Shape-persistent cyclyne-type azamacrocycles: synthesis, unusual light-emitting characteristics, and specific recognition of the Sb(V) ion

Shigeya Kobayashi,[a] Yoshihiro Yamaguchi,[a] Tateaki Wakamiya,[a] Yoshio Matsubara,[a] Kunihisa Sugimoto[b] and Zen-ichi Yoshida[a],*

[a]*Faculty of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka 577-8502, Japan*
[b]*X-Ray Research Laboratory, Rigaku Corporation, 3-9-12 Matsubara, Akishima, Tokyo 196-8666, Japan*

Abstract—Simple members of arene–azaarenecyclynes as a novel family of geometrically-controlled and shape-persistent azamacrocycles have been synthesized. Noteworthy is the specific recognition function for Sb(V). The synthesized azamacrocycles, in particular the Sb(V) complex, have unusually strong light-emitting property. © 2003 Elsevier Science Ltd. All rights reserved.

Structually well-defined macrocycles continue to attract strong interest, because of the emerging unique properties (such as specific recognition, selective binding, and complexation) and the resulting molecular functions. As such an example, we recently reported a novel family of cyclynes (oxaarenecyclynes) (**1**) containing oxygen atoms and benzene rings, focusing on (1) synthesis, (2) very unique reaction of a simple member ($n = 2$, m-phenylene system),[1] and (3) supramolecular C_{60} complexes with higher members ($n = 4$, m- and p-phenylene system).[2]
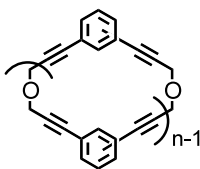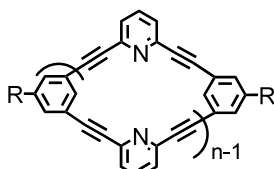
1   **2**
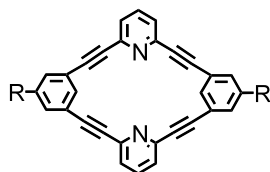
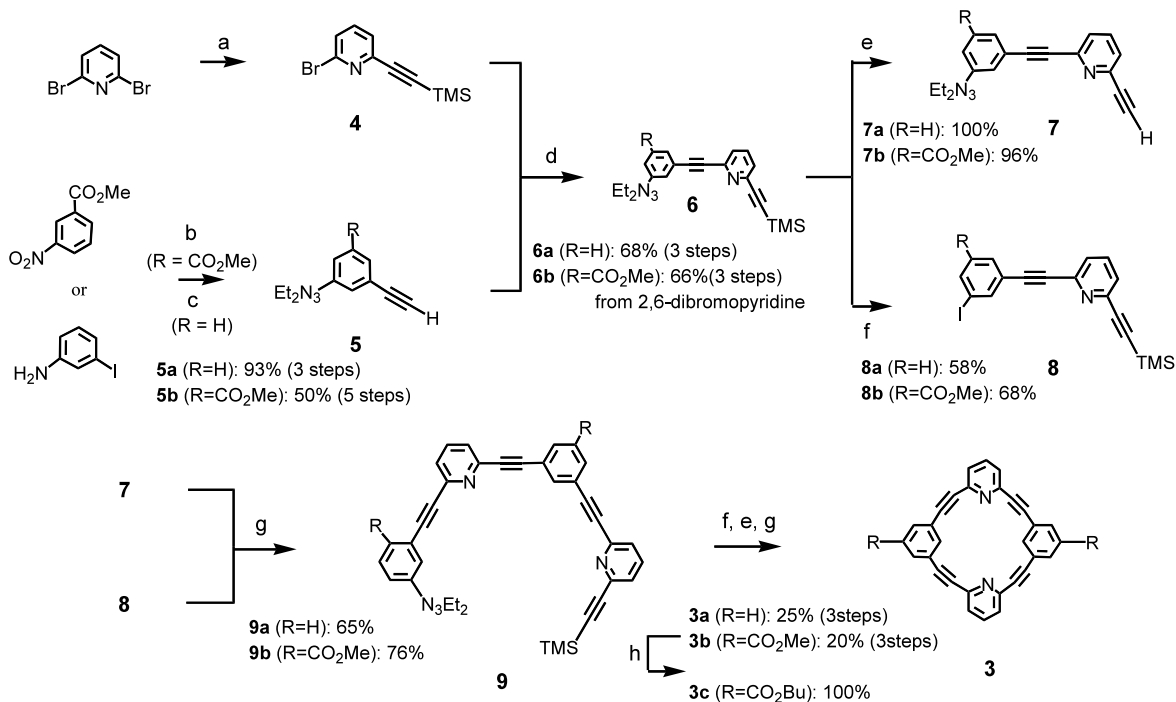**3 a (R = H)**
3 b (R = CO$_2$Me)
3 c (R = CO$_2$Bu)

