3. In (c) and (d), macrocycles and solvents are represented by stick and space-filling models, respectively, and colors for the carbon atoms of (*P*)- and (*M*)-stereoisomers are yellow-green and pale-red, respectively.

 C_{3h} - and C_s -symmetry structures at 300 K, respectively. This higher symmetry in solution suggests that the rate of racemization of *syn*-2 and *anti*-3 between (*P*)- and (*M*)-isomers is significantly faster than the NMR timescale in CDCl₃.

The dynamic behaviors of *syn-***2** and *anti-***3** in solution were then examined by VT 1 H NMR measurements in CD₂Cl₂. When

the temperature of syn-2 in CD₂Cl₂ was lowered to 203 K, the methylene signals around 5.65 ppm split into geminally coupled two doublet signals. In contrast, the other aromatic signals did not split except for the appearance of small broad signals probably due to the presence of a minor conformational isomer at 203 K (Fig. 4). The desymmetrization of only the methylene protons indicates that the temperature-dependent dynamic behavior is mainly derived from the racemization of (P)- and (M)-stereoisomers by the bowl-to-bowl inversion that is slower than the NMR timescale at 203 K. To estimate the coalescence temperature (T_c) and inversion barrier ΔG_c^{\ddagger} of syn-2 at $T_{\rm c}$, the Eyring plot was drawn based on the dynamic ¹H NMR line-shape simulation (Fig. S24^{\ddagger}). As a result, the T_c and $\Delta G_{
m c}^{\ddagger}$ values were estimated to be 231 K and 11.2 \pm 0.6 kcal mol⁻¹, respectively, and ΔH^{\ddagger} and ΔS^{\ddagger} were also calculated to be 17.8 \pm 0.3 kcal mol⁻¹ and 28.5 \pm 1.4 cal mol⁻¹ K⁻¹, respectively. Macrocycle anti-3 also exhibited similar behaviors, and VT ¹H NMR spectra were similarly analyzed to estimate T_{c} , $\Delta G_{\rm c}^{\dagger}$, ΔH^{\dagger} , and ΔS^{\dagger} , which were found to be 230 K, 11.0 \pm 0.4 kcal mol $^{-1}$, 13.8 \pm 0.2 kcal mol $^{-1}$, and 12.3 \pm 0.9 cal mol $^{-1}$ K⁻¹, respectively (Fig. S25 and S26[‡]). The resultant inversion barriers of syn-2 (11.2 kcal mol⁻¹) and anti-3 (11.0 kcal mol⁻¹) were found to be almost the same, and it should be noted that the inversion barriers are comparable with that of corannulene $(11.5 \text{ kcal mol}^{-1})$,¹² which is a representative bowl-shaped hydrocarbon.



Fig. 4 Schematic representation of the bowl-to-bowl inversion of syn-2, and simulated (blue lines, 5.5–5.8 ppm) and obtained (black lines, 5.0–8.0 ppm) ¹H NMR spectra (500 MHz, CD₂Cl₂) of syn-2 at (a) 243, (b) 233, (c) 223, (d) 213, and (e) 203 K.



Fig. 5 UV-vis absorption and normalized fluorescence spectra (CHCl₃, 298 K) of syn-2 (1.5 μ M, λ_{ex} = 300 nm) and anti-3 (3.0 μ M, λ_{ex} = 310 nm).

The optical properties of syn-2 and anti-3 were examined by UV-vis absorption and fluorescence spectroscopies (Fig. 5). The UV-vis spectra of syn-2 and anti-3 in CDCl₃ at 298 K showed absorption bands at $\lambda_{max} = 296$ nm and 312 nm, respectively. The red-shifted absorption of anti-3 can be best explained by the presence of the 1,4-bis(benzimidazol-2-yl)benzene moiety with an extended conjugation system. This structural feature of anti-**3** also gave fluorescence at longer wavelength ($\lambda_{max} = 390 \text{ nm}$) than that of syn-2 ($\lambda_{max} = 339, 354, 369 \text{ nm}$) in CHCl₃ at 293 K. Quantum yields of syn-2 and anti-3 in degassed CHCl₃ were determined to be 0.60 and 0.71, respectively, which are to the quantum yield comparable of 1-methyl-2phenylbenzimidazole ($\phi_{\rm FL} = 0.70$), the structural unit of syn-2 and anti-3.13

As benzimidazole[3] arenes possess three imidazole nitrogen atoms on the periphery of the macrocyclic skeletons, these nitrogen atoms were expected for further functionalization (Fig. 6a). For instance, *anti-3* underwent tri-methylation by reaction with CH₃I, and the resulting tri-methylated product was found to be soluble in water, maintaining similar fluorescence properties (Fig. S27–S29[‡]). In addition, *anti-3* was fully protonated by mixing with *p*-toluenesulfonic acid monohydrate as confirmed by single-crystal XRD analysis. In the resultant crystal structure of $[H_3(anti-3)(p-TsO)_3] \cdot (H_2O)_3$, all peripheral nitrogen atoms were protonated, interacting with *p*-TsO⁻ anions (Fig. 6b). The *p*-TsO⁻ anions further formed a hydrogen bonding network with water molecules along the *b*-axis. As a result, the crystal adopted a layer-by-layer structure composed of the macrocycle layers of *anti-3* and the hydrated layers of *p*-TsO⁻ anions (Fig. S32⁺₄).

