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Axially- and *Meso*-substituted Aza-Crown-Ether-Incorporated B^{III} Subporphyrins: Control of Electron-Donating Ability by Metal Ion Chelation

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Abstract: A series of subporphyrin-based fluorescent probes bearing 1-aza-15-crown-5 or 1-aza-18-crown-6 moieties at the *meso* or axial positions were prepared by Pd-catalyzed Buchwald–Hartwig amination reaction of the corresponding bromosubporphyrins. Both types of aza-crown-ether-incorporated subporphyrins were fluorescent in solution and exhibited cation-dependent absorption and fluorescence changes. In fluorescence titration experiments, opposite responses were observed for the two types of subporphyrins. Namely, fluorescence quenching occurred for the *meso*-substituted subporphyrins while fluorescence enhancement was observed for the axially-substituted subporphyrins. These results demonstrate the advantage of subporphyrins being viable to serve as turn-off-type or turn-on-type fluorescence probes, depending upon substitution pattern.

Since the discovery by C. J. Pedersen in 1967,[1a] crown-ethers have been actively studied in the field of molecular recognition,[1g,2] ion transport,[3] phase transfer catalysts,[4] and so on due to their strong binding abilities to metal ions and cationic organic molecules.[1,5] Nitrogen- and sulfur-incorporated variants of crown-ethers, especially aza-crown-ether (ACE) and thia-crown-ether (TCE) are also attractive functional pigments since they show different selectivities to metal ions compared to that of the parent crown-ethers.[1b,g] Especially, ACE can accommodate various functional groups at the nitrogen pivot, by which the ACE unit can be directly attached to the target chromophores. Along this line, numerous colorimetric chemosensors have been developed in light of the practical applications for the detection of toxic heavy metals, alkali metals, alkaline earth metals, and bio-active molecules.[5–8] Holdt *et al.* reported coumarin–ACE dyads **A** and **B** for the turn-on type fluorescent probes of Na⁺ and K⁺ (Scheme 1).[7f] Interestingly, **A** showed more effective fluorescence enhancement as compared to **B** despite the slight difference in the substitution pattern of the bridging 1,2,3-triazole unit. This finding led to the development of new fluorescent probes for selective detection of K⁺ over Na⁺.[7g] ACEs have also been installed into porphyrinoids and phthalocyaninoids, such as *meso*-ACE-appended metalloporphyrins,[9a] phthalocyanines with

benzo-ACE moieties,[9b] and ACE-appended aza-phthalocyanines (**C**).[9c,e] In the study of **C**, its affinity to alkali metal cations and alkaline earth metal cations was thoroughly investigated in combination with a small structural and electronic modification such as central metal ions and ring sizes of aza-crown-ethers, which brought to a conclusion that alkali metal cations show clear size preference of ACE units whereas alkaline earth metal cations do not.
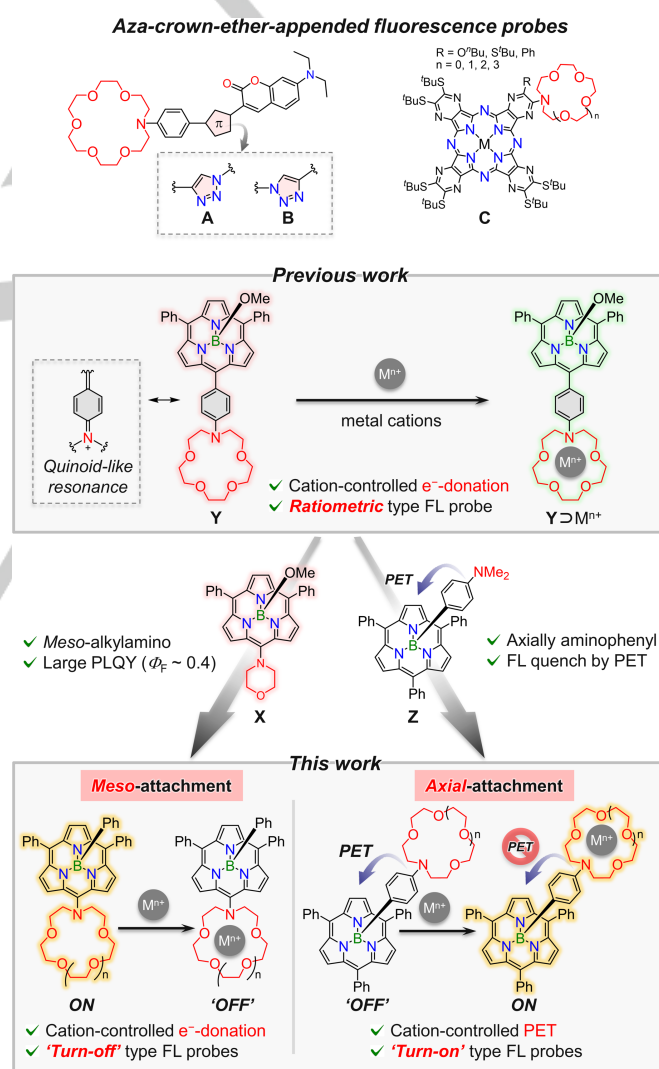
Scheme 1. Selected examples of aza-crown-ether-appended fluorescent compounds (**A**–**C**) and the concept of new subporphyrin-based fluorescence probes in this work based on the previously reported subporphyrins (**X**–**Z**).

