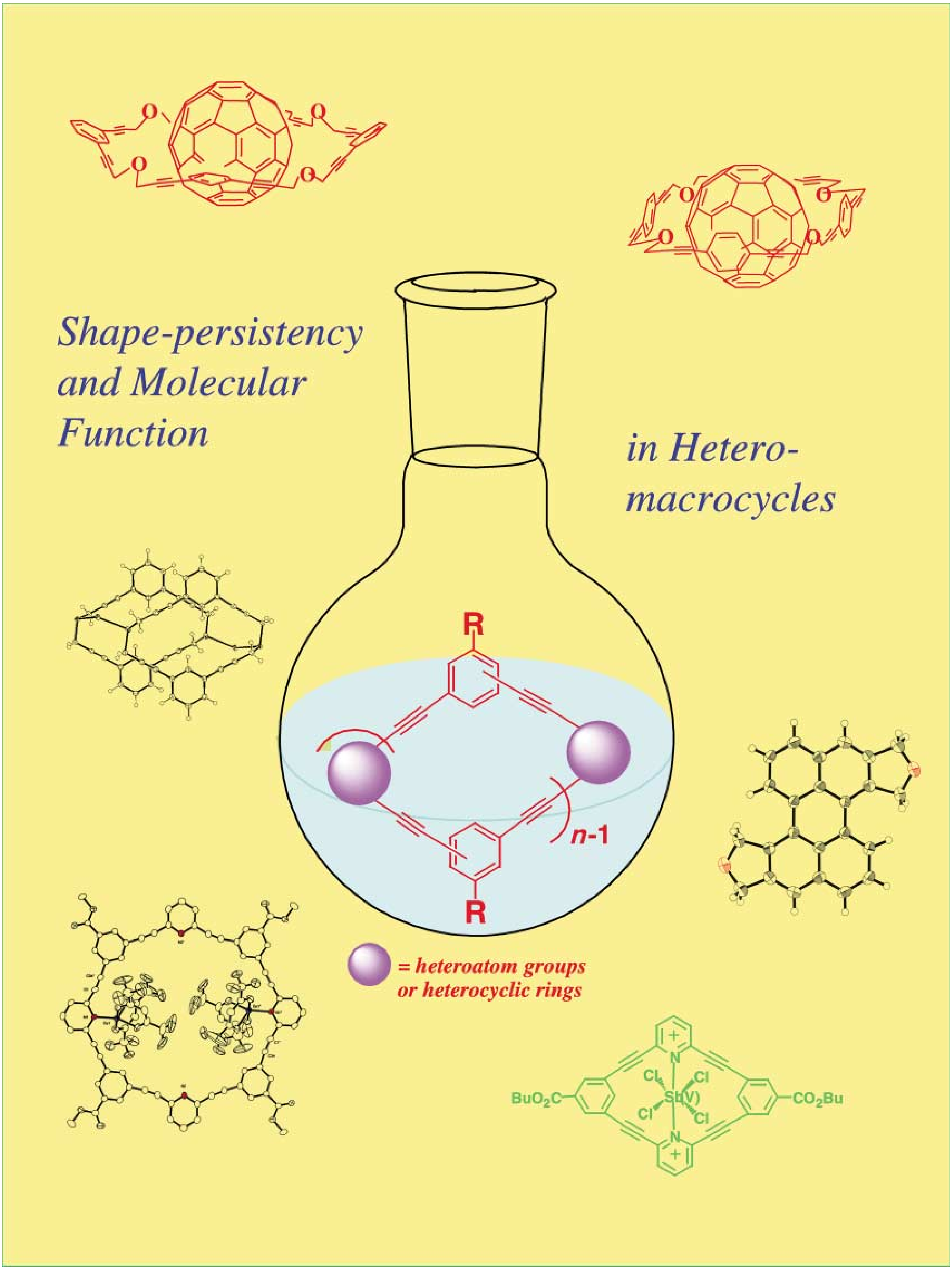

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Shape-persistency and Molecular Function in Heteromacrocycles: Creation of Heteroarenecyclynes and Arene – Azaarenecyclynes

Yoshihiro Yamaguchi* and Zen-ichi Yoshida*[a]

Abstract: On the basis of our concept that the introduction of heteroatoms and shape-persistency into the π-macrocycles should bring forth striking functions or properties, heteroarenecyclynes (such as oxaarenecyclynes and thiaarenecyclynes) with semi-shape-persistent structure, and arene – azaarenecyclynes with shape-persistent structure have been prepared. Their novel functions and characteristic properties are disclosed. Noteworthy is that heteroarenecyclynes include C_{60} to provide a Saturn-type complex with a N_2 binding function. A simple member of the oxaarenecyclyne compounds undergoes the Ag^I-induced cyclization leading to the quantitative formation of strongly luminescent perylene derivative. Arene – azaarenecyclynes are versatile compounds. For example, they exhibit intense luminescence in spite of the *meta*-bonding structure, providing the circular luminophore. Also they serve as receptors for special metal, organic, and inorganic substrates. The observed molecular functions are valuable for scientific and practical application.

Keywords: cyclophanes · heteroatoms · macrocycles · molecular function · shape-persistency

Introduction

Chemistry that creates organic and organometallic molecules or molecular assemblies with a biological, chemical, or physical function (i.e., "molecular functional chemistry" or "functional synthesis"[1] introduced in 1949 and developed by one of the authors) has currently become a flourishing field of research. For further development of this field, active research on novel nanosized π-systems seems to be indispensable. Recent remarkable progress in synthetic methodology has made it possible to realize various kinds of nanosized molecules with fascinating properties. Dendrimers,[2] molecular capsules,[3] molecular wires,[4] and π-macrocycles[5] (carbomacrocycles with π-electron systems) are such examples. The introduction of a heteroatom and a shape-persistent structure into the π-macrocycles should be of particular interest because of emerging potential biological, chemical, and/or physical functions. The definition of important terms used in this article follows. Cyclyne is defined as a ring system having one or more alkyne units.[6, 7] Arenecyclyne is a dehydroannulene composed of cyclooligomeric alkynes of general formula $[RC{\equiv}C]_n$ in which all R groups are phenylene (arene) groups.[7] Heteroarenecyclyne is a semi-shape-persistent heteromacrocycle composed of flexible heteroatom units (such as CH_2XCH_2, X = heteroatom) and rigid diethynylbenzene units. Arene – azaarenecyclyne means that the R groups in $[RC{\equiv}C]_n$ are alternately arranged benzene and pyridine rings. The shape-persistent macrocycle is defined as a rigid, noncollapsible macrocycle with a cavity whose size ranges from slightly less than one to several nanometers.[5a]

Such sorts of macrocycles can be constructed, for example, by connecting aromatic and heteroaromatic rings to acetylenic bonds (formation of arene – heteroarenecyclynes), or by linking acetylenic bonds with carbon atom groups (formation of pericyclynes) or with heteroatom groups (formation of heterocyclynes). Synthetic details of shape-persistent macrocycles described in this article are omitted, but can be seen in the respective references.

As shape-persistent carbomacrocycles, arenecyclynes have attracted the considerable attention of organic chemists over the past decade. Arenecyclynes with pertinently arranged functional groups permit a specific interaction with appropriate organic guest molecules or inorganic ions. The π-stacking interactions between aromatic units play an important role as a pivotal force for assembling in many supramolecular systems, including discotic liquid crystals, nucleic acids, molecular catalysts, and various protein and enzyme – substrate complexes. In addition, *ortho*-arenecyclynes and their metal complexes have been the subject of a recent review article.[7]

On the other hand, the shape-persistent heteromacrocycles seem to be a current target in molecular functional chemistry, and their very active investigation has been undertaken to create functional substances and materials. Under such circumstances, this article focuses on the forefront of 1)

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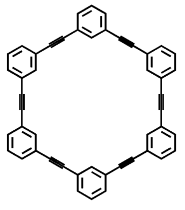
arenecyclynes as shape-persistent carbomacrocycles, 2) heteroarenecyclynes as semi-shape-persistent heteromacrocycles, and 3) arene-azaarenecyclynes as shape-persistent azamacrocycles, centering around our own research.

