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ORIGINAL ARTICLE

Convenient synthesis of macrocycles with catechol-type moiety and their neutral boron complexes with pyrene fluorophore for anion sensing

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Abstract A series of medium ring-sized macrocycles **4a–4e** bearing catechol-type moiety were synthesized readily by direct cyclization of di(acid chloride) **1** with diamine derivatives without high-dilution conditions followed by tandem Claisen rearrangement. Complexation of macrocycles **4** with 1-pyrene-boronic acid yielded their corresponding neutral macrocyclic boron complexes **5** with pyrene unit as fluorophore in high yields. Anion sensing properties of these neutral boron complexes were also investigated.

Keywords tandem Claisen rearrangement · Catechol moiety · Macrocycle synthesis · Boron complex · Pyrene fluorophore · Anion sensing

Introduction

Macrocycles containing multi-hydrogen bonding sites have gained considerable attention recently because of their ability of complexation toward ionic and/or neutral molecules [1–3]. Although the excellent capabilities of catechol derivatives in the chelation with metal cations and construction of supramolecular architectures have been well known and extensively studied over recent years [4–8], little attention has been paid to macrocycles functionalized by catechol moieties owing to synthetic inconvenience.

In the course of our continuous studies on tandem Claisen rearrangement [9–14], we found that catechol moieites could be readily introduced into acyclic and/or cyclic molecular structures by this method [15–17]. More recently, we developed a novel and efficient synthetic route to macrocycles under normal conditions (that is, without high dilution method or template method) (Scheme 1), further exploration revealed that isobutenyl group and ether oxygen atoms in the di(acid chloride) compound played the key role in making macrocyclization [18].

Accordingly, on the basis of this discovery, we describe here an efficient synthesis of novel macrocycles with catechol moiety, and the complexation of these macrocycles with 1-pyrene-boronic acid in order to prepare neutral boron complexes with pyrene fluorophore. The preliminary results on anion sensing properties of this type of boron complex are also reported.

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Experimental

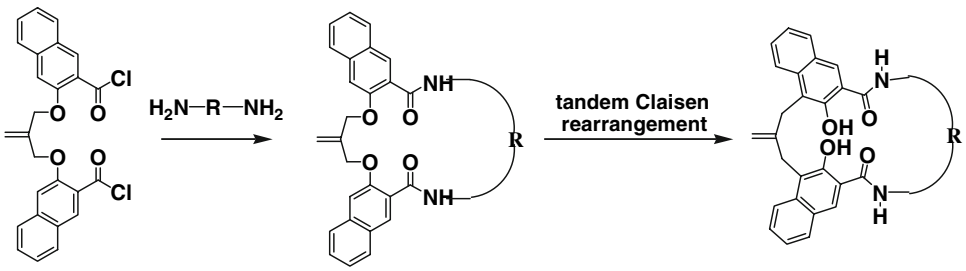
General information

All commercial-grade chemicals and solvents were used without further purification. Tetra-*n*-butylammonium salts were dried under vacuum prior to use. ^{1}H NMR spectra were recorded on a Varian NMR System 500 spectrometer operating at 500 MHz in $CDCl_3$ with Me_4Si as an internal standard. Elemental analyses were obtained on a Fisons EA1108 CHNS–O. MS were measured on BRUKER MALDI–TOF–MS apparatus. The fluorescence data were measured on a JASCO FP-6300 fluorescence spectrophotometer.

General procedure for synthesis of macrocyclic polyether **3**

A solution of diamine derivatives (1 mmol) containing $(Et)_3N$ (200 mg, 2 mmol) in 20 mL dry tetrahydrofuran

Scheme 1 Novel synthetic route to macrocycles



(THF) was prepared in a flask and was cooled by ice-water bath, then isobutenyl binaphthyl di(acid chloride) **1** (0.677 g, 1 mmol), also in 20 mL THF, was added dropwise to the solution over period of about 20 min and stirring was continued for overnight at room temperature. THF was evaporated off under reduced pressure and water was added into the residue to give a solid. The solid was filtered off, washed several times with water and dried. Purification was performed by column chromatography with mixed AcOEt and $CHCl_3$ as the eluent. Polyether compounds (**3a–3e)** were obtained as the main products in moderate to good yields.

3a: yellowish solid, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.60–1.63 (–CH_2–, 4H, m), 3.30–3.34 (CONH–CH_2–, 4H, m), 4.76 (=C–CH_2–O, 2H, s), 4.97 (=C–CH_2–O, 2H, s), 5.59 (CH_2=C, 2H, s), 5.67(CH_2=C, 2H, s), 7.16 (Ar–*H*, 2H, s), 7.22 (Ar–*H*, 2H, s), 7.32–7.34(Ar–*H*, 2H, m), 7.38–7.41(Ar–*H*, 2H, m), 7.50–7.53(Ar–*H*, 2H, m), 7.60–7.63(Ar–*H*, 2H, m), 7.71 (Ar–*H*, 2H, d, 8 Hz), 7.85(Ar–*H*, 2H, d, 8 Hz), 7.98(*NH*, 2H, broad), 8.67(Ar–*H*, 2H, s); TOF–MS: m/z 701.4 $(M + Na)^+$; Anal calcd. for $C_{43}H_{38}N_2O_6 \cdot 2/3CHCl_3$: C, 69.29; H, 5.25; N, 3.70. Found: C, 69.26; H, 5.32; N, 3.29.

