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Spiroborate-based dimeric assembly of oligo(ethylene glycol) end-capped with phenolic gallates

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ABSTRACT

The synthesis of oligo(ethylene glycol) with biphenolic gallates as termini and their assembly to dimeric structures upon spiroborate formation are described. Complexation of these dimeric structures with alkali metal ions showed selectivity to lithium and potassium by tuning the length of the ethyleneoxy units. The methoxycarbonyl group on the dimeric compound could be manipulated in harsh conditions without destruction of the dimeric structure.

Introduction

Since the classical crown ethers, cryptands, and calixarenes pioneered by Pedersen, Lehn, and Cram,[1] boron-assisted crown ethers,[2] borocryptands,[3] and other boron-based molecular assemblies[4] also have been attracting much attention. For example, spiroborate linkage has been utilized for the synthesis of double-stranded supramolecular architectures,[5] which consist of *ortho*-linked oligophenol chains bearing bipyridine units. Herein, we would like to report the preparation of oligo-ethyleneoxy ether strands bearing two gallic acid esters as termini, and their assembly to dimeric structures (Fig. 1. 2L+2B+M) upon spiroborate formation on the catechol-like motifs, and their complexation with alkali metal ions.

Results and discussions

As shown in Scheme 1, the synthesis was straightforward from gallic acid methyl ester **1**, which was converted into compound **2** in 61% yield by reacting with triethyl orthoformate in the presence of *p*-toluenesulfonic acid,[6] and subsequent alkylation with bis-tosylates of oligo(ethylene glycol) with K_2CO_3 as the base in DMF gave **3a**–**e** in 80–89% yields.[7] Liberation of the ortho-biphenolic motifs with 2 M aq HCl in methanol afforded the oligo-ethyleneoxy chain-linked bis-biphenolic compound **4a**–**e** in nearly quantitative yields.

To examine whether the assembly of the single stand ligands with boron and alkali metal ions could occur, the simple mixing experiments of **4a**–**e** with $Na_2B_4O_7$ were conducted and measured by ESI-MS (negative mode) with results shown in Table 1. The data revealed that *m*/*z* peaks bearing negative charges corresponding to $[2L+2B]^{2-}$ and $[2L+2B+Na]^{-}$ had been detected. Therefore, we postulated that dimeric structures of **4a**–**e** upon spiroborate linkage formation could be generated and their complexes with alkali metal ions would be attainable. As shown in Scheme 2, when refluxing **4a**–**e** with boric acid (1.03 equiv) in THF and toluene (v/v = 4/1) in the presence of 4A molecular sieves, the dimeric compound **5a**–**e** were obtained in 72–88% yields.

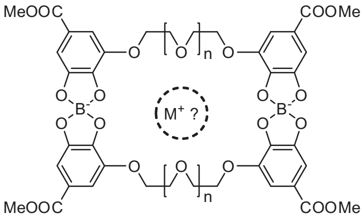

Figure 1. 2L+2B+M.

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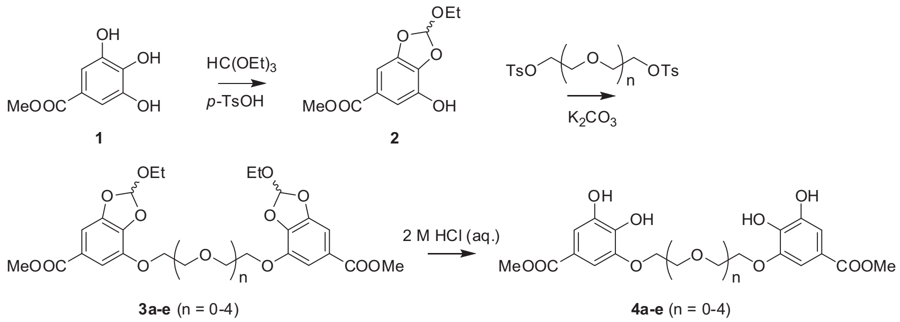


Scheme 1. Synthesis of oligo(ethylene glycol) with end-functionalities.