Arenecyclynes as Shape-Persistent Carbomacrocycles

First of all, we introduce arenecyclynes, which are shape-persistent but do not contain any heteroatoms in the cyclyne ring. Moore et al.[8] have synthesized a shape-persistent carbomacrocycle **1**, in which *meta*-phenylene and acetylene units are alternately arranged. They demonstrate its self-assembling property due to the π–π stacking in either solution or crystal. Arenecyclyne **2**, which is a functionized derivative of **1** with a butyl ester group (R), exhibits a discotic liquid-crystal property. Arenecyclyne **3**, composed of phenylethynyl units with extraannular alkyl side chains, has a solvent-polarity-dependent aggregation.[9] The degree of association increases with decrease in solvent polarity. Arenecyclyne **3** can be used to make a two-dimensional arrangement of rings by adsorption on highly oriented pyrolitic graphite. Recently, Tour et al.[10] discover that the π-stacking forces between arenecyclynes **4** can be enhanced through hydrogen-bonding interactions. Yamaguchi and coworkers[11] report that the configuration of the three helicene units plays an important role in the self-dimerization of stereoisomers of arenecyclyne **5** in organic solvents. Interestingly, *para*-arenecyclynes **6**, synthesized by an intramolecular McMurry-type reaction followed by an addition–elimination sequence, form inclusion complexes with C_{60} and hexamethylbenzene.[12] (*R*)-Binol-derived tetraphosphate (*R*,*R*,*R*,*R*)-arenecyclyne **7** exhibits a high affinity for two disaccharides in the competitive solvent mixture (CD_3OD/CD_3CN).[13] As mentioned above, many kinds of arenecyclynes are formed, but unique functions seem not yet to be disclosed except for the liquid-crystalline properties and molecular recognition.



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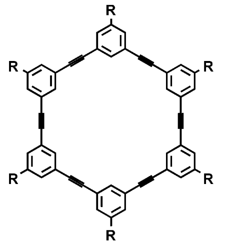
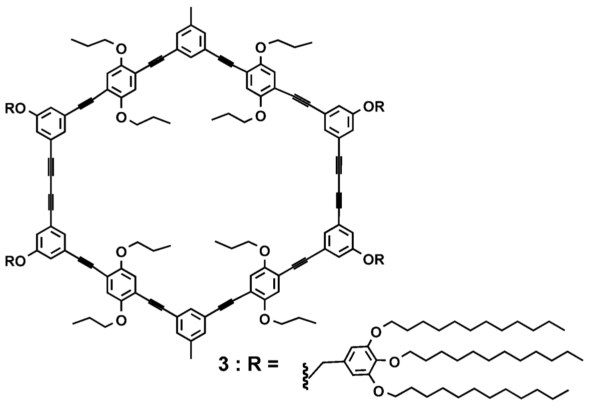
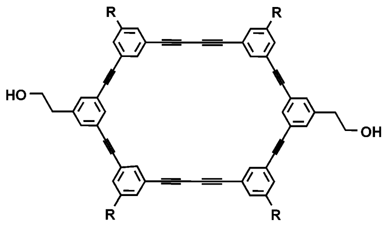


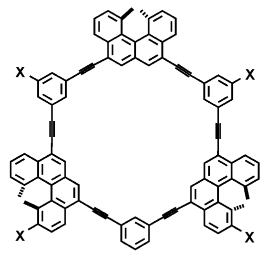
2 : R = $CO_2C_4H_9$



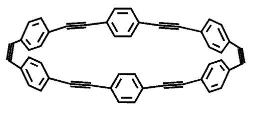
3 : R =



4 : R = $OC_{12}H_{25}$



5 : X = COO*n*-$C_{10}H_{21}$



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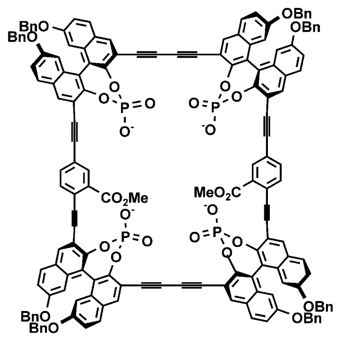

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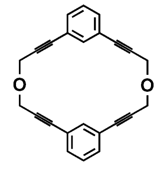
Heteroarenecyclynes as Semi-Shape-Persistent Heteromacrocycles

Oxaarenecyclynes: We have designed a family of novel oxaarenecyclynes **8**, **9**, and **10**; these consist of rigid 1,3-diethynylbenzene units and flexible ether units, which have three kinds of donor groups. The simple member **8** of this family aroused special interest in its structure and reaction behavior owing to bond-angle strain, besides the expected complex formation with transition metals. On the other hand, the oxaarenecyclynes **9** and **10**, which have large cavities, are expected to form functional supramolecular complexes with various substrates (e.g., C_{60}).

For the synthesis, we chose the strategy that involves Sonogashira Pd coupling as the key step.[14, 15] Oxaarenecyclyne **8** is not coplanar and has a small bond angle strain at C−C≡C−C and C−O−C (Figure 1). Cyclynes are expected to form π-complexes with transition metals by the interaction at their triple bonds. Of the transition metals, we are particularly interested in the reaction with the silver(I) ion, since Komatsu's group have reported an inner Ag^I π-complex with cyclotetrayne,[16] and Youngs' group have reported a sandwich-type Ag^I π-complex with cyclotriyne. [17]



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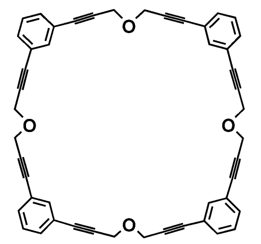

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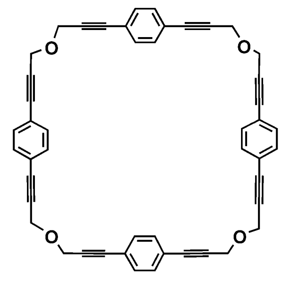

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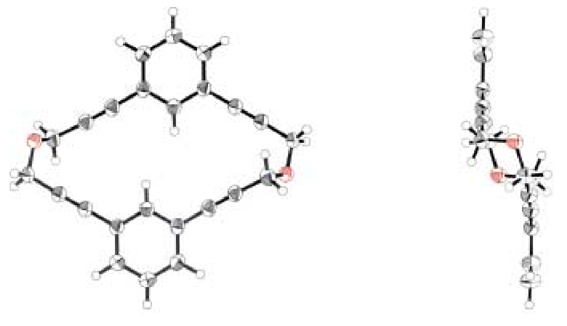
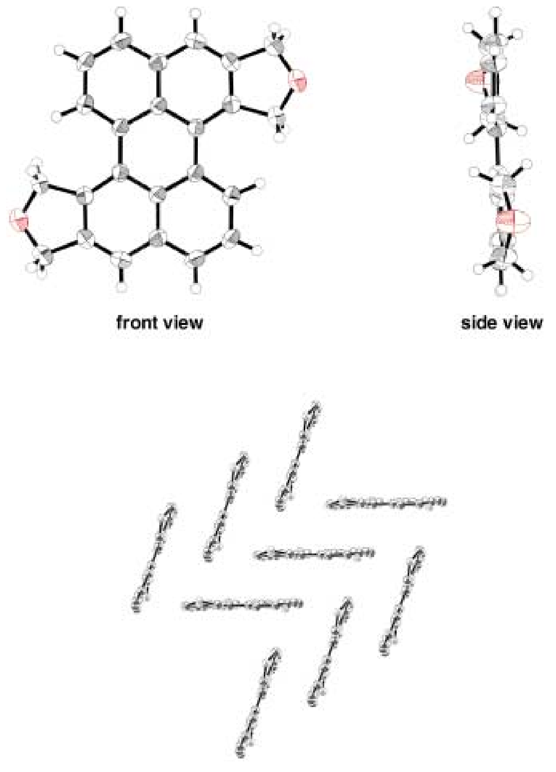