3b: white solid, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.16–1.19 (–CH_2–, 4H, m), 1.40–1.43 (–CH_2–, 4H, m), 3.30–3.33 (CONH–CH_2–, 4H, m), 4.81 (=C–CH_2–O, 2H, s), 4.99 (=C–CH_2–O, 2H, s), 5.57 (CH_2=C, 2H, s), 5.72 (CH_2=C, 2H, s), 7.20 (Ar–*H*, 2H, s), 7.28(Ar–*H*, 2H, s), 7.35–7.38(Ar–*H*, 2H, m), 7.41–7.44(Ar–*H*, 2H, m), 7.52–7.55(Ar–*H*, 2H, m), 7.66–7.69(Ar–*H*, 2H, m), 7.75 (Ar–*H*, 2H, d, 8 Hz), 7.93(Ar–*H*, 2H, d, 8 Hz), 7.98(*NH*, 2H, broad), 8.78(Ar–*H*, 2H, s); TOF-MS: m/z 743.5 $(M + Na)^+$; Anal calcd. for $C_{46}H_{44}N_2O_6 \cdot 1/3CHCl_3$: C, 73.25; H, 5.88; N, 3.69. Found: C, 73.15; H, 5.98; N, 3.51.

3c: yellowish solid, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.50–3.55 (O–CH_2–, 8H, m), 3.61–3.64 (CONH–CH_2–, 4H, m), 4.85 (=C–CH_2–O, 2H, s), 4.95 (=C–CH_2–O, 2H, s), 5.51 (CH_2=C, 2H, s), 5.64 (CH_2=C, 2H, s), 7.18 (Ar–*H*, 2H, s), 7.23 (Ar–*H*, 2H, s), 7.34–7.36 (Ar–*H*, 2H, m), 7.39–7.42 (Ar–*H*, 2H, m), 7.49–7.52 (Ar–*H*, 2H, m), 7.62–7.65 (Ar–*H*, 2H, m), 7.68 (Ar–*H*, 2H, d, 8.5 Hz), 7.89 (Ar–*H*, 2H, d, 8 Hz), 8.32 (*NH*, 2H, broad), 8.75(Ar–*H*, 2H, s); TOF–MS: m/z 753.5 $(M + H)^+$; Anal calcd. for $C_{46}H_{44}N_2O_8 \cdot 1/3CHCl_3 \cdot H_2O$: C, 68.73; H, 5.77; N, 3.46; Found: C, 68.65; H, 5.68; N, 3.42.

3d: yellowish solid, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 4.36–4.38 (CONH–CH_2–, 4H, m), 4.50 (=C–CH_2–O, 2H, s), 4.94 (=C–CH_2–O, 2H, s), 5.42 (CH_2=C, 2H, s), 5.51 (CH_2=C, 2H, s), 7.06 (Ar–*H*, 6H, s), 7.28 (Ar–*H*, 2H, s), 7.39–7.42 (Ar–*H*, 2H, m), 7.43–7.45 (Ar–*H*, 2H, m), 7.53–7.56 (Ar–*H*, 2H, m), 7.66–7.69 (Ar–*H*, 2H, m), 7.76 (Ar–*H*, 2H, d, 8 Hz), 7.94 (Ar–*H*, 2H, d, 8 Hz), 8.24 (*NH*, 2H, broad), 8.84 (Ar–*H*, 2H, s); TOF–MS: m/z 741.3 $(M + H)^+$; Anal calcd. for $C_{48}H_{40}N_2O_6 \cdot 1/3CHCl_3$: C, 74.40; H, 5.21; N, 3.59. Found: C, 74.31; H, 5.39; N, 3.44.

3e: It had been reported before by us synthesized by high-dilution method in 36% yield [17]. Pale yellow solid, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.61–1.64 (–CH_2–, 4H, m), 3.30–3.39 (O–CH_2–, 12H, m), 4.76 (=C–CH_2–O, 2H, s), 4.82 (=C–CH_2–O, 2H, s), 5.38 (CH_2=C, 2H, s), 5.50 (CH_2=C, 2H, s), 7.06 (Ar–*H*, 2H, s), 7.16 (Ar–*H*, 2H, s), 7.24–7.27 (Ar–*H*, 4H, m), 7.33–7.36 (Ar–*H*, 2H, m), 7.49 (Ar–*H*, 2H, d, 8 Hz), 7.54–7.57 (Ar–*H*, 2H, m), 7.74 (Ar–*H*, 2H, d, 8 Hz), 8.02 (*NH*, 2H, broad), 8.54(Ar–*H*, 2H, s); TOF–MS: m/z 839.5 $(M + H)^+$.