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Subporphyrinatoboron(III) (hereafter called subporphyrin, subP),[10–14] is the genuine ring-contracted porphyrin consisting of three pyrroles and three bridging methine carbons. The subP exhibits 14π aromaticity and serves as a novel fluorophore. Its prototype, 5,10,15-triphenyl-subP,[11] exhibits green emission in the range of 475–650 nm with nearly 15% quantum yield. Interestingly, recent developments in the synthetic subporphyrin chemistry enabled the installation of various functional groups at the *meso-* and β-positions of subPs as well as at the boron center (hereafter called axial-attachment). The two substitution modes, *i.e.* peripheral attachment and axial attachment, are useful to study the interchromophoric interactions. For example, a set of tetracyanobuta-1,3-diene (TCBD)-aniline substituted subPs has recently been documented to illuminate the contrasting optical features; charge-transfer state formation in *meso*-TCBD-aniline-substituted subP opposed to exciplex formation in axial-TCBD-aniline-substituted subP.[15] Inspired by this study, we came up with a design utilizing an ACE unit as a controllable electron-donating functionality. Attachment of an ACE unit at the *meso*-position of subPs enhances its fluorescent character as reported in *meso*-morpholinosubporphyrin **X**,[12b] and the ion chelation inhibits its electron-donating ability, leading to gradual emission quenching. Although an ACE-substituted subP **Y**, which has been reported to most preferably capture Ca^{2+} among various alkali metals, exhibited quite large absorption and emission energy shifts in response to the addition of other alkali ions due to the contribution of the quinoid-type resonance structures,[14] directly *meso*-alkylamino-substituted subPs are regarded as more suitable chromophores for the systematic study on pure turn-off-type fluorescence response. On the other hand, axially ACE-substituted subPs can serve as a turn-on type fluorophore given the following scenarios; i) an axially 4-aminophenyl-substituted subP **Z** shows emission quenching due to the photo-induced electron transfer (PET) from the aniline moiety to the subporphyrin core as reported in the literature[13b] and ii) metal-chelation in the ACE unit prohibits the PET process by coordinating to the donating amino moiety. With these ideas in mind, here we show the synthesis of a series of subPs with *meso-* and axially-attached ACE units (**4**, **5**, **7**, and **8**) and their characteristic chelation-induced optical responses. Both aza-15-crown-5-ether (aza-15-c-5) and aza-18-crown-6-ether (aza-18-c-6) were chosen for the systematic study. After screening, we found that subP-(aza-18-c-6)$_{meso}$ **5** serves as the turn-off-type fluorescence probe while subP-(aza-15-c-5)$_{axial}$ **7** and subP-(aza-18-c-6)$_{axial}$ **8** work in a turn-on-type fashion. These results demonstrate that different substitution patterns of subP enable us to control the electron transfer behaviors and design new fluorescence probes for various metal ions.