front view side view

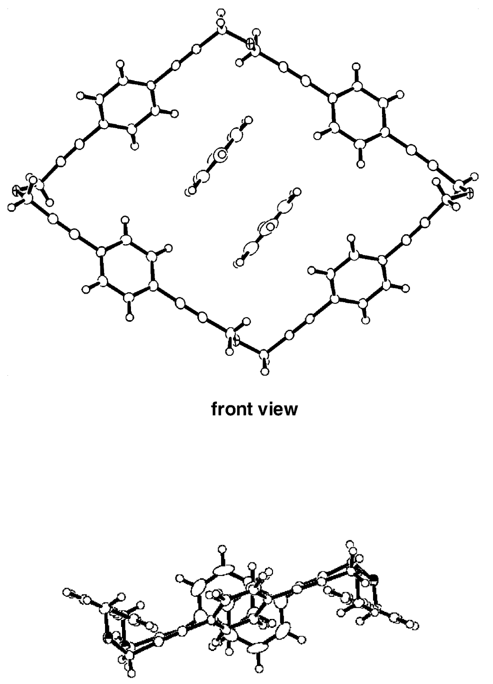
Figure 1. ORTEP drawing of **8** (this figure has been adapted from Figure 1 in reference [14]).



front view side view

packing structure

Figure 2. ORTEP drawing of **11** (this figure has been adapted from Figure 2 in reference [14]).



front view

side view

Figure 3. ORTEP drawing of **10** (this figure has been adapted from Figure 1 in reference [15]).

On the basis of various trials, we carried out the reaction of **8** with AgOTf (7.5 equiv) in benzene at 25–80°C. The molecular structure of product **11** was determined to be 1,2:7,8-bis(tetrahydrofuro)perylene by single-crystal X-ray analysis (Figure 2). Therefore **11** is a structural isomer of **8**, and not the silver(I) π-complex ([(AgOTf)(**8**)]).

From Figure 2, we can see that compound **11** has a coplanar structure with normal bond angles and bond lengths; it also has an intense blue fluorescence ($\phi_f = 0.5$ in $CHCl_3$). This Ag^I-ion-induced cyclization leading to the quantitative formation of the perylene skeleton is unprecedented and quite interesting from the synthetic viewpoint.

Interestingly, compound **10** included two benzene (the solvent used for recrystallization) molecules in the cavity, suggesting that the cavity of oxaarenecyclyne is hydrophobic (Figure 3). The diagonal O–O distances of **10** obtained from its crystal structure with the two benzene molecules in the cavity are 13.4 Å and 20.3 Å. Taking the van der Waals radius of the oxygen atom (1.4 Å) into consideration, the cavity size of **10** is estimated at 10.6 × 17.5 Å. On the other hand, the cavity size of **9** obtained from its MM2-optimized structure is estimated at 11.5 × 11.5 Å.

Judging from the results of the MM2 calculations and X-ray analysis, oxaarenecyclynes **9** and **10**, in which oxygen atoms (σ-donor) and benzene rings (π-donor) are alternately arranged, are expected to include large hydrophobic substrates (e.g., C_{60}). C_{60} is considered to have similar properties to transition metals and octahedral coordination sites from Yoshida's "superatom concept".[18] Furthermore its van der Waals diameter is almost 10 Å. As mentioned above, **9** and **10** have four symmetrical ether-type oxygen atoms that can interact well with four equatorial double bond carbons of C_{60}. Therefore, **9** and **10** incorporate C_{60} to form supramolecular complexes, provided under appropriate conditions.

The color change from purple to reddish-brown was observed only upon refluxing the solution of C_{60} and **9** (or **10**) (molar ratio 1:1) in toluene for 45 minutes. The absorption spectra measurements were made for the solution after cooling to 298 K. As shown in Figures 4 and 5, the intensity of the C_{60} absorption band in the 400–550 nm region increased with concentration of **9** (or **10**). This is ascribed to the formation of the oxaarenecyclyne(**9** or **10**)–C_{60} complex in solution.[19] A Job plot[20] and an isosbestic point (**9**: 607 nm, **10**: 608 nm) between C_{60} and the receptor (**9** or **10**) provided evidence for 1:1 complex formation.

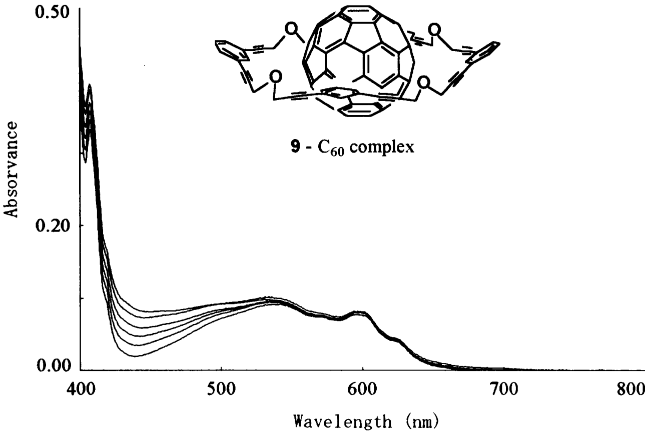


Figure 4. Absorption spectra of C_{60} (1.05×10^{-4} mol dm^{-3}) in the presence of oxaarenecyclyne **9** in toluene. Concentrations of **9**: 0.00, 0.21, 0.42, 0.63, 0.84, 1.05 ($\times 10^{-4}$ mol dm^{-3}) from the bottom (this figure has been adapted from Figure 2 in reference [15]).

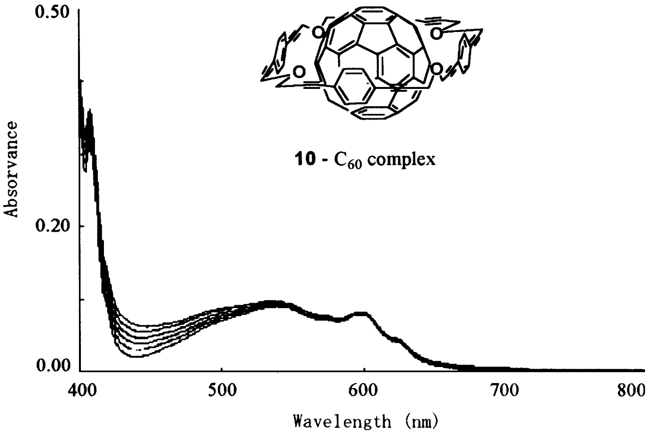


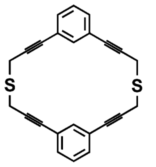
Figure 5. Absorption spectra of C_{60} (1.03×10^{-4} mol dm^{-3}) in the presence of oxaarenecyclyne **10** in toluene. Concentrations of **10**: 0.00, 0.21, 0.41, 0.62, 0.82, 1.03 ($\times 10^{-4}$ mol dm^{-3}) from the bottom (this figure has been adapted from Figure 3 in reference [15]).