Synthesis of macrocycles **4** with catechol moiety

Polyethers **3** (100 mg) were dissolved in NMP (5 mL) and the solution was heated at 160 °C for some time different with the ring-size under Argon atmosphere. After removal of NMP under reduced pressure, the residue was subjected to column chromomatography on silica gel using mixed solvents of AcOEt and $CHCl_3$ as an eluent. The target macrocycles **4** were obtained as the main product in more than 90% yields.

4a: brown powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.25–1.29 (–CH_2–, 4H, m), 3.58–3.62 (CONH–CH_2–, 4H, m), 3.78 (=C–CH_2–O, 2H, s), 3.84 (=C–CH_2–O, 2H, s), 5.03 (CH_2=C, 2H, s), 5.17(CH_2=C, 2H, s), 6.28 (Ar–*OH*, 2H, s), 7.14–7.16(Ar–*H*, 2H, m), 7.20 (*NH*, 2H, broad), 7.44–7.47 (Ar–*H*, 4H, m, broad), 7.66–7.68(Ar–*H*, 2H, m), 7.86

(Ar–*H*, 2H, d, 8 Hz), 7.93 (Ar–*H*, 2H, s), 9.79 (Ar–*OH*, 2H, s); TOF–MS: m/z 677.5 $(M - H)^-$.

4b: brown powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.44–1.48 (–CH_2–, 4H, m), 1.63–1.67 (–CH_2–, 4H, m), 3.46–3.50 (CONH–CH_2–, 4H, m), 3.84 (=C–CH_2–O, 2H, s), 3.97 (=C–CH_2–O, 2H, s), 4.72 (CH_2=C, 2H, s), 4.82(CH_2=C, 2H, s), 6.34 (Ar–*OH*, 2H, s), 6.85(*NH*, 2H, broad), 7.12–7.14(Ar–*H*, 2H, m), 7.27–7.30 (Ar–*H*, 2H, m), 7.48–7.52 (Ar–*H*, 2H, m), 7.64–7.66(Ar–*H*, 2H, m), 7.70 (Ar–*H*, 2H, d, 8 Hz), 7.89 (Ar–*H*, 2H, s), 7.99(Ar–*H*, 2H, d, 8 Hz), 11.28(Ar–*OH*, 2H, s); TOF–MS: m/z 719.9 $(M - H)^-$.

4c: brown powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.47–3.49 (O–CH_2–, 8H, m), 3.59–3.65 (CONH–CH_2–, 4H, m), 3.74 (=C–CH_2–O, 2H, s), 3.97 (=C–CH_2–O, 2H, s), 4.96 (CH_2=C, 2H, s), 5.05 (CH_2=C, 2H, s), 6.04 (Ar–*OH*, 2H, s), 6.51 (*NH*, 2H, broad), 6.80–6.85 (Ar–*H*, 2H, m), 7.20–7.23 (Ar–*H*, 2H, m), 7.31–7.33 (Ar–*H*, 2H, m), 7.39–7.42 (Ar–*H*, 2H, m), 7.53 (Ar–*H*, 2H, d, 8 Hz), 7.63 (Ar–*H*, 2H, s), 7.86 (Ar–*H*, 2H, d, 8 Hz), 11.68(Ar–*OH*, 2H, s); TOF–MS: m/z 751.5 $(M - H)^-$.

4d: brown powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.74 (=C–CH_2–O, 2H, s), 3.98 (=C–CH_2–O, 2H, s), 4.43 (CH_2=C, 2H, s), 3.61–4.62 (CONH–CH_2–, 4H, m), 4.64(CH_2=C, 2H, s), 6.60 (Ar–*OH*, 2H, s), 7.21 (Ph–*H*, 4H, s), 7.23–7.24 (Ar–*H*, 2H, m), 7.28–7.31 (Ar–*H*, 2H, m), 7.51–7.54 (Ar–*H*, 2H, m), 7.71–7.74 (Ar–*H*, 4H, m), 8.01 (Ar–*H*, 2H, d, 8 Hz), 8.09 (*NH*, 2H, broad), 8.31 (Ar–*H*, 2H, s), 10.63 (Ar–*OH*, 2H, s); TOF–MS: m/z 739.5 $(M - H)^-$.