Table 1
ESI-MS (negative mode) of **4a–e** with $Na_2B_4O_7$

Entry	M	H_4L1-5 (n = 0–4)	MS-1 m/z	Composition	MS-2 m/z	Composition
1	Na	**4a** (n = 0)	401	$[2L1+2B]^{2-}$	825	$[2L1+2B+Na]^{-}$
2	Na	**4b** (n = 1)	445	$[2L2+2B]^{2-}$	913	$[2L2+2B+Na]^{-}$
3	Na	**4c** (n = 2)	489	$[2L3+2B]^{2-}$	1001	$[2L3+2B+Na]^{-}$
4	Na	**4d** (n = 3)	533	$[2L4+2B]^{2-}$	1089	$[2L4+2B+Na]^{-}$
5	Na	**4e** (n = 4)	577	$[2L5+2B]^{2-}$	1177	$[2L5+2B+Na]^{-}$

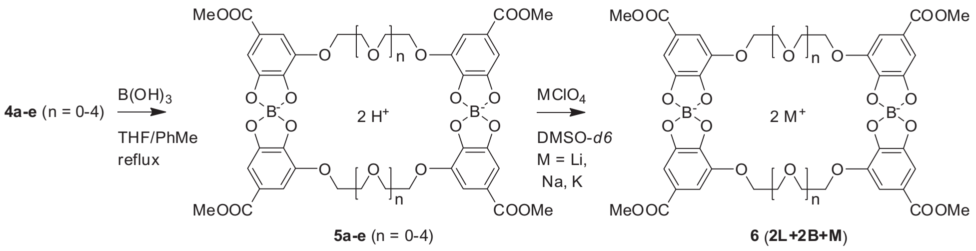
Then ion-exchange experiments of the dimeric **5a–e** with $MClO_4$ (M = Li, Na, K) were carried out. The reactions were monitored by NMR analysis, and significant changes in chemical shifts for combinations of **5c** with $LiClO_4$ and **5d** with $KClO_4$ compared to those of **5c** and **5d** were observed. As shown in Figure 2, addition of 2 equiv of $LiClO_4$ to **5c** resulted in downfield shifts for the aromatic Ha and Hb of **5c** (0.017 and 0.71 ppm), while the NMR spectra remained essentially the same upon addition of $NaClO_4$ and $KClO_4$. The lithium ion adduct was measurable by ESI-MS (negative mode) with m/z 489 and 985, which could be assigned to [**5c**$-2H]^{2-}$ and [**5c**$-2H+Li]^{-}$, respectively.

When mixing of **5d** with $KClO_4$, upfield shifts were observed as shown in Figure 3 for the aromatic Hb (−0.08 ppm), and the ethylene Hc (−0.068 and −0.175 ppm), and Hd (−0.041 ppm), which probably resulted from the inclusion of potassium-ions and their coordination to oxygen atoms. The potassium ion adduct was measurable by ESI-MS (negative mode) with m/z: 533 and 1105, corresponding to [**5d**$-2H]^{2-}$ and [**5d**$-2H+K]^{-}$, respectively. The dimeric structure was further supported by high resolution mass spectrum (positive mode): calcd for $C_{48}H_{52}B_2O_{26}K_2H^+$: 1145.2296, found 1145.2299, corresponding to [**5d**$-2H+2K+H]^+$; calcd for $C_{48}H_{52}B_2O_{26}K_3^+$: 1183.1855, found 1183.1860, corresponding to [**5d**$-2H+3K]^+$.