The formation constant[21] of the complexes at 298 K was determined by spectroscopic titration method (**9** for C_{60}: $3.41 \pm 1.51 \times 10^3$ dm^{3}mol^{-1}, **10** for C_{60}: $5.43 \pm 0.37 \times 10^3$ dm^{3}mol^{-1}; Figures 4 and 5). From the MM2/AM1 calculations, the LUMO coefficients at the apical position for Saturn-type C_{60}-complexes of **9** and **10** become larger than those of C_{60}, suggesting an increase in reactivity of C_{60} in these kinds of complexes. Therefore, the Saturn-type C_{60} complex is expected to have a different reactivity to that of C_{60}.

Thus, introduction of oxygen atoms and semi-shape-persistent structures into the π-macrocycles brought forth 1) an unprecedented cyclization characteristic leading to the quantitative formation of highly luminescent materials (perylene derivatives) for the smaller oxaarenecyclyne **8**, and 2) the inclusion ability to form Saturn-type C_{60} complexes for larger oxaarenecyclynes **9** and **10**.

Thiaarenecyclynes: Judging from the properties of sulfur (e.g., ionization potential, electron affinity, electro-negativity, and standard electrode potential), which are quite different from those of oxygen, thiaarenecyclynes are attractive goals. Three kinds of thiaarenecyclynes, **12**, **13** and **14**, as novel semi-shape-persistent heteromacrocycles, analogous to oxaarenecyclynes **8**, **9** and **10**, have been designed.

Intramolecular thioether bond formation by treatment of the precursor dibromide with Na_2S/Al_2O_3 provided the small member **12** of this family.[22] As shown in Figure 6, **12** is not



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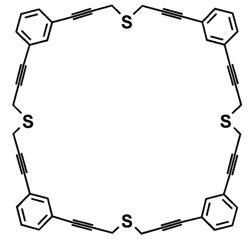

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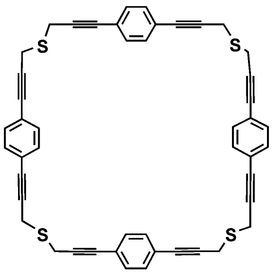

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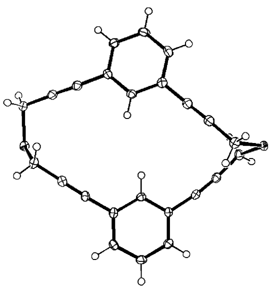


12

Figure 6. ORTEP drawing of thiaarenecyclyne **12** (this figure has been adapted from Figure 1 in reference [22]).

coplanar and there is a samll amount of bond angle strain at C−C≡C−C and C−S−C. The size and shape of the cavity of **12** is similar to that of oxaarenecyclyne **8**.

As a characteristic property of **12**, we were greatly interested in its reaction behavior toward AgOTf, because oxaarenecyclyne **8** quantitatively provided the tetrahydrofuran ring-fused perylene **11** by Ag^I-induced cyclization. The reaction of **12** with AgOTf in benzene at ambient temperature leads to the formation of a precipitate immediately after mixing the reaction components. IR and ^1H NMR spectra suggest that the precipitate could not be the corresponding perylene derivative,[23] but rather the silver complexe with an Ag^I−S bond. The structure of the Ag–**12** complex was determined by single-crystal X-ray analysis.

Two types of Ag–**12** complex coexist in the crystal: 1) a linear polymer complex (Figure 7a), in which thiaarenecyclyne **12** and Ag are alternately arranged, and 2) a cyclic dimer complex (Figure 7b), composed of two moleucles of **12** and two Ag atoms. The crystal structure is a unique one, because the linear polymer complex layer and the cyclic dimer complex layer are alternate (Figure 7c). Also, the X-ray structure clearly indicates that the Ag^I ions are placed outside the ring, in contrast to the unsaturated thiacrown-ether–Ag^I complex[24] in which the Ag^I ion is included in the cavity. Recently it has been observed by fluorescence microscopy that nanoscale silver oxide (Ag_2O) reveals strong photoactivated emission for exitation wavelengths shorter than 520 nm;[25] however, the Ag–**12** complex does not emit any luminescence neither in solution nor in the solid state.

Following on from this, we investigated the synthesis and properties of thiaarenecyclynes **13** and **14**,[26] which have larger ring sizes than that of **12**. The intermolecular thioether bond formation reaction of the corresponding precursor dibromides afforded the desired thiaarenecyclynes **13** and **14**. The structures of **13** and **14** were confirmed by spectral data (^1H NMR, ^{13}C NMR, and HR FAB MS). The ^1H and ^{13}C NMR spectra of **13** and **14** are simple, indicating the high symmetry of molecules. The MM2-optimized structure of **13** and **14** is shown in Figure 8.

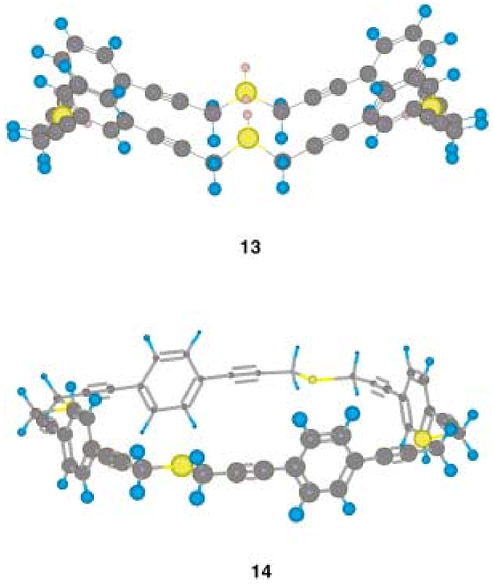


Figure 8. MM2 structures of **13** and **14**.

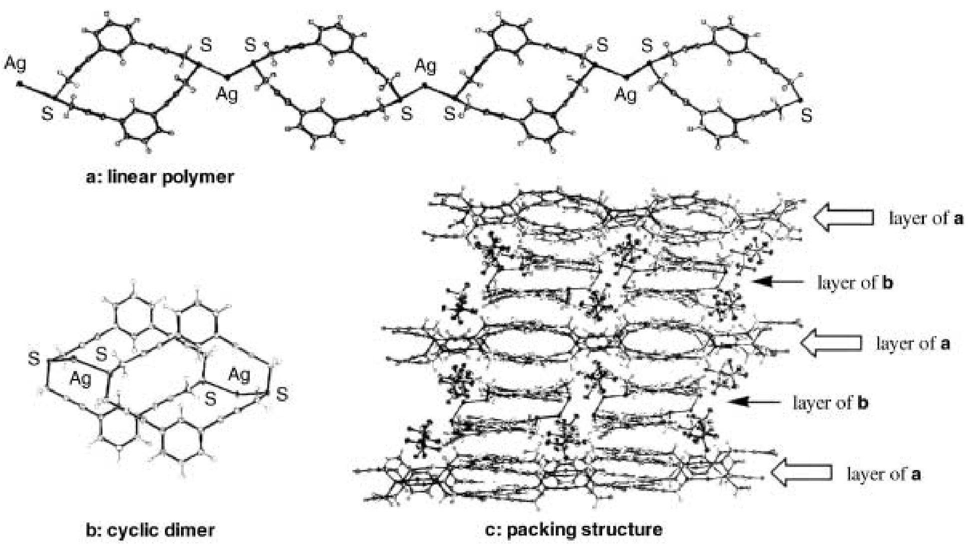


Figure 7. ORTEP drawing of **12**–Ag complex (this figure has been adapted from Figure 2 in reference [22]).