4e: see Ref [17]. brown powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.77–1.81 (–CH_2–, 4H, m), 3.43–3.53 (O–CH_2–, 12H, m), 3.56–3.58 (CONH–CH_2–, 4H, m), 3.85 (=C–CH_2–O, 2H, s), 3.93 (=C–CH_2–O, 2H, s), 4.92 (CH_2=C, 2H, s), 4.93 (CH_2=C, 2H, s), 6.15 (Ar–*OH*, 2H, s) , 7.00–7.02 (Ar–*H*, 2H, m), 7.14–7.17 (Ar–*H*, 2H, m), 7.29 (*NH*, 2H, broad), 7.31–7.33 (Ar–*H*, 2H, m), 7.52 (Ar–*H*, 2H, d, 8 Hz), 7.57–7.59 (Ar–*H*, 2H, m), 7.64 (Ar–*H*, 2H, s), 7.71 (Ar–*H*, 2H, d, 8 Hz), 12.12 (Ar–*OH*, 2H, s); TOF–MS: m/z 837.4 $(M - H)^-$.

Synthesis of macrocyclic boron complexes **5**

A mixture of the same equivalent of macrocycles **4** and 1-pyrene-boronic acid was dissolved in dry $CHCl_3$ in the presence of molecular sieve 4A, and the solution was continued to reflux overnight. After removal of the molecular sieve 4A by filtration and $CHCl_3$ by evaporation under vacuum, the residue was washed several times by cool methanol to give pure boron complexes **5** in excellent yields.

5a: green powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.18–1.23 (–CH_2–, 2H, m), 3.84–3.86 (CONH–CH_2–, 4H, m), 4.02 (=C–CH_2–O, 2H, s), 4.15 (=C–CH_2–O, 2H, s), 5.15 (CH_2=C, 2H, s), 5.24 (CH_2=C, 2H, s), 6.90 (*NH*, 2H, broad), 7.30–7.32(Ar–*H*, 2H, m), 7.38 (Ar–*H*, 2H, broad), 7.48–7.53 (Ar–*H*, 4H, m), 7.63 (Ar–*H*, 2H, broad), 7.73 (Ar–*H*, 2H, broad), 7.81–7.83 (Py–H, 1H, m), 7.99–8.02 (Py–H, 2H, m), 8.13 (Ar–*H*, 2H, s), 8.15–8.22 (Py–H, 4H, m), 8.38 (Py–*H*, 1H, d, 7.5 Hz), 8.43 (Py–*H*, 1H, d, 7.5 Hz), 9.35 (Ar–*OH*, 2H, s); TOF–MS: m/z 887.6 $(M - H)^-$.

5b: green powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.12–1.17 (–CH_2–, 8H, broad, m), 3.18–3.22 (CONH–CH_2–, 4H, m), 4.00 (=C–CH_2–O, 2H, s), 4.08 (=C–CH_2–O, 2H, s), 5.05 (CH_2=C, 2H, s), 5.14 (CH_2=C, 2H, s), 6.03 (*NH*, 2H, broad), 7.29–7.32(Ar–*H*, 2H, m), 7.36–7.38 (Ar–*H*, 2H, m), 7.49–7.53 (Ar–*H*, 4H, m), 7.59 (Ar–*H*, 2H, d, 8.5 Hz), 8.05–8.07 (Ar–*H*, 2H, m), 8.09–8.10 (Py–H, 1H, m), 8.10–8.12 (Py–H, 2H, m), 8.17 (Ar–*H*, 2H, s), 8.18–8.32 (Py–H, 4H, m), 8.38 (Py–*H*, 1H, d, 7.5 Hz), 8.96 (Py–*H*, 1H, d, 7.5 Hz), 11.35 (Ar–*OH*, 2H, s); TOF–MS: m/z 929.4 $(M + H)^+$; Anal calcd. for $C_{62}H_{51}BN_2O_6 \cdot 1/3CHCl_3 \cdot H_2O$: C, 75.74; H, 5.44; N, 2.84. Found: C, 75.57; H, 5.45; N, 2.84.

5c: green powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ3.35–3.38 (CONH–CH_2–, 4H, m), 3.49–3.52 (O–CH_2–, 8H, m), 3.96 (=C–CH_2–O, 2H, s), 4.05 (=C–CH_2–O, 2H, s), 5.09 (CH_2=C, 2H, s), 5.23 (CH_2=C, 2H, s), 6.60 (*NH*, 2H, broad), 7.07–7.09 (Ar–*H*, 2H, m), 7.17–7.21 (Ar–*H*, 2H, m), 7.45–7.249 (Ar–*H*, 4H, m), 7.71–7.74 (Ar–*H*, 2H, m), 7.97 (Ar–*H*, 2H, d, 8.5 Hz), 8.16–8.22 (Py–H, 1H, m), 8.18 (Ar–*H*, 2H, s), 8.24–8.40 (Py–H, 7H, m), 8.97 (Py–*H*, 1H, d, 7.5 Hz), 11.56 (Ar–*OH*, 2H, s); TOF–MS: m/z 961.7 $(M + H)^+$.