Slow evaporation of the solution of **5d** and $KClO_4$ in water and DMF precipitated single crystals for X-ray diffraction analysis. The X-ray crystallographic data[8] unambiguously revealed that the [**5d**$-$2H+2K] complex adopts a pseudo-D_2-symmetry (Fig. 4). Each spiroborate bridges two catechol-like biphenolic aromatic rings perpendicular to each other (O23/O24, B1, O25/O26; O19/O20, B2, O21/O22). Each potassium ion is embraced in the center of the tetra(ethylene glycol) loop and coordinated by five oxygen atoms (K1, O6–O10; K2, O1–O5) of the oligoether chain and two oxygen atoms (K1, O21/O25; K2, O19/O23) of the spiroborate linkages. According to the stereochemical arrangement, the [**5d**$-$2H+2K] complex should be in racemic form.

As for **5a**, **5b**, and **5e**, their ^1H NMR spectra showed no changes in chemical shifts upon addition of $LiClO_4$, $NaClO_4$, or $KClO_4$. We deduced that the above differences in binding affinities might have resulted from the variable cavity spaces, being limited in **5a** (n = 0) and **5b** (n = 1), loose in **5e** (n = 4), and optimal in **5c** (n = 2) for lithium ions and **5d** (n = 3) for potassium ions.

In order to test the stability of the dimeric assembly, as shown in Scheme 3, under nitrogen atmosphere, compound **5d** was treated with $LiAlH_4$ at 0 °C in THF, and further reaction with NaH and CH_3I afforded compound **7** in 60% yield over two steps. The NMR analysis showed that the tetrakis(methoxycarbonyl) groups had been converted into tetrakis(methoxymethyl) groups on the benzene ring, and the mass spectroscopic data[9] indicated that the dimeric structure had survived the harsh conditions without destruction during the post-modification process.



Scheme 2. Preparation of dimeric **5a–e** with spiroborate linkage and complexes with alkali metal ions.

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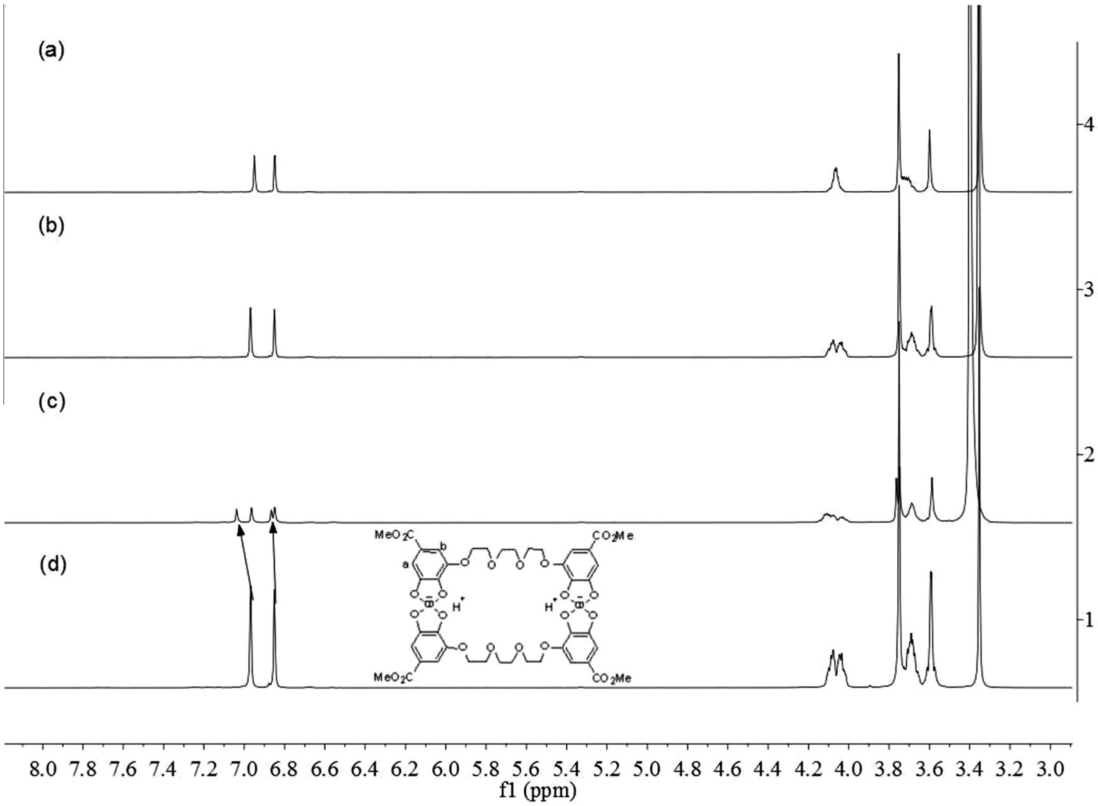