Arene–azaarenecyclynes (**2**) containing alternately arranged pyridine and benzene rings in a m-bonding fashion are more geometrically-controlled and shape-persistent azamacrocycles than oxaarenecyclynes **1**. We report here (1) synthesis[3] of simple members (**3a**–**c**), (2) unusual light-emitting characteristics, and (3) specific recognition of the Sb(V) ion.

Cyclynes **3** can be effectively synthesized by repeating the Sonogashira Pd coupling reaction.[4] Thus, dimer **6**, which is a key compound in the synthetic route, was prepared by the Pd coupling reaction between bromo-derivative **4** prepared from 2,6-dibromopyridine and **5** having a terminal acetylene unit prepared from m-iodoaniline or methyl 3-nitrobenzoate (Scheme 1). The obtained **6** was converted to **7** by alkaline hydrolysis of its TMS group, and to **8** by iodination[5] of the triazene group. The Pd coupling reaction between **7** and **8** gave compound **9**. Finally, **3a** and **3b** were provided by the intramolecular Pd-catalyzed cyclization of the precursor compound obtained by iodination followed by alkaline hydrolysis of **9a** and **9b**. The cyclyne **3b** with methoxy-carbonyl groups was converted into **3c** with butoxycarbonyl groups by treatment with BuONa in almost quantitative yield. Although the solubility of **3a** and **3b** toward the organic solvent was extremely low, that of **3c** was much improved.

The structure of **3a**–**c** was confirmed by spectral data (^{1}H and ^{13}C NMR and HR-FAB MS).[6] The ^{1}H and ^{13}C NMR spectra of **3a**–**c** are simple, comprising high

Scheme 1. *Reagents and conditions*: (a) (i) ^{i}PrMgCl/THF, then I_2, (ii) trimethylsilylacetylene/Pd(Ph$_3$P)$_2$Cl$_2$/CuI/Et$_3$N; (b) (i) Br$_2$/Ag$_2$SO$_4$/conc. H$_2$SO$_4$, (ii) SnCl$_2$·2H$_2$O/EtOH, (iii) NaNO$_2$/conc. HCl, then Et$_2$NH/K$_2$CO$_3$/H$_2$O, (iv) trimethylsilylacetylene/ Pd(Ph$_3$P)$_2$Cl$_2$/CuI/Et$_3$N, (v) KOH/MeOH/CHCl$_3$; (c) (i) NaNO$_2$/conc. HCl, then Et$_2$NH/K$_2$CO$_3$/H$_2$O, (ii) trimethylsilylacetylene/ Pd(Ph$_3$P)$_2$Cl$_2$/CuI/Et$_3$N, (iii) KOH/MeOH/CHCl$_3$; (d) Pd(Ph$_3$P)$_2$Cl$_2$/CuI/Et$_3$N; (e) KOH/MeOH/CHCl$_3$; (f) I$_2$/CH$_2$ClCH$_2$Cl; (g) Pd(Ph$_3$P)$_2$Cl$_2$/CuI/Et$_3$N–THF (2:1, v/v); (h) BuONa/BuOH/CHCl$_3$.