First, *meso*-bromosubporphyrin **1**[12a] and axial-(4-bromophenyl)subporphyrin **6**[13e] were prepared according to the reported procedures. With these precursors in hand, the ACE units were installed by palladium-catalyzed amination reactions (Scheme 2).[12b] *meso*-Bromosubporphyrin **1** was reacted with 3 equivalents of ACEs in the presence of 5 mol% of a Pd-NHC catalyst (Pd-PEPPSI-IPent). In the initial trial, a mixture in THF was heated at reflux temperature, but most of the substrates were recovered. Under microwave heating at the elevated temperature (up to 150 °C), the reactions proceeded to afford subP-(aza-15-c-5)$_{meso}$ **2** and subP-(aza-18-c-6)$_{meso}$ **3** in 33% and 47% yields,

respectively. However, subporphyrins **2** and **3** are unstable since they are prone to undergo axial-exchange reactions to form B-OH and μ-oxo-dimeric subPs.[16] (see section 2.7 in the supporting information for detail) In our previous work, we suggested that the axial-exchange reaction proceeds via borenium cation by S_N1-type mechanism.[17] In **2** and **3**, the borenium cation intermediates are stabilized by electron-donating aza-crown-ether units to facilitate the axial-exchange reaction. Then, we changed the axial substituents with phenyl group, expecting that undesired axial-exchange reactions do not occur due to the strong B—C bond.[13b] B-OMe subPs **2** and **3** were converted to B-Ph subPs **4** and **5** in 57% and 45% yields, respectively, by the reaction with phenylmagnesium bromide in the presence of trimethylsilyl chloride.[13e] Fortunately, **4** and **5** are sufficiently stable for handling under ambient conditions. Axial-(4-bromophenyl)subporphyrin **6** was reacted with 3 equivalents of ACEs in the presence of 20 mol% of a palladium precatalyst (XPhos Pd G2)[18] in 1,4-dioxane at 100 °C to furnish subP-(aza-15-c-5)$_{axial}$ **7** and subP-(aza-18-c-6)$_{axial}$ **8** in 14% and 18% yields, respectively. During the optimization of these reactions, we found that the starting bromide **6** was not consumed at all in refluxing THF and protodeborylation of **6** occurred under microwave heating at 150 °C in THF. Finally, refluxing the reaction mixture in 1,4-dioxane resulted in the formation of coupling products **7** and **8** in low but reproducible yields.
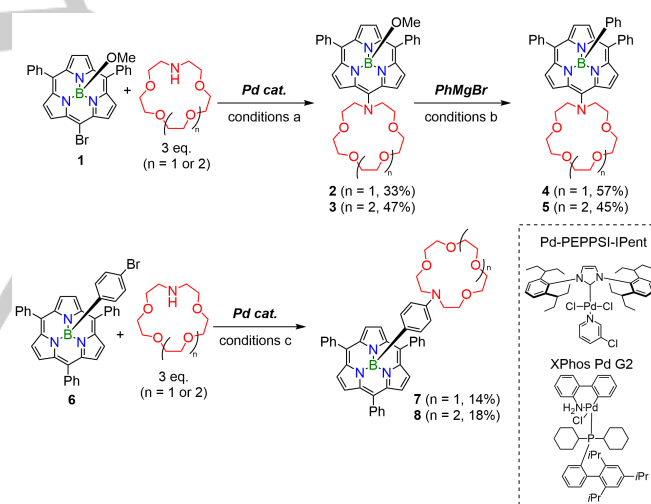

Scheme 2. Synthesis of ACE-appended subPs **2–5**, **7**, and **8**. (Conditions a) Pd-PEPPSI-IPent (5 mol%), Cs$_2$CO$_3$ (4 eq.), THF, 150 °C (microwave), 4 h; (Conditions b) Trimethylsilyl chloride (20 eq.), phenylmagnesium bromide (*ca.* 1.0 M in THF, 70 eq.), THF, RT to 40 °C 2–5 h; (Conditions c) XPhos Pd G2 (20 mol%), Cs$_2$CO$_3$ (4 eq.), 1,4-dioxane, 100 °C, 2 d.