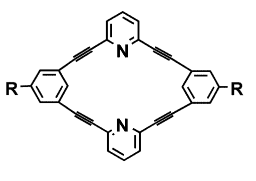
The cavity size (> 10 Å) of **13** and **14** appears to be sufficient for including C_{60}. In a preliminary experiment, it is shown that thiaarenecyclynes **13** and **14** readily form a Saturn-type C_{60} supramolecular complex in $CHCl_3$ even at room temperature. The MM2/AM1 calculations show that the LUMO coefficients at the apical position of C_{60} in each complex become larger than those of C_{60}, suggesting that the complex of C_{60} with **13** (or **14**) may possess novel properties that C_{60} does not. As such an example, the N_2 antisymmetric stretching vibration was observed at 2192 cm^{-1} (for complex of C_{60} with **13**) and

2186 cm^{-1} (for complex of C_{60} with **14**) upon contact with N_2, indicating that these C_{60} complexes possess N_2-binding function (cf. $\nu_{N2,free} = 2331$ cm^{-1}).

Thus introduction of sulfur atoms and semi-shape-persistent structure into the π-macrocycles lead to: 1) a characteristic reaction that lead to cyclic Ag^I complexes for smaller thiaarenecyclyne **12**, whose unique properties are not yet disclosed, and 2) ready formation of the Saturn-type C_{60} complexes with N_2-binding properties for the larger thiaarenecyclynes **13** and **14**. Ammonia formation from the N_2 complexes should be the exiting subject in near future.

Arene–azaarenecyclynes as shape-persistent azamacrocycles

The shape-persistent azamacrocycles, which are composed of triple bonds and pyridine rings (and benzene rings), are novel nanomacrocycles. They are expected to serve as receptors for various substrates by the choice of ring size in the macrocycles and the direction of N atom of pyridine ring (inner or outer).



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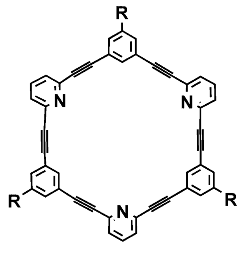

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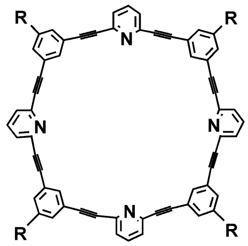

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Arene–azaarenecyclynes in which pyridine N atoms are directed inside the macrocycles: Arene–azaarenecyclynes, which contain alternately arranged pyridine and benzene rings in a *meta*-bonding fashion, are geometrically controlled and shape-persistent azamacrocycles. We have designed and synthesized three kinds of arene–azaarenecyclynes (**15**, **16**, and **17**: also abbreviated as tetrakis *m*-cyclyne, hexakis *m*-cyclyne, and octakis *m*-cyclyne, respectively) with the different ring sizes.

We accomplished the synthesis of arene-azaarenecyclynes **15**–**17** by the effective method in which the Sonogashira reaction is repeatedly used as a coupling reaction. The structures of **15**–**17** have been confirmed by spectral data (^{1}H NMR, ^{13}C NMR, and IR spectroscopy, and HR FAB MS), and finally the structures of tetrakis *m*-cyclynes **15** (**15a**: R = H, **15b**: R = COOMe and **15c**: R = COOBu) have been determined by single-crystal X-ray analysis (Figure 9).[27]

As shown in Figure 9, all tetrakis *m*-cyclynes have a completely coplanar structure with some bond angle strain (about 10°) at C–C≡C–C. Tetrakis *m*-cyclynes do not construct the self-assembled layer due to π–π stacking in spite of the completely coplanar structure in solution, but they form a nice stacking structure in the solid state (Figure 9c).[27]

It is worth noting that all arene-azaarenecyclynes **15**–**17** emit an unusually intense fluorescence (Table 1), different from the acyclic homologue, 1,3-di(pyridylethynyl)benzene ($\lambda_{em} = 329$ nm, $\phi_{em} = 0.026$ in $CHCl_3$). It is very interesting to observe such strong fluorescence in spite of the interruption of π-electron conjugation by *meta*-bonding. The small Stokes shift is also a characteristic photophysical property of arene–azaarenecyclynes, indicating that the conformation of arene–azaarenecyclynes is very rigid even at the exited state.

Surprisingly dramatic changes in the UV-visible and fluorescence spectra are observed upon addition of antimony pentachloride to a solution of **15c** in CH_2Cl_2 at ambient temperature.[27] In particular, the fluorescence emission maximum (λ_{em}) is shifted significantly to a longer wavelength (about 70 nm) and fluorescence yield (ϕ_{em}) increases by about twofold (Table 1). The structure of the strongly luminescent product formed from **15c** and $SbCl_5$ is not clear yet. However,

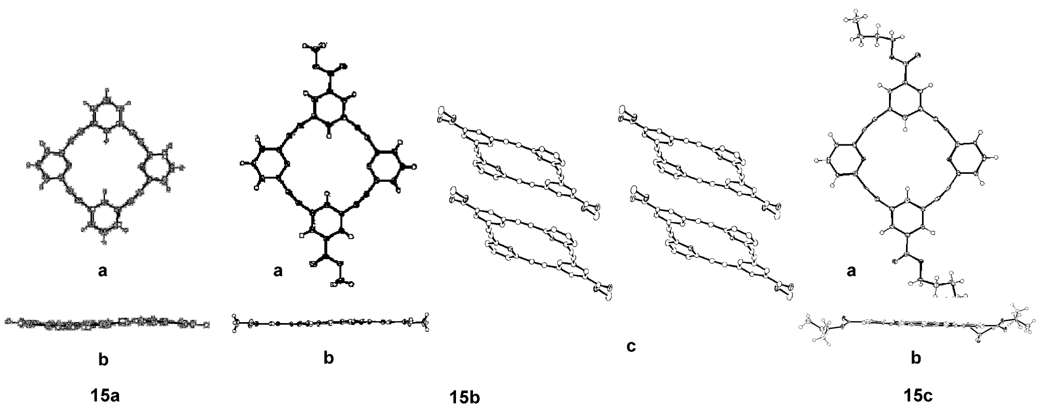


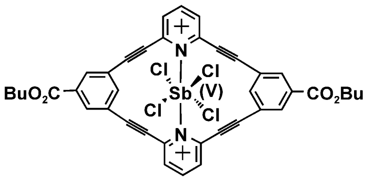
Figure 9. ORTEP drawings of **15a**, **15b**, and **15c**: a) front views, b) side views, c) packing structure of **15b** (this figure has been adapted from Figure 1 in reference[27]).

Table 1. Light-emitting properties of **15**–**17**, **15c**–$SbCl_5$ and **17a**–$[Cu(hfa)_2]$.

	Absorption λ_{max} [nm] (log ε)	Fluoresence λ_{em} [nm]	Stokes Shift [nm]	Quantam yield ϕ_f[a]
15a (R = H)[b,c]	322 (4.56)	357	35	0.27
15b (R = COOMe)[b,c]	322 (4.64)	356	34	0.11
15c (R = COOBu)[b,d]	322 (4.62)	355	33	0.18
18 (**15c**–$SbCl_5$)[b,d]	382 (4.46)	433	51	0.41
16a (R = H)[b,c]	321 (5.16)	352	33	0.22
16b (R = COOMe)[b,c]	323 (4.81)	345	22	0.37
17b (R = COOBu)[b],[c]	313 (4.92)	344	31	0.37
19 (**17a**–$[Cu(hfa)_2]$)[b],[c]	313 (5.14)	344	31	0.30

[a] Quantum yield is determined relative to Quinine ($\phi_{em} = 0.55$ in 0.1 M H_2SO_4) at 295 K. [b] $\lambda_{ex} = 315$ nm (**15a**), 312 nm (**15b**), 312 nm (**15c**), 379 nm (**15c**-$SbCl_5$), 318 nm (**16a**), 314 nm (**16b**), 312 nm (**17a**), 311 nm (**17b**), 313 nm (**17a**-$Cu(hfa)_2$). [c] Solvent: $CHCl_3$. [d] Solvent: CH_2Cl_2.