symmetry of the molecules. The inner protons of **3** are observed at the lowest field (**3a**: δ 8.67; **3b**: δ 8.84; **3c**: δ 8.85) among the aromatic protons and at lower field than the corresponding proton of 1, 3-di(pyridylethynyl)benzene (1,3-PBP) (δ 7.82), an acyclic homologue of arene–azaarenecyclynes. Since the chemical shifts of the outer protons on the benzene ring of **3** are comparable to those of 1,3-PBP, the low-field shift of the inner protons is presumably due to greater anisotropic effects from the neighboring triple bonds

and pyridine rings involving shape-persistent macrocycles. The *sp* carbon atoms of **3** (**3a**: δ 92.1, 90.6; **3b**: δ 93.0, 89.6; **3c**: δ 92.7, 89.6) also resonate at slightly lower field than those of phenylpyridylacetylene (δ 88.9, 88.4) and 1,3-PBP (δ 88.8, 88.6), reflecting the ring strain in the molecule.

The molecular structure of **3b** and **3c** was determined by single-crystal X-ray analysis.[7] As shown in Figure 1, **3b** has a completely coplanar structure with some bond
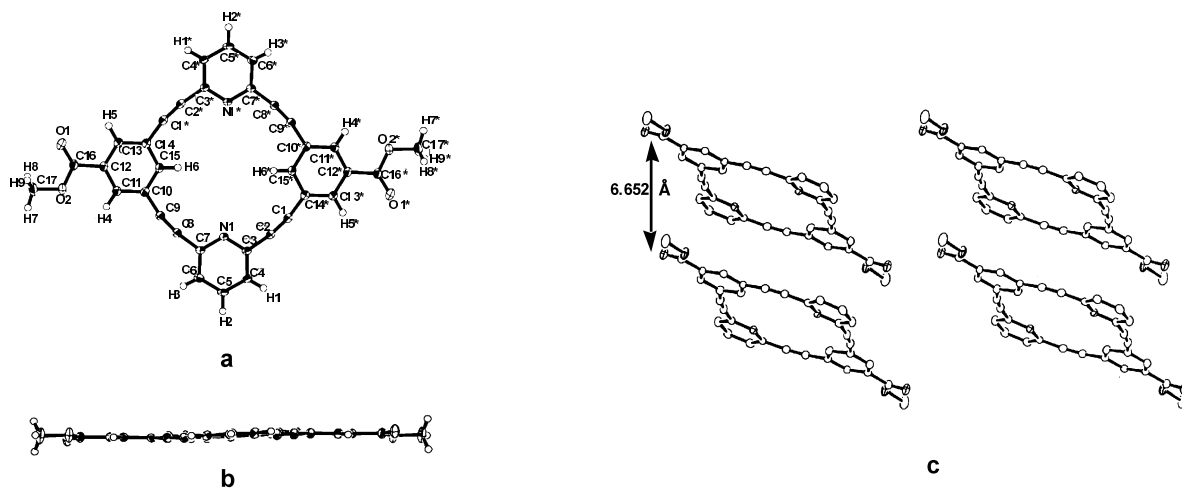

Figure 1. ORTEP drawing of **3b** (a: front view; b: side view; c: packing structure). Ellipsoids are drawn at 50% probability.

angle strain at C–C≡C–C (168.7 and 171.0°).[8] This result is consistent with that obtained from ^{13}C NMR. The crystal structure of **3c** was similar to that of **3b**. Unfortunately, both **3b** and **3c** did not construct the assembling layer by π–π stacking in spite of their completely coplanar structure.

The absorption spectra (including the absorption coefficients) of **3a**–**c** are very similar to each other. Noteworthy is that arene–azaarenecyclynes emit unusually intense fluorescence (Table 1), different from the acyclic homologue, 1,3-PBP ($\lambda_{em} = 329$ nm, $\Phi_{em} = 0.026$). It is very interesting to observe such strong fluorescence in spite of the interruption of π-electron conjugation by *m*-bonding.