Fortunately, single crystals of **4** were obtained and the structure was unambiguously determined by X-ray diffraction analysis (Figure 1). The bowl-depth of the subporphyrin core[19] was 1.33 Å, which is in the typical range of subporphyrins (1.3–1.5 Å). The sum of bond angles around nitrogen pivot in the 1-aza-15-crown-5 unit was close to 360° ($\Sigma\theta$ = 359.67°), which indicates the flattened sp^2-hybridized nitrogen atom. Moreover, the torsion angle around the C(*meso*)—N bond was small (1.19°
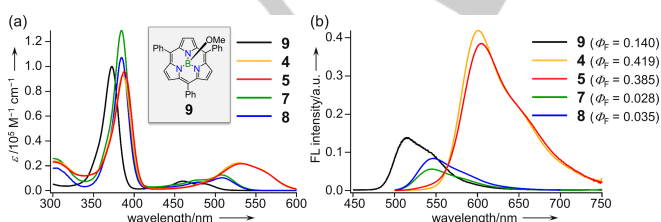
and 7.24°), suggesting the effective conjugation of the lone pair electron of the nitrogen atom with the subporphyrin network.
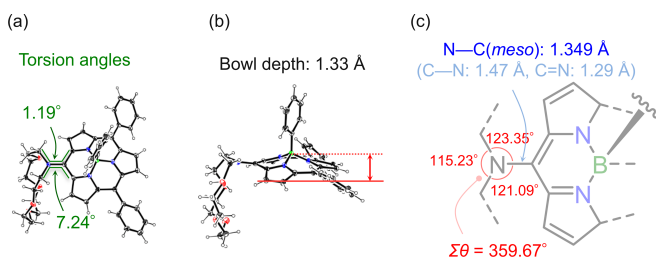

Figure 1. X-Ray crystal structure of **4**. Solvent molecules (*n*-hexane) were omitted for clarity. The thermal ellipsoids are scaled at 50% probability level. (a) Top view and torsion angles around *meso*-methine carbon atom and nitrogen atom in 1-aza-15-crown-5 unit. (b) Side view and bowl-depth of the subporphyrin. Crystallographic data have been deposited with the Cambridge Crystallographic Data Centre as a supplementary publication (CCDC-2079940). (c) Selected bond lengths and bond angles around the nitrogen pivot.