5d: green powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.39 (=C–CH_2–O, 2H, s), 3.95 (=C–CH_2–O, 2H, s), 4.34 (CH_2=C, 2H, s), 4.56 (CONH–CH_2–, 4H, m), 4.83 (CH_2=C, 2H, s), 6.08 (*NH*, 2H, broad), 7.33–7.36 (Ar–*H*, 2H, m), 7.56–7.60 (Ar–*H*, 2H, m), 7.85–7.87 (Ar–*H*, 2H, m), 8.01–8.02 (Ar–*H*, 2H, m), 8.07–8.08 (Py–H, 1H, m), 8.08 (Ph–*H*, 4H, s), 8.13–8.15 (Py–H, 2H, m), 8.19–8.22 (Py–H, 2H, m), 8.26–8.27 (Ar–*H*, 4H, m), 8.31–8.34 (Py–H, 2H, m), 8.59 (Ar–*H*, 2H, s), 8.61 (Py–*H*, 1H, d, 7.5 Hz), 9.96 (Py–*H*, 1H, d, 7.5 Hz), 12.58 (Ar–*OH*, 2H, s); TOF–MS: m/z 949.8 $(M + H)^+$.

5e: green powder, ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.63–1.64 (–CH_2–, 4H, m), 3.24–3.27 (CONH–CH_2–, 4H, m), 3.30–3.33 (O–CH_2–, 4H, m), 3.48–3.49 (O–CH_2–, 8H, m), 4.03 (=C–CH_2–O, 2H, s), 4.05 (=C–CH_2–O, 2H, s), 5.09 (CH_2=C, 2H, s), 5.14 (CH_2=C, 2H, s), 7.02 (*NH*, 2H, broad), 7.15–7.17 (Ar–*H*, 2H, m), 7.20–7.23 (Ar–*H*, 2H, m), 7.52–7.53 (Ar–*H*, 4H, m), 7.92 (Ar–*H*, 2H, d, 8.5 Hz), 7.96–7.97 (Ar–*H*, 2H, m), 8.07–8.16 (Py–H, 3H, m), 8.17 (Ar–*H*, 2H, s), 8.18–8.32 (Py–H, 4H, m), 8.44 (Py–*H*, 1H, d, 7.5 Hz), 8.98 (Py–*H*, 1H, d, 7.5 Hz), 12.04 (Ar–*OH*, 2H, s); TOF–MS: m/z 1033.8 $(M - H)^-$.

Results and discussion

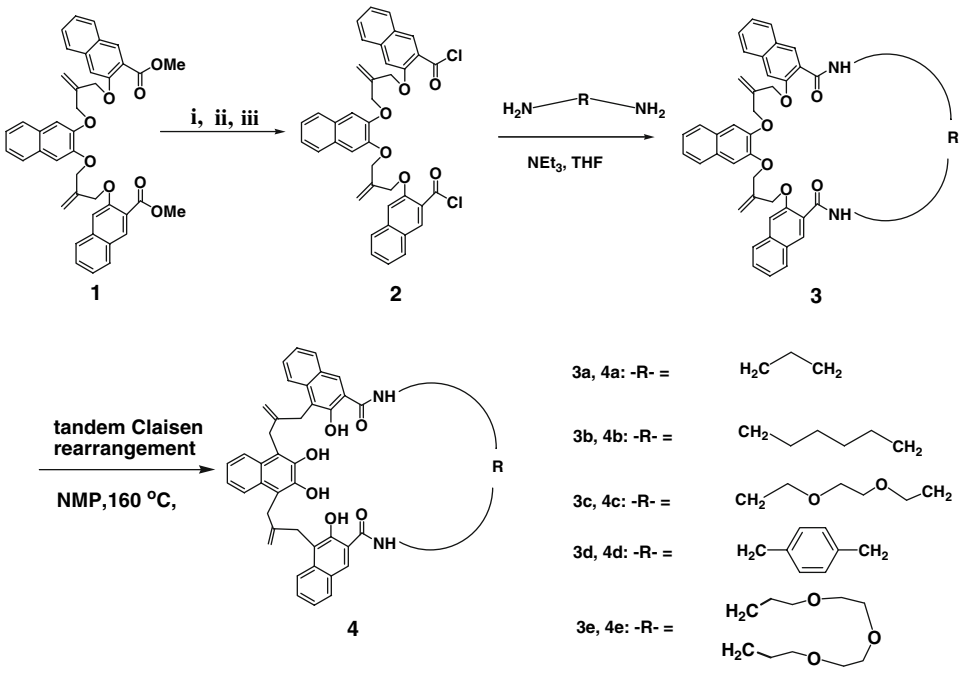
Synthesis of macrocycles **4** functionalized by catechol-type moiety

Scheme 2 shows the synthetic route to macrocycles **4** with catechol-type moiety. Aryl ether **1** was prepared according to previously reported procedure, which has two methallylarylether moieties as the key component for introduction of catechol-type unit *via* tandem Claisen rearrangement (TCR) [19]. After hydrolysis of **1** and then treatment with thionyl chloride, di(acid chloride) **2** was prepared readily. Macrocyclic polyether **3** were obtained by the direct cyclization between di(acid chloride) **2** and diamine derivatives under normal conditions in good yields. Then, by tandem Claisen rearrangement our target macrocycles **4** were prepared in excellent yields. The results are summarized in Table 1.