Figure 2. ^{1}H NMR spectra of (a) **5c**-$KClO_4$, (b) **5c**-$NaClO_4$, (c) **5c**-$LiClO_4$, (d) **5c**.

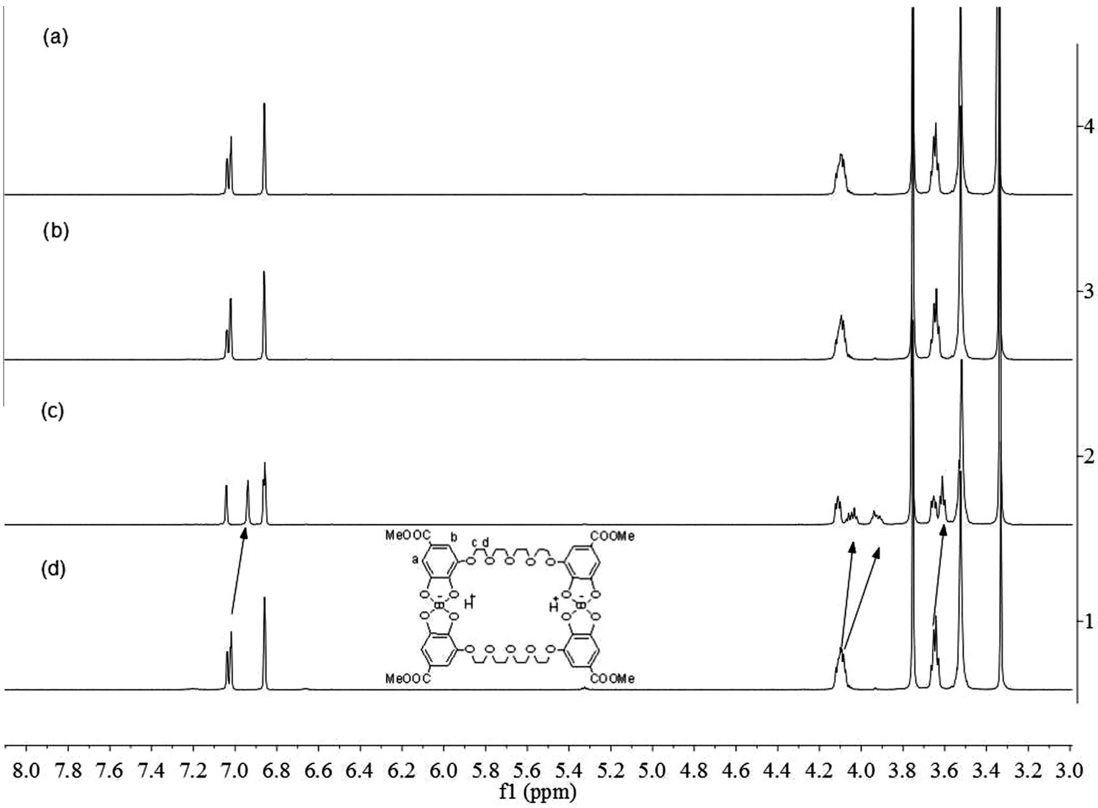

Figure 3. ^{1}H NMR spectra of (a) **5d**-$LiClO_4$, (b) **5d**-$NaClO_4$, (c) **5d**-$KClO_4$, (d) **5d**.