The UV/vis absorption spectra of **4**, **5**, **7**, and **8** were recorded in CH_2Cl_2 (Figure 2a). Axially-attached subPs **7** and **8** exhibit intense Soret-like bands and weak Q-like bands similar to those of usual A_3-type subPs such as **9**, whereas *meso*-attached subPs **4** and **5** exhibit Soret-like bands and relatively intensified Q-like bands, reflecting their lower molecular symmetry (*i.e.* A_2B-type) and partially allowed HOMO–LUMO transitions. Their fluorescence spectra are shown in Figure 2b. As expected, *meso*-ACE-appended subPs **4** and **5** are highly fluorescent with large fluorescence quantum yields (Φ_F = 0.419 for **4** and 0.385 for **5**).[20] On the other hand, the fluorescence quantum yields of axially-ACE-appended subPs **7** and **8** are much smaller (Φ_F = 0.028 for **7** and Φ_F = 0.035 for **8**)[20] presumably due to the photo-induced electron transfer (PET) from the electron-rich axial-aminophenyl moieties to the electron-deficient subporphyrin cores as reported in the case of axially 4-dimethylaminophenyl-substituted and 4-ferrocenylphenyl-substituted subPs.[13b] To confirm this mechanism, femtosecond transient absorption (fs-TA) measurements were conducted for **7** (Figure S6-1 a,b) and **8** (Figure S6-2 a,b). The TA spectra of **7** and **8** both exhibited broad excited-state absorption (ESA) bands at 550 nm. The decay profiles of **7** and **8** were fitted by double exponential components with time constants of 45 ps and a few ns. The fast dynamics of 45 ps represents the PET process from the ACE moieties to the subporphyrin cores. The longer time component corresponds to the fluorescence lifetime of the subporphyrins.
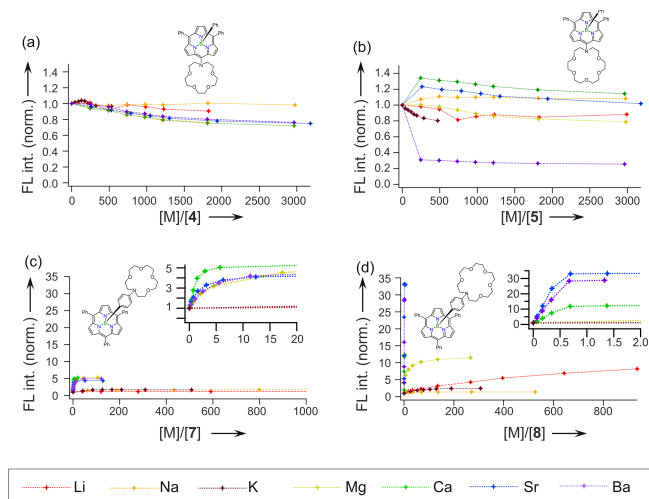
Next, we examined their optical spectral changes upon the addition of metal ions. To an acetonitrile solution of subPs (**4**, **5**, **7**, and **8**) was added an acetonitrile solution of metal perchlorates, $M(ClO_4)_n \cdot xH_2O$ (M = Li, Na, K, Mg, Ca, Sr, and Ba). The UV/vis spectral changes were small; slight changes for **4** and **5**, and almost no change for **7** and **8** (See SI; Figures S5-1–S5-28).[21] In contrast, clear spectral changes were observed for the fluorescence spectra (Figure 3). For *meso*-ACE-appended subPs **4** and **5**, the fluorescence intensity decreased significantly while their spectral profiles were maintained except for the combination of **5** and Ba. On the other hand, for axially-ACE-appended subPs **7** and **8**, their fluorescence intensity increased upon the addition of metal perchlorates.[22] Conceivably, this can be ascribed to chelation-induced suppression of PET from the aza-crown-ether units to the subporphyrin cores. Fs-TA measurements were also carried out for magnesium perchlorate added **7** and **8** (See SI). By comparing the decay profiles with those of **7** and **8** without the addition of Mg, we observed the decrease in the amplitude of the decay component of 45 ps which is attributed to PET dynamics from 84 to 19% for **7** and 89 to 29% for **8**. The reduction of the indicated decay component successfully confirms the suppression of PET due to ion chelation, which also leads to fluorescence enhancement. The fluorescence lifetime remained unchanged with the introduction of Mg (See SI; Figure S6-3).
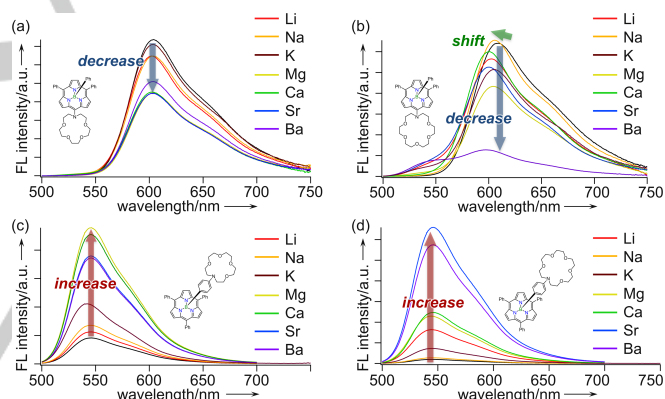
Figure 3. Fluorescence spectral changes upon addition of excessive amount of $M(ClO_4)_n \cdot xH_2O$ (M = Li, Na, K, Mg, Ca, Sr, and Ba) in acetonitrile. (a) **4**, (b) **5**, (c) **7**, and (d) **8** (λ_{ex}: peak-top-wavelengths of the Soret-like bands, Concentration of subporphyrins: (a) 1×10^{-6} M, (b) 1×10^{-6} M, (c) 8–9$\times10^{-6}$ M, (d) 1×10^{-5} M. Concentration of metal ions: 4×10^{-3} M).