Surprisingly dramatic changes in the UV–vis (Fig. 2) and fluorescence (Fig. 3 and Table 1) spectra were observed upon addition of antimony pentachloride to a CH₂Cl₂ solution of **3c** at ambient temperature. As shown in Figure 3 and Table 1, fluorescence emission maximum (λ_{em}) is shifted significantly to longer wavelength and fluorescence yield (Φ_{em}) greatly increases. From the ^{1}H NMR spectra[9] (appeared at lower field with very simple structure) and Job plots (Fig. 4), this luminophor is inferred to be the 1:1 complex (**10**) with an antimony–nitrogen bond.[10,11]

Table 1. Photophysical data of arene–azaarenecyclynes (**3a**–**c**) and **3c**–SbCl₅ complex (**10**)

Compd	λ_{max} (nm)	λ_{em} (nm)	Φ_{em}[a]
3a[b,c]	277, 292, 316, 322	357	0.27
3b[b,c]	277, 287, 314, 322	356	0.11
3c[b,d]	277, 292, 316, 322	355	0.18
3c–SbCl₅[b,d]	286, 293, 301, 323, 382	433	0.41

[a] Quantum yield is determined relative to Quinine ($\Phi_{em} = 0.55$ in 0.1 M H₂SO₄) at 295 K.
[b] $\lambda_{ex} = 315$ nm (**3a**), 312 nm (**3b**), 312 nm (**3c**), 379 nm (**3c**–SbCl₅).
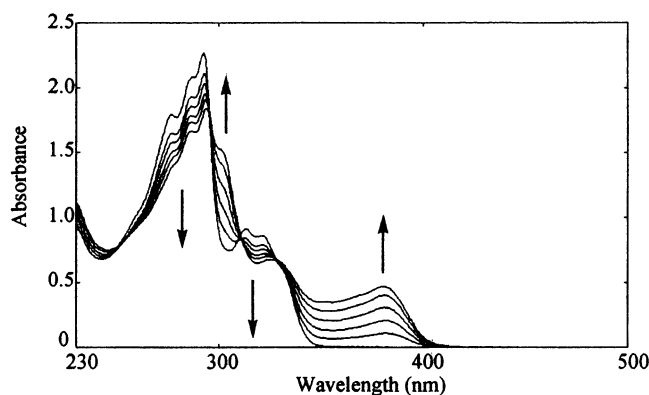[c] Solvent: CHCl₃.
[d] Solvent: CH₂Cl₂.

Figure 2. Changes in the UV–vis spectrum of **3c** (1.99×10^{-5} M in CH₂Cl₂) upon addition of SbCl₅ (0.00, 0.40, 0.80, 1.19, 1.59, 1.99 ($\times 10^{-5}$ M)) at 295 K.
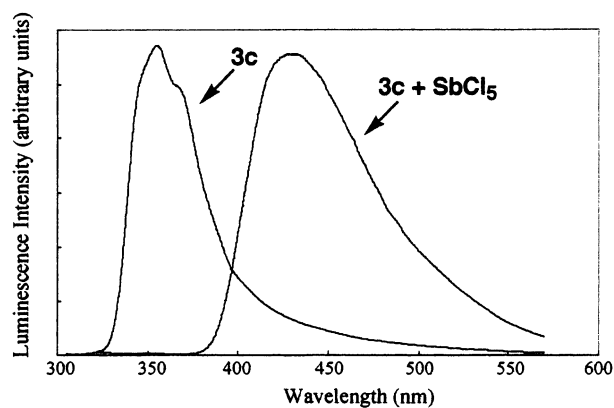