Finally, to discuss the reaction mechanism of this postmacrocyclization transformation, a diluted CD₃CN solution of 1 (0.34 mM) and $Cu(OAc)_2 \cdot H_2O$ (1.1 mM) was mixed at room temperature to monitor the reaction by ¹H NMR measurements. We found that a yellow clear solution obtained after 20 min contained two different intermediates. Based on the chemical shifts, integral ratios, ¹H-¹H COSY, and NOESY correlations (Fig. S33-S35[‡]), the intermediates were most likely to be macrocyclic triimine compounds 2' and 3' (Fig. 7). For instance, singlet signals around 8.7-8.8 ppm and broad signals around 5.3-5.6 ppm can be assigned to imine and amine protons, respectively. The remaining methylene protons were also observed around 4.3-4.6 ppm. The signal patterns suggested that the main species was C_s -symmetrical macrocyclic triimine 3', and the minor one appeared to be C_{3h} -symmetrical triimine 2'. The molar ratio of 2' to 3' was *ca.* 1 : 10, and further reaction of this solution for 8 days resulted in the formation of syn-2 and anti-3 in the molar ratio of ca. 1: 10, which was almost the same as that under the synthetic conditions at 55 °C (Fig. 2b). This result indicated that the final ratio of syn-2 to anti-3 was determined at the first partial oxidation of 1 into triimine 2' and 3' (Fig. 7). The formation of the triimine intermediates was also confirmed by the ESI-TOF mass spectrometry measurement of a similarly prepared CH₃CN reaction solution after 20 min (m/z) $= 647.26 \text{ for } [1-6H + Na]^+) \text{ (Fig. S36-S38$;)}.$

The molar ratio of the formation of 2' and 3' (*ca.* 1 : 10) was more biased than the statistical ratio of 1 : 3. The more biased formation of 3' is possibly attributed to the superiority in the kinetic and/or thermodynamic stability due to its extended conjugated structure. In the next reaction, the resultant imine carbons are subject to cyclization by the attack of the neighboring amino groups, followed by oxidative aromatization to afford benzimidazole moieties (Fig. 7). On the other hand, predominant formation of *syn*-2 was not observed by changing the amount of Cu(OAc)₂·H₂O, reaction temperature, or solvent ratio as far as we examined.

In a plausible reaction mechanism shown in Fig. 7, $Cu(OAc)_2 \cdot H_2O$ serves as an oxidant and a Lewis acid to facilitate several steps including oxidation to imine, cyclization, and oxidative aromatization. Because the conversion from 1 to *syn-2* or *anti-3* is a twelve-electron oxidation reaction, an equimolar



Fig. 6 (a) Chemical structures of tri-methylated and tri-protonated *anti*-**3**. (b) Crystal structure of $[H_3(anti-3)(p-T_sO)_3] \cdot (H_2O)_3$. Disordered water molecules are omitted for clarity. The carbon atoms of *p*-T_sO are shown in pink.



Fig. 7 Plausible reaction mechanism of the formation of syn-2 and anti-3 via intermediates 2' and 3'.

amount of $Cu(OAC)_2 \cdot H_2O$ should work as the catalyst in air. Moreover, we found that this reaction proceeded at higher temperature without $Cu(OAC)_2 \cdot H_2O$. When a solution of **1** in CD_3CN was heated at 180 °C under microwave irradiation, *syn*-2 and *anti*-3 were formed after 105 min with some impurities (Fig. S39‡). Another oxidant, 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ) (12 equiv.), also converted **1** into *syn*-2 and *anti*-**3**, but a substantial amount of byproducts was also formed (Fig. S40‡). These results clearly indicate that O_2 in air is the oxidant and that $Cu(OAC)_2 \cdot H_2O$ catalyzes both the oxidation and cyclization steps to cleanly promote this reaction.

Conclusions

In summary, two isomeric benzimidazole[3]arenes syn-2 and *anti*-3 have been rationally synthesized as a new series of calix[*n*] arene analogues by the Cu^{II}-catalyzed post-macrocyclization transformation reaction of 1 via two triimine intermediates 2' and 3'. The C_3 - and C_1 -symmetrical macrocyclic structures and their dynamic inversion behavior in solution were revealed by single-crystal XRD and VT NMR analyses, respectively. The three benzimidazole moieties also led to strong fluorescence and allowed chemical modification at the macrocyclic periphery. As another potential use of benzimidazole[3]arenes, study on metal complexation is in progress, and the resultant supramolecular structures will be reported elsewhere as separate studies. The present rational synthetic method and the potential applications are thus expected to make benzimidazole[3]arenes versatile as with calix[n]arenes and pillar[n]arenes that are being utilized around the world.

Conflicts of interest

There are no conflicts to declare.

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