The most significant step within this synthetic route is the 1:1 macrocyclization between di(acid chloride) and diamine derivatives under mild conditions since the existing synthetic methods at present for macrocycles have to employ some special reaction conditions, such as high dilution, and template control, to pay for the extra large enthalpic and entropic penalties. We deduced in our latest study that the isobutenyl group in the di(acid chloride) seemed to be entropically advantageous for formation of macrocycles [18]. Therefore, in the present study, we utilized di(acid chloride) bearing two isobutenyl moieties as the starting material for macrocyclization, with one aim to explore the generality of this novel synthetic strategy for macrocycles and the other aim to introduce catechol unit into the macrocycles conveniently. Just as expected, the reaction of di(acid chloride) bearing two isobutenyl groups with diamine derivatives also yielded macrocycles in good yields, although the corresponding yields were relatively lower compared to the former case. This result proved further the significantly important role of isobutenyl groups for compensating the extra large enthalpic and entropic penalties in the course of 1:1 macrocyclization under no high dilution conditions. As for the lower yields obtained in this case, we attributed it to the more flexibility of di(acid chloride) used here than the former case.

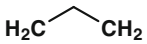
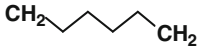
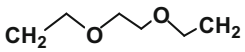
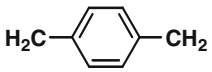
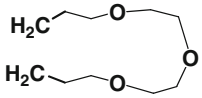
Catechol-type moiety was introduced readily into macrocyclic polyethers **3** to give macrocycles **4** by tandem Claisen rearrangement. In our previously reported case, tandem Claisen rearrangement was performed in the molten state without solvent, and the products were obtained in excellent yields. By contrast, for the ploye thers **3** containing two methallyarylether moieties, rearrangement in the molten state gave poor results under the same conditions as the previously reported. Accordingly, the rearrangement was carried out in solution of *N*-methyl-2-pyrrolidinone (NMP), which had been proved to be a good solvent for the tandem Claisen rearrangement [11–13]. After treatment, the corresponding macrocycles **4** were yielded in nearly quantitative yields. It was clear from the ^{1}H NMR spectra that macrocyclic polyethers **3** were successfully converted into macrocycles **4**.

As an example, Fig. 1 shows the ^{1}H NMR spectra of **3b** and **4b**. After tandem Claisen rearrangement, catechol OH proton appeared at 6.34 ppm; in contrast, the other two



Scheme 2 Synthetic route to macrocycles with catechol moiety. Reaction conditions: (i) 1:4 THF/EtOH, 5 eq.NaOH, 60 °C, 4 h; (ii) excess HCl; (iii) excess $SOCl_2$, 70 °C,1 h

Table 1 Yields[a] of the macrocyclization and rearrangement

Entry	–R–	Cyclization		Conditions of rearrangement	Rearrangement	
		Product	Yield (%)		Product	Yield (%)
1		**3a**	65	NMP, 160 °C, 1.5 h	**4a**	93
2		**3b**	60	NMP, 160 °C, 30 min	**4b**	94
3		**3c**	45	NMP, 160 °C, 1 h	**4c**	93
4		**3d**	35	NMP, 160 °C, 30 min	**4d**	94
5		**3e**	36	NMP, 160 °C, 1 h	**4e**	92

[a] Isolated yields

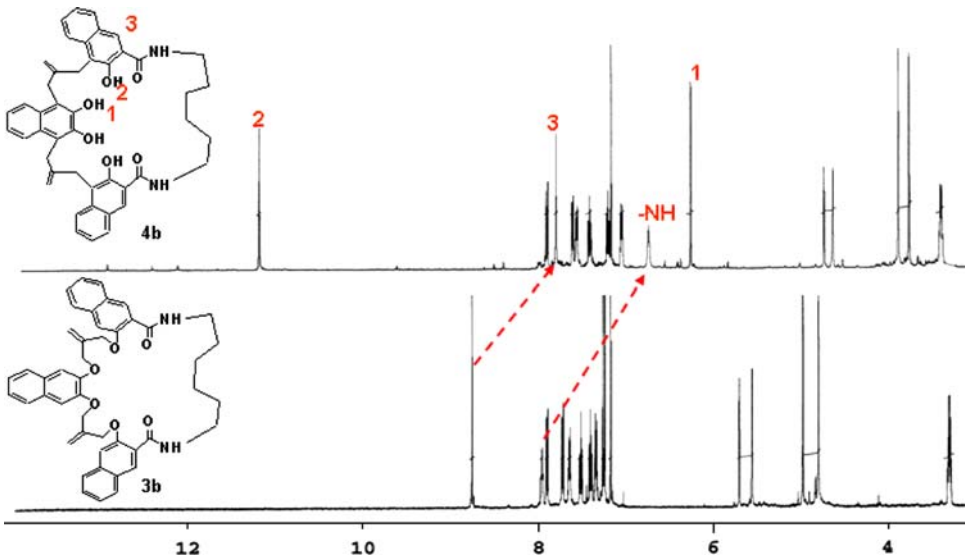


Fig. 1 Partial ^{1}H NMR spectra of macrocycles **3b** (before rearrangement) and **4b** (after rearrangement)