Figure 2. (a) UV/vis absorption and (b) fluorescence spectra of **4**, **5**, **7**, and **8** in CH_2Cl_2 (λ_{ex}: peak-top-wavelengths of the Soret-like bands.).

Figure 4. Changes in fluorescence intensity of subporphyrins (a) **4**, (b) **5**, (c) **7**, and (d) **8** during titration experiments with metal perchlorates $M(ClO_4)_n \cdot xH_2O$ (M = Li, Na, K, Mg, Ca, Sr, and Ba, λ_{ex}: peak-top-wavelengths of the Soret-like bands, Concentration of subporphyrins: (a) 1×10^{-6} M, (b) 1×10^{-6} M, (c) 8–9×10^{-6} M, (d) 1×10^{-5} M.).

To show the fluorescence changes during titration experiments, the normalized maximum fluorescence intensities were plotted against the relative concentration of metal perchlorates (Figure 4). For *meso*-ACE-appended subP **4**, the fluorescence intensity decreased gradually with no significant differences for all metal ions within the range of 0.8–1.0. On the other hand, for **5** which bears larger-sized aza-crown-ether unit, more obvious changes in the fluorescence intensity were observed. In particular, effective fluorescence quenching was observed for Ba, reaching around 30% of the original fluorescence intensity. Similarly, fluorescence enhancements were more significant for subP-(aza-18-c-6)$_{axial}$ **8** than subP-(aza-15-c-5)$_{axial}$ **7**, especially in the case with Sr and Ba.

Table 1. Absolute fluorescence quantum yields of **4**, **5**, **7**, and **8** measured with and without metal perchlorates $M(ClO_4)_n \cdot xH_2O$ (M = Li, Na, K, Mg, Ca, Sr, and Ba) in acetonitrile. (λ_{ex}: peak-top-wavelengths of the Soret-like bands, Concentration of subporphyrins: 1×10^{-6} M, Concentration of metal ions: 2×10^{-2} M).

M	4	5	7	8
None	0.398	0.379	0.012	0.003
Li	0.394	0.330	0.016	0.045
Na	0.376	0.391	0.025	0.031
K[a]	0.393	0.338	0.016	0.073
Mg	0.384	0.405	0.145	0.100
Ca	0.386	0.415	0.119	0.064
Sr	0.396	0.356	0.103	0.136
Ba	0.388	0.115	0.100	0.135

[a] Concentration of potassium perchlorate: 2×10^{-3} M (due to low solubility of the salt).
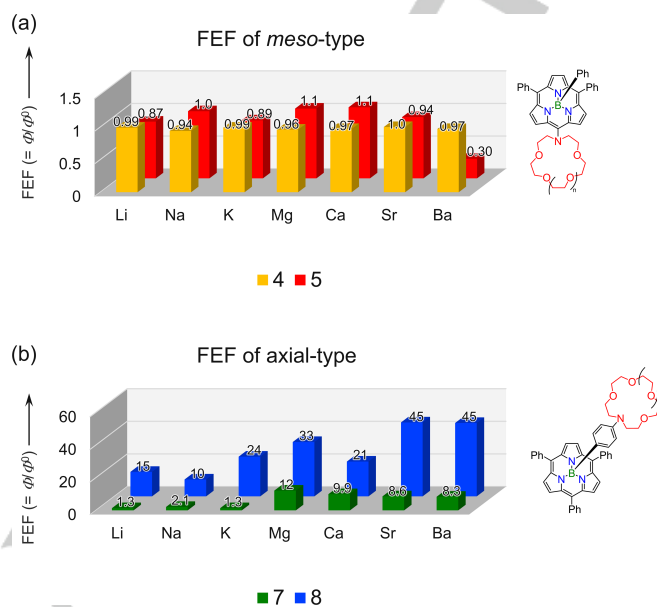
Figure 5. Fluorescence enhancement factors (FEFs) calculated based on the absolute fluorescence quantum yields before and after addition of excessive amount of metal perchlorates $M(ClO_4)_n \cdot xH_2O$ (M = Li