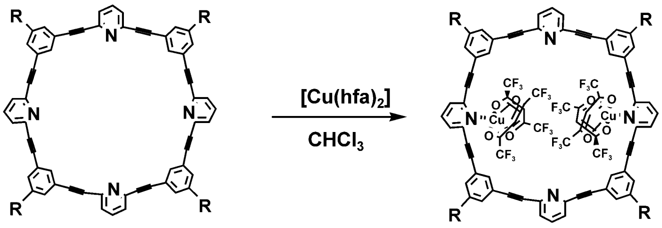
from the following facts 1) the ^1H NMR spectrum is very similar with that of **15c**, 2) each signal appears at lower field ($\delta = 0.5$–1.0 ppm), 3) the molar ratio based on a Job plot is 1:1, and 4) Sb^V has octahedral coordination sites,[28] this luminophor is inferred to be the 1:1 complex **18** with an antimony–nitrogen bond. Other metal salts, for example, antimony trichloride and zinc halides,[29] do not exert any effects on fluorescence. Thus, **15c** (and even **15** in general) is very useful for the specific recognition of the Sb^V ion. To our knowledge, this is the first example for the recognition of toxic Sb^V ion. Since the fluorescence intensity due to the complex formation varies in proportion to the concentration of the Sb^V ion, tetrakis *m*-cyclyne **15c** is valuable as a sensing material.



18

The hexakis *m*-cyclynes **16** having a larger ring size than that of **15** and recognize guanidine salts to form the corresponding 1:1 adducts. As for the structure of the adduct, there seem to be two possibilities (face-to-face and rotaxane-type adducts). If a guanidine cation is incorporated into the cavity of **16a** as a rotaxane-type adduct and the incorporated cation is able to move along the hexagonal π-frame, this adduct may provide an example of a molecular motor.

We have investigated the formation of transition-metal complexes with octakis-*m*-cyclynes **17**, which have the largest ring size of this family, as part of the search for novel functional materials. Based on the results of various trials, we have carried out the reaction of **17a** with $[Cu(hfa)_2]$ in $CHCl_3$ for a week at ambient temperature to obtain a greenish blue crystal **19**. The structure of **19** was determined to be 1:2 complex between **17a** and $[Cu(hfa)_2]$ by single-crystal X-ray analysis.



17a: R = COOMe
17b: R = COOBu

19
(**17a** - Cu^{II} Complex)

The Cu^{II} complex **19** has a structure in which two opposite pyridine nitrogen atoms of **17a** coordinate to the Cu^{II} ion in $[Cu(hfa)_2]$ (Figure 10); the cyclyne part has a coplanar structure with normal bond lengths and angles. The N–N distance between each Cu-coordinated pyridine ring is 15.56 Å, and that between each free pyridine ring is 14.16 Å. Although the Cu–Cu distance is larger than is usual, its mixed valence complex seems to have some interesting properties.

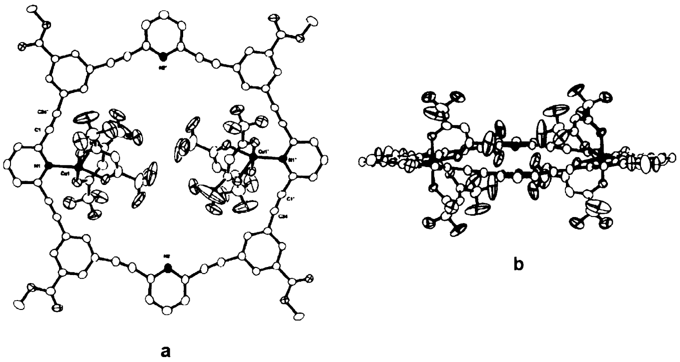
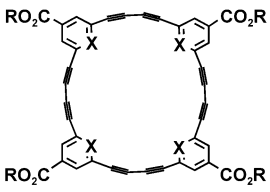


Figure 10. ORTEP drawing Cu^{II} complex **19**: a) front view, b) side view.

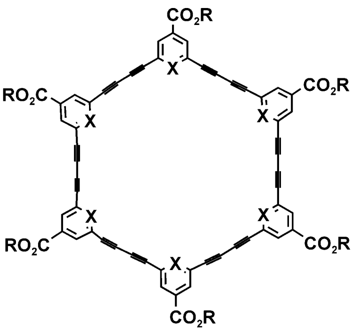
It is worth noting that the Cu^{II} complex **19** emits remarkably intense fluorescence (larger ϕ_{em} relative to that of the corresponding cyclyne **17a**), because transition-metal complexes are known to decrease in ϕ_{em} relative to that of the parent system by spin-orbit coupling. The reason of this interesting observation is not clear at present, but seems to inhibit the internal conversion by increase in rigidity of the macrocyclic ring due to the steric bulk effect of Cu^{II}-coordinated hexafluoroacetylacetone ligands.

Octakis *m*-cyclynes **17** has a big enough cavity size (around 11 Å) to include C_{60} (van der Waals diameter: 10 Å). It is pointed out[30] that the rigid host is difficult to include the rigid guest even if inclusion is conceivable from the host cavity size and guest size. Therefore, the examination of inclusion of C_{60} by **17b** is an important and exciting subject. Although the Saturn-type **17b**–C_{60} complex has not yet been isolated, we believe this complex could be obtained soon.

Tobe and co-workers' arene–azaarenecyclynes **20** and **21**,[31] which contain both pyridine rings and butadiyne units, show a very unique association behavior. Although neither **20** nor **21** show any self-association in $CDCl_3$, because of the electrostatic repulsion between the nitrogen atoms, they form heteroaggregates with arenecyclynes **22** and **23**, respectively,



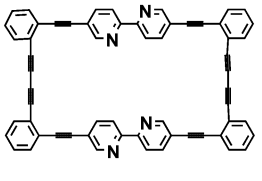
20: X = N
22: X = CH



21: X = N
23: X = CH

which have the same ring size. This is because of dipole–dipole interaction between the pyridine rings of **20** and **21** and the benzene rings of **22** and **23**. Also, **20** and **21** are capable of binding a tropylium cation to form 1:1 and 2:1 complexes, respectively.

The synthesis of a structurally new type of arene–azaarenecyclyne **24**, which is composed of a dehydroannulene framework that incorporates two 2,2′-bipyridine units, has been reported by Baxter.[29] This cyclyne is able to detect Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+}, and, in particular, functions as a multiple readout sensor, giving different sequences of signal output depending upon the type of metal ion analyte with which the system is addressed. Arene–azaarenecyclyne **24** also gives a highly characteristic and specific visual output response in the presence of Zn^{2+}, consisting of bright turquoise fluorescence, and in this respect may find applications in the sensing of this biologically important metal ion.



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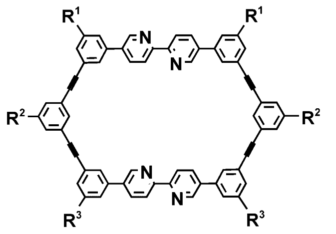


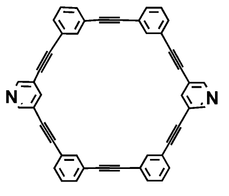
25a: $R^1 = R^3 = CH_2OHex$, $R^2 = H$
25b: $R^1 = R^3 = CH_2OMOM$, $R^2 = CH_2OHex$

Schlüter et al.[32] have reported the synthesis and X-ray analysis of similar shape-persistent arene–azaarenecyclyne **25**, which has two 2,2′-bipyridine units. X-ray analysis of single crystals of **25b** shows a layered structure with channels filled with solvent molecules and parts of the flexible chains. The reaction of **25a** with two equivalents of $[Ru(bipy)_2Cl_2]$ furnishes a doubly *exo*-cyclic-complexed macrocycle.