Figure 3. Changes in the fluorescence spectrum of **3c** (3.31×10^{-7} M in CH₂Cl₂) upon addition of SbCl₅ (6.62×10^{-7} M) at 295 K.
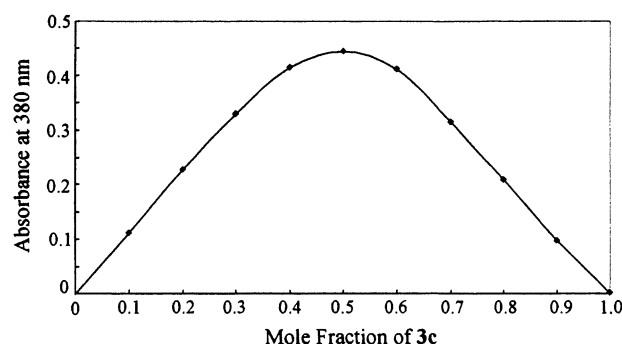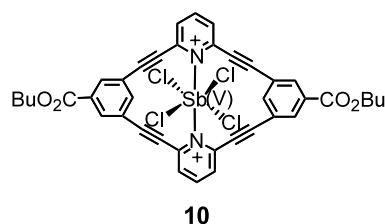

Figure 4. Continuous-variation method for the complex between **3c** and SbCl₅ in CH₂Cl₂. Total concentration $= 3.98 \times 10^{-5}$ M.

10

Other metal salts, for example, antimony trichloride and zinc halides, did not exert any effects on fluorescence. Thus, **3c** (**3** 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). Since the fluorescence intensity due to the complex formation varies in proportion to the concentration of the Sb(V) ion (Fig. 5), **3c** could serve as a sensor for the Sb(V) ion. We note that antimony pentachloride does not react with the benzene ring[12] and triple bond[13] in **3c**, different from Komatsu's and Swager's papers. Investigation on novel functions emerging from the **3c**–SbCl₅ complex is currently in progress. The result will be published in due course.
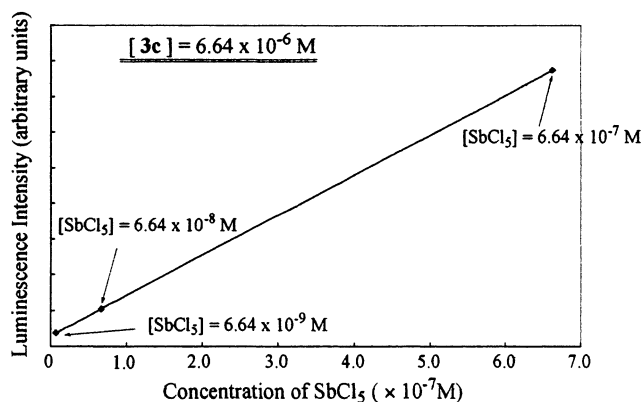
Figure 5. Plot of the luminescence intensity (at 433 nm) of the complex versus concentration of $SbCl_5$ ($[3c] = 6.64 \times 10^{-6}$ M, $[SbCl_5] = 6.64 \times 10^{-7}$ M, 6.64×10^{-8} M and 6.64×10^{-9} M) at 295 K.

Acknowledgements

References

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

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

3. The carbocyclic system of **3** was reported by Oda and co-workers. See: Kawase, T.; Ueda, N.; Darabi, H. R.; Oda, M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1556–1557.

4. For a review, see: Sonogashira, K. In *Comprehensive Organic Synthesis*; Trost, B. M.; Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 3, pp. 521–549.

5. Wu, Z.; Moore, J. S. *Tetrahedron Lett.* **1994**, *35*, 5539–5542.

6. Compound **3a**: ^{1}H NMR (300 MHz, $CDCl_3$; ring-proton chemical shift): δ 8.67 (2H, t, $J = 1.2$ Hz), 7.68 (2H, t, $J = 7.5$ Hz), 7.43 (4H, dd, $J = 8.4$ and 1.2 Hz), 7.35 (2H, t, $J = 8.4$ Hz), 7.32 (4H, d, $J = 7.5$ Hz); ^{13}C NMR (75.4