phenolic OH protons appeared at relatively lower field, 11.28 ppm, due to the formation of intramolecular hydrogen bonding between –OH and carbonyl group. Whilst, the intramolecular hydrogen bonding interaction also induced the amide NH proton shift from 7.98 ppm (before rearrangement) to 6.85 ppm at higher field (after rearrangement). In addition, it is note that proton of naphthoate at 4 position shift from 8.78 ppm to 7.89 ppm at higher field. It is assumed that intramolecular hydrogen bonding between proton at 4 position of naphthoate group and O atom of carbonyl group is broken after TCR accompanied with the new formation of intramolecular hydrogen bonding between –OH and C=O group as shown in Fig. 2. The peaks based on the isobutenyl unit shifted upfield significantly, which were attributed to the formation of *C*-isobutenyl bonds from *O*-isobutenyl bonds. The same behaviors were observed in ^{1}H NMR spectra for all of other cases.

Synthesis of macrocyclic boron complexes **5** and its anion sensing properties

As well-known in previously reported literatures [15, 16], catechol-type moieties easily formed anionic and neutral complexes with boronic acid. Accordingly, complexation of macrocycles **4** with boronic acid was carried out in the presence of MS 4A in boiling $CHCl_3$ solution overnight to give neutral boron complex **5** in excellent yields. Herein 1-pyrene-boric acid was utilized as the complexation ligand in order to introduce pyrene fluorophore into the macrocycles (Scheme 3). Up to now, although a substantial number of fluorescent chemosensors for ions and molecules have been reported, only a few systems are based on neutral boron complex bound directly with pyrene fluorophores [20]. It can be expected that this new macrocyclic boron complexes **5** is attractive for anion sensing owing to

its plural hydrogen bonding sites (hydroxy and amide groups), Lewis acid site (neutral boron atom) and signaling subunit (pyrene fluorophore). From the ^{1}H NMR spectra shown in Fig. 3, it was clearly found that, neutral boron complexes **5** bearing pyrene fluorophore was successfully obtained from the reaction of macrocycles **4** with 1-pyreneboronic acid. After boron complexation, the peak based on catechol OH proton disappeared together with the peaks assigned to pyrene moiety appeared. On the other hand, OH peaks based on naphtoate group remain without significant shift (**4b**: 11.28 ppm, **5b**: 11.35 ppm).

The anion sensing properties of this new type of neutral boron complex were explored by using fluorescent spectroscopy. It was found that only complex **5e** exhibited F^- selectivity among certain anions, such as F^-, Cl^-, Br^-, I^-, $H_2PO_4^-$, CH_3COO^-, and HSO_4^- with tetrabutylammonium as counter ion. Upon addition of F^- anion, a new emission band at around 500 nm increased in intensity at the expense of the original emission band at 400 nm due to pyrene fluorophore (Fig. 4). Other boron complexes were proved no ability to discriminate the F^-, CH_3COO^- and $H_2PO_4^-$, indicating some structural or ring-size effect on them. We are currently investigating these unique phenomena in greater detail.

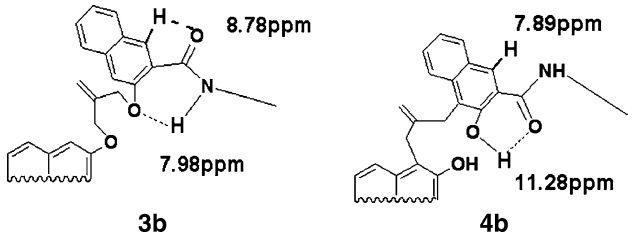
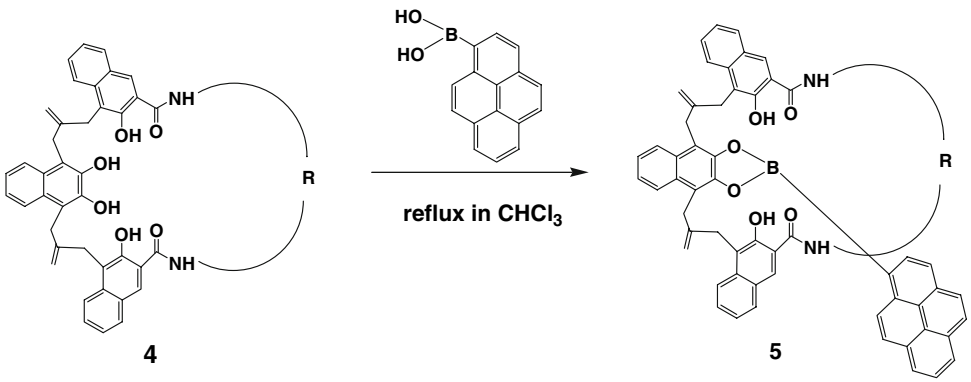