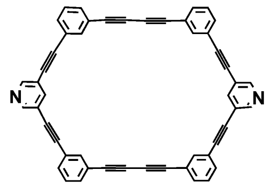
Thus introduction of both pyridine N atoms directed inside and a shape-persistent structure into the π-macrocycles lead to 1) a light-emitting function in spite of *meta*-bonding structure and very rigid conformation, even at the exited state, for all *m*-cyclynes prepared (**15**–**17**); 2) specific Sb^V recognition function for tetrakis *m*-cyclyne **15**, which is valuable as a sensing material for toxic Sb^V; 3) specific recognition function of guanidinium ion for hexakis *m*-cyclyne **16**; 4) inclusion function of two $[Cu(hfa)_2]$ leading to the formation of very strong luminophore for octakis *m*-cyclyne (**17**); 5) unique association behavior due to dipole–dipole interaction between pyridine rings and benzene rings; and 6) Zn^{II}-sensing function of arene–azaarenecyclyne **24**.

Arene–azaarenecyclynes in which pyridine N atoms are directed outside the macrocycles: The two novel pyridine-containing hexagonal arene–azaarenecyclynes **26** and **27** have been synthesized by Lees et al.[33] Both shape-persistent arene–azaarenecyclynes and dinuclear 4,4′-di-*tert*-butyl-2,2′-bipyridine Re^I tricarbonyl complexes **28** and **29** show strong luminescence in solution at room temperature. There is no concentration dependence in the ^1H NMR spectra for these cyclynes and complexes, which rules out ground-state self-association. However, both of the cyclynes exhibit concentration-dependent fluorescence. The fluorescence bands of **26** and **27** red-shift with increasing concentration, and this behavior is ascribed to the formation of excimers in the exited states. In contrast, both organometallic complexes **28** and **29** do not exhibit any concentration-dependenct luminescence.

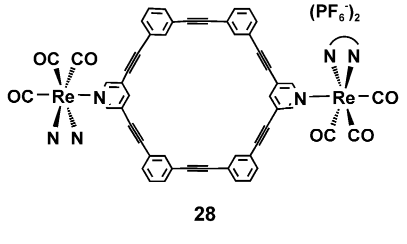
The unique cross-conjugated cyclynes **30** bearing a pyridine functionality have been reported by Tykwinski and co-workers.[34] These cyclynes behave as 4,4′-bipyridine mimics in self-assembly reactions to form nanoscale assemblies **31** by axial coordination to metalloporphyrins. X-ray crystallographic analysis of solid-state assemblies of **31** provides insight into the scope and flexibility of these cyclynes **30** as supramolecular building blocks. Furthermore, in the presence of



26



27



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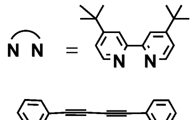
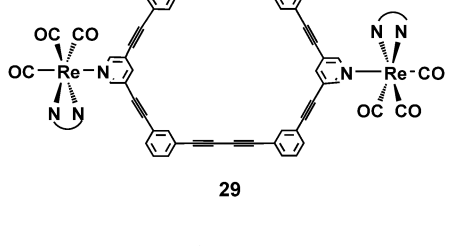
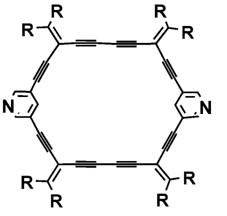




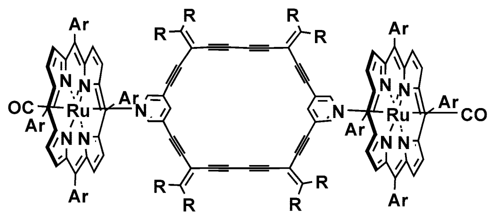
29

the metal species (*cis*-[Pt(TfO)$_2$(PEt$_3$)$_2$]), cross-conjugated cyclynes **30** self-assemble in solution to provide discrete supramolecular complexes, which subsequently crystallized to give a solid with bi-directional porosity.[34b]

Thus introduction of pyridine N atoms directed outside and shape-persistent structure into the π-macrocycles lead to 1) strong luminescent function of dinuclear Re^I–**26** (or **27**) complexes, 2) formation of nanoscale assemblies **31** by axial coordination of cyclynes **30** to matalloporphyrin, and 3) creation of Pt^{II}–**30** supramolecular complexes with bi-directional porosity.



30a: R = Me
30b: R = Ph



31a: R = Me
31b: R = Ph

Concluding Remarks

We describe here the kind of molecular functions or particular properties that are produced by the introduction of a heteroatom and shape-persistent structure into π-macrocycles. For this purpose, various kinds of semi-shape-persistent heteromacrocycles and shape-persistent heteromacrocycles have been prepared. Their novel functions and characteristic properties are as follows:

Oxaarenecyclynes: 1) Unprecedented cyclization characteristic leading to the quantitative formation of highly luminescent materials and 2) inclusion function providing the Saturn-type C$_{60}$ complexes.

Thiaarenecyclynes: 1) Characteristic reaction leading to an interesting cyclic Ag^I complex and 2) ready formation of Saturn-type C$_{60}$ complexes with an N$_2$-binding function, from which NH$_3$ formation is expected.

Arene–azaarenecyclynes: 1) Highly light-emitting function in spite of *meta*-bonding structure, and very rigid conformation even at the excited state; 2) specific Sb^V recognition function, which is valuable as the sensing materials for Sb^V; 3) inclusion function of two [Cu(hfa)$_2$] molecules leading to the formation of very strong luminophore; and 4) Zn^{II}-sensing function of arene–azaarenecyclyne.[29] Other important functions, for example, biological and/or catalytic functions will be disclosed in near future.

So far, synthesis, structure, and reaction have been the central theme in chemistry. However, molecular functional chemistry directed towards the creation of organic and organometallic molecules or molecular assemblies with novel biological, chemical, and/or physical functions has currently become a flourishing field. It will make a valuable contribution to creating new drugs, catalysts, advanced materials, and so on. In this sense, it may be said that chemistry, in particular, molecular functional chemistry of heteromacrocycles, has a strikingly bright and wide-ranging future.

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[1] a) Z. Yoshida, R. Oda, *Mem. Fac. Eng. Kyoto Univ.* **1951**, *13*, 108–122; b) Z. Yoshida, *Pure Appl. Chem.* **1981**, *53*, 293–304; c) Z. Yoshida, *Heterocycles* **1984**, *21*, 331–350; d) Z. Yoshida, *J. Photochem.* **1985**, *25*, 27–40; e) Z. Yoshida, T. Sugimoto, *Angew. Chem.* **1988**, *100*, 1633–1637; *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 1573–1577; f) Z. Yoshida, in *Organic Synthesis in Japan* (Ed.: R. Noyori), Tokyo Kagaku Dojin, Tokyo, **1992**, pp. 63–71; g) Y. Wada, H. Yamada, K. Matsushige, *Oyo Butsuri* **2001**, *70*, 1395–1405.

[2] For example: a) M. Fischer, F. Vögtle, *Angew. Chem.* **1999**, *111*, 934–955; *Angew. Chem. Int. Ed.* **1999**, *38*, 884–905; b) M.-S. Choi, T. Aida, T. Yamazaki, I. Yamazaki, *Angew. Chem.* **2001**, *113*, 3294–3298; *Angew. Chem. Int. Ed.* **2001**, *40*, 3194–3198.