MHz, $CDCl_3$; ring and triple bond carbon chemical shift): δ 144.2, 143.8, 137.0, 129.1, 128.6, 123.4, 122.9, 92.1, 90.6; HR-MS (FAB, positive-ion mode, matrix: 3-NBA) calcd. for $C_{30}H_{15}N_2$ ([M+H]+) 403.1235, found 403.1219.
Compound **3b**: ^{1}H NMR (300 MHz, $CDCl_3$; ring-proton chemical shift): δ 8.84 (2H, t, $J = 1.2$ Hz), 8.11 (4H, d, $J = 1.2$ Hz), 7.73 (2H, t, $J = 8.0$ Hz), 7.38 (4H, d, $J = 8.0$ Hz); ^{13}C NMR (75.4 MHz, $CDCl_3$; ring and triple bond carbon chemical shift): δ 147.8, 143.8, 137.0, 131.3, 130.2, 123.7, 123.6, 93.0, 89.6; HR-MS (FAB, positive-ion mode, matrix: 3-NBA) calcd. for $C_{34}H_{18}N_2O_4$ 518.1267, found 518.1233.
Compound **3c**: ^{1}H NMR (300 MHz, $CDCl_3$; ring-proton chemical shift): δ 8.85 (2H, t, $J = 1.8$ Hz), 8.10 (4H, d, $J = 1.8$ Hz), 7.73 (2H, t, $J = 7.8$ Hz), 7.38 (4H, d, $J = 7.8$ Hz); ^{13}C NMR (75.4 MHz, $CDCl_3$; ring and triple bond carbon chemical shift): δ 147.1, 143.6, 137.2, 131.4, 130.1, 123.8, 123.2, 92.7, 89.6; HR-MS (FAB, positive-ion mode, matrix: 3-NBA) calcd. for $C_{40}H_{30}N_2O_4$ 602.2206, found 602.2181.

7. Crystal data for **3b**·4CHCl$_3$: $C_{38}H_{22}N_2O_4Cl_{12}$, $M = 996.04$, triclinic, $P\bar{1}$ (#2), $a = 7.624(2)$, $b = 9.677(2)$, $c = 15.715(5)$ Å, $\beta = 96.927(9)°$, $V = 1071.4(5)$ Å^3, $Z = 1$, $D_{calcd} = 1.544$ g/cm^3, $R = 0.085$, $R_W = 0.225$, Quantum CCD area detector coupled with a Rigaku AFC8 diffractometer, 15959 measured reflections, Mo Kα, 4896 unique ($R_{int} = 0.021$), 286 variables [$I > 2\sigma(I)$].
Crystal data for **3c**·2CHCl$_3$: $C_{42}H_{32}N_2O_4Cl_6$, $M = 841.44$, triclinic, $P\bar{1}$ (#2), $a = 8.743(6)$, $b = 9.912(8)$, $c = 12.357(9)$ Å, $\beta = 70.27(2)°$, $V = 969.7(13)$ Å^3, $Z = 1$, $D_{calcd} = 1.441$ g/cm^3, $R = 0.103$, $R_W = 0.236$, Rigaku Mercury, 7723 measured reflections, Mo Kα, 5920 unique ($R_{int} = 0.075$), 261 variables [$I > 2\sigma(I)$].

8. Similar angle strain at the triple bonds was observed in [2.2.2.2]metacyclophane-1,9,17,25-tetrayne (see Ref. 3).

9. Ring-proton chemical shifts for **3c** and **3c**–SbCl$_5$: **3c**: ^{1}H NMR (300 MHz, CD_2Cl_2): δ 8.92 (2H, t, $J = 1.2$ Hz), 8.10 (4H, d, $J = 1.2$ Hz), 7.77 (2H, t, $J = 8.0$ Hz), 7.41 (4H, d, $J = 8.0$ Hz).
3c–SbCl$_5$: ^{1}H NMR (300 MHz, CD_2Cl_2): δ 9.59 (2H, t, $J = 1.2$ Hz), 8.58 (2H, t, $J = 8.0$ Hz), 8.40 (4H, d, $J = 1.2$ Hz), 7.99 (4H, d, $J = 8.0$ Hz).

10. Fluorescence spectrum of this complex does not change after one week at ambient temperature in the dark.

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

12. Matsuura, A.; Nishinaga, T.; Komatsu, K. *J. Am. Chem. Soc.* **2000**, *122*, 10007–10012.

13. Yamaguchi, S.; Swager, T. M. *J. Am. Chem. Soc.* **2001**, *123*, 12087–12088.