Fig. 2 Intramolecular hydrogen bonding pathway proposed for macrocycles **3b** (before TCR) and **4b** (after TCR)

Conclusion

A series of novel macrocycles **4** with catechol-type moiety have been readily synthesized by means of a convenient cyclization method and then tandem Claisen rearrangement. The obtained macrocycles **4** are significantly attractive because of the array of plural hydron-bonding groups in the cavity. Furthermore, new macrocyclic neutral boron complexes **5** have been also prepared by complexation of this kind of macrocycles with 1-pyrene-boric acid. Preliminary results have indicated the corresponding boron complexes **5** have the ability to act as anion sensor utilizing multiple hydrogen-bonding and Lewis acid–base interactions.

Scheme 3 Synthetic route to macrocyclic neutral boron complex



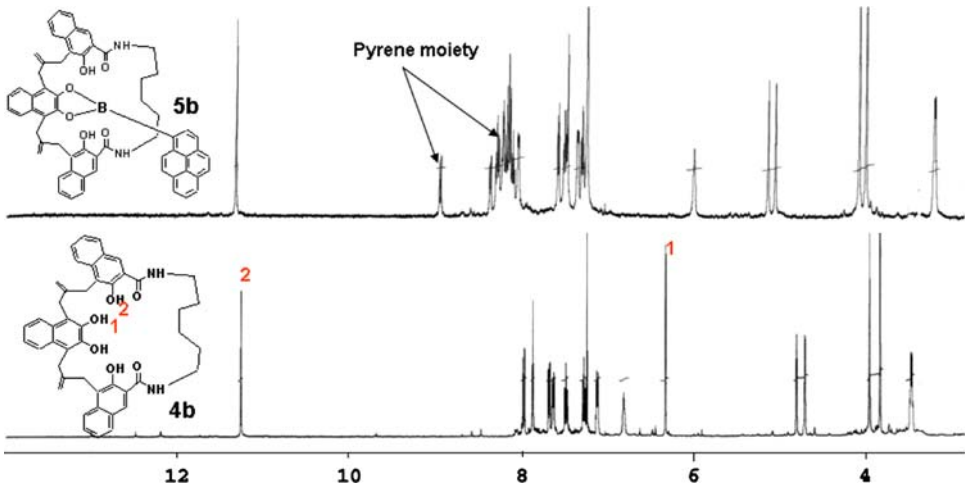


Fig. 3 Partial ^{1}H NMR spectra of macrocycles **4b** (before complexation) and **5b** (after complexation)

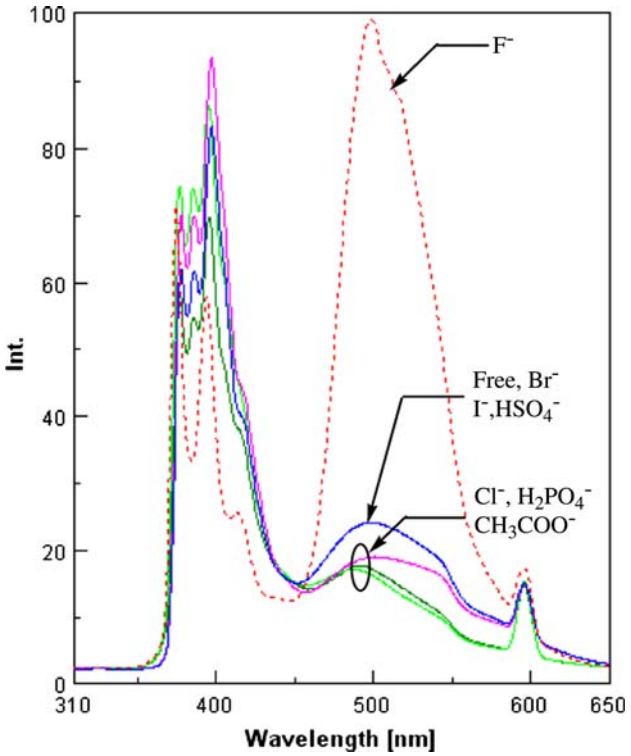


Fig. 4 Changes in the fluorescence spectra of **5e** upon addition of 50 eq various anions using tetrabutylammoium as counter ion (in CH_3CN, [**5e**]=5 $\times$ 10^{-5} M)

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