[3] For example: J. Rebek, Jr., *Acc. Chem. Res.* **1999**, *32*, 278–286.

[4] For example: R. E. Martin, F. Diederich, *Angew. Chem.* **1999**, *111*, 1440–1469; *Angew. Chem. Int. Ed.* **1999**, *38*, 1350–1377.

[5] For example: a) S. Höger, *J. Polym. Sci. Part A* **1999**, *37*, 2685–2698; b) C. Grave, A. D. Schlüter, *Eur. J. Org. Chem.* **2002**, 3075–3098; c) D. Zhao, J. S. Moore, *Chem. Commun.* **2003**, 807–818.

[6] a) L. T. Scott, G. J. Recieco, J. L. Hyun, G. J. Reinhardt, *J. Am. Chem. Soc.* **1985**, *107*, 6546–6555; b) M. A. Bennett, H. P. Schwenlein, *Angew. Chem.* **1989**, *101*, 1349–1373; *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 1296–1320; c) A. Krebs, in *Chemistry of Acetylenes* (Ed.: H. G. Vieke), Marcel Dekker, New York, **1969**, pp. 987–1062.

[7] W. J. Youngs, C. A. Tessier, J. D. Bradshaw, *Chem. Rev.* **1999**, *99*, 3153–3180.

[8] a) J. S. Moore, *Acc. Chem. Res.* **1997**, *30*, 402–413; b) A. S. Shetty, J. Zhang, J. S. Moore, *J. Am. Chem. Soc.* **1996**, *118*, 1019–1027; c) T. C. Bedard, J. S. Moore, *J. Am. Chem. Soc.* **1995**, *117*, 10662–10671; d) J. Zhang, D. J. Pesak, J. L. Ludwick, J. S. Moore, *J. Am. Chem. Soc.* **1994**, *116*, 4227–4239; e) J. Zhang, J. S. Moore, *J. Am. Chem. Soc.* **1994**, *116*, 2655–2656.

[9] a) S. Höger, K. Bonard, A. Mourran, U. Beginn, M. Möller, *J. Am. Chem. Soc.* **2001**, *123*, 5651–5659; b) S. Höger, A.-D. Meckenstock, S. Müller, *Chem. Eur. J.* **1998**, *4*, 2423–2434.

[10] C.-H. Lin, J. Tour, *J. Org. Chem.* **2002**, *67*, 7761–7768.

[11] K. Nakamura, H. Okubo, M. Yamaguchi, *Org. Lett.* **2001**, *3*, 1097–1099.

[12] a) T. Kawase, N. Ueda, K. Takano, Y. Seirai, M. Oda, *Tetrahedron Lett.* **2001**, *42*, 5509 – 5511; b) T. Kawase, Y. Seirai, H. R. Darabi, M. Oda, Y. Sarakai, K. Tashiro, *Angew. Chem.* **2003**, *115*, 1659 – 1662; *Angew. Chem. Int. Ed.* **2003**, *42*, 1621 – 1624; c) T. Kawase, K. Tanaka, N. Fujiwara, H. R. Darabi, M. Oda, *Angew. Chem.* **2003**, *115*, 1662 – 1666; *Angew. Chem. Int. Ed.* **2003**, *38*, 1624 – 1628.

[13] A. S. Droz, F. Diederich, *J. Chem. Soc. Perkin Trans. 1* **2000**, 4224 – 4226.

[14] Y. Yamaguchi, S. Kobayashi, T. Wakamiya, Y. Matsubara, Z. Yoshida, *J. Am. Chem. Soc.* **2000**, *122*, 7404 – 7405.

[15] Y. Yamaguchi, S. Kobayashi, N. Amita, T. Wakamiya, Y. Matsubara, K. Sugimoto, Z. Yoshida, *Tetrahedron Lett.* **2002**, *43*, 3277 – 3280.

[16] T. Nishinaga, T. Kawamura, K. Komatsu, *Chem. Commun.* **1998**, 2263 – 2264.

[17] J. D. Ferrara, A. Djebli, C. Tessier-Youngs, W. J. Youngs, *J. Am. Chem. Soc.* **1988**, *110*, 647 – 649.

[18] Z. Yoshida, presented at *The IUPAC Third International Symposium on Functional Dyes*, July 16 – 21, **1995**, Santa Crus (USA), and at **Japan – Northern Baltic Symposium on Synthetic Chemistry**, June 25 – 26, **1996**, Helsinki, Finland, Abstracts PL18.

[19] H. Matsubara, S. Oguri, K. Asano, K. Yamamoto, *Chem. Lett.* **1999**, 431 – 432.

[20] a) U. M. Rabie, B. P. Patal, R. H. Crabtree, M. R. Mahmoud, *Inorg. Chem.* **1997**, *36*, 2236 – 2238; b) S. C. Zimmerman, W. Wu, Z. Zeng, *J. Am. Chem. Soc.* **1991**, *113*, 196 – 201.

[21] K. Hirose, Y. Tobe, K. Inamura, *Jasco Report* **1999**, *41*, 6 – 17.

[22] S. Kobayashi, S. Wakumoto, Y. Yamaguchi, T. Wakamiya, K. Sugimoto, Y. Matsubara, Z. Yoshida, *Tetrahedron Lett.* **2003**, *44*, 1807 – 1810.

[23] The formation of perylene derivative was observed in the thermal reaction (reflux in 1,3,5-trimethylbenzene) of **12** (See ref. [22]).

[24] T. Tsuchiya, T. Shimizu, K. Hirabayashi, N. Kamigata, *J. Org. Chem.* **2002**, *67*, 6632 – 6637.

[25] L. A. Peyser, A. E. Vinson, A. P. Bartko, R. M. Dickson, *Science* **2001**, *291*, 103 – 106.

[26] Y. Yamaguchi, S. Kobayashi, S. Wakumoto, T. Wakamiya, K. Sugimoto, Y. Matsubara, Z. Yoshida, unpublished results.

[27] S. Kobayashi, Y. Yamaguchi, T. Wakamiya, Y. Matsubara, K. Sugimoto, Z. Yoshida, *Tetrahedron Lett.* **2003**, *44*, 1469 – 1472.

[28] T. M. Klapötke, H. Nöth, T. Schütt, M. Suter, M. Warchhold, *Z. Anorg. Allg. Chem.* **2001**, *627*, 1582 – 1588.

[29] P. N. W. Baxter, *J. Org. Chem.* **2001**, *66*, 4170 – 4179.

[30] T. Tashiro, T. Aida, J.-Y. Zheng, K. Kinbara, K. Saigo, S. Sakamoto, K. Yamaguchi, *J. Am. Chem. Soc.* **1999**, *121*, 9477 – 9478.

[31] Y. Tobe, A. Nagano, K. Kawabata, M. Sonoda, K. Naemura, *Org. Lett.* **2000**, *2*, 3265 – 3268.

[32] a) O. Henz, D. Lentz, A. D. Schlüter, *Chem. Eur. J.* **2000**, *6*, 2362 – 2367; b) O. Henz, D. Lentz, A. Schater, P. Franke, A. D. Schlüter, *Chem. Eur. J.* **2002**, *8*, 357 – 365.

[33] S.-S. Sun, A. J. Lees, *Organometallics* **2001**, *20*, 2353 – 2358.

[34] a) K. Campbell, R. McDonald, R. R. Tykwinski, *J. Org. Chem.* **2002**, *67*, 1133 – 1140; b) K. Campbell, C. J. Kuehl, M. J. Ferguson, P. J. Stang, R. R. Tykwinski, *J. Am. Chem. Soc.* **2002**, *124*, 7266 – 7267.