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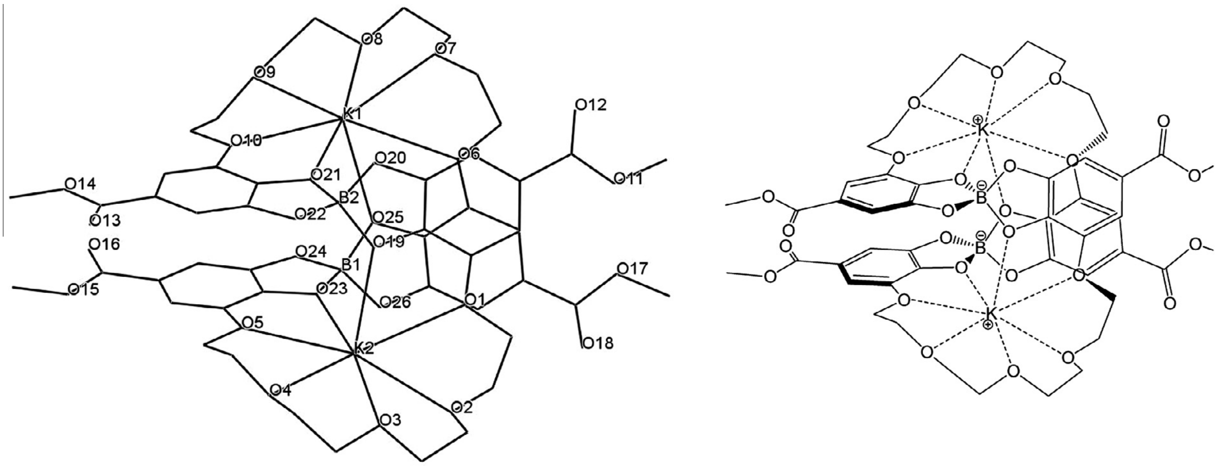
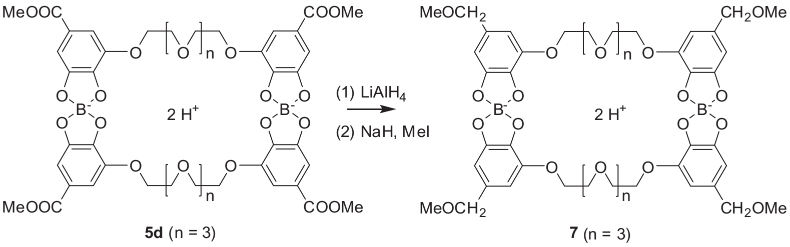


Figure 4. X-ray crystal structure of [**5d**−2H+2K] complex (hydrogen atoms and solvent molecules omitted for clarity).



Scheme 3. Post-modification of dimeric compound **5d**.

Conclusion

In summary, we have prepared a series of oligo(ethylene glycol) compounds with end-functionalities as gallate motifs from easily available starting materials. The spiroborate linkage formation on the catechol-like termini afforded dimeric structures. The flexible and tunable structures of the oligoether compounds make them potentially selective hosts for alkali metal ions. Further work on the supramolecular structure of these boron-assisted dimeric macrocyclic oligoethers and their applications for selective separation of alkali metal salts are underway in this laboratory.

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Supplementary data

Supplementary data (detailed experimental procedures and identification of the intermediates and products) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2016.05.008.

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8. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 1468293.
9. The ESI-MS (negative mode) analysis showed *m*/*z*: 505 and 1033, corresponding to $[\mathbf{7}-2H]^{2-}$ and $[\mathbf{7}-2H+Na]^{-}$, respectively. The structure was further supported by high resolution mass spectrum (positive mode): calcd for $C_{48}H_{60}B_2O_{22}H_3^+$: 1013.3997, found 1013.3996, corresponding to $[\mathbf{7}+H]^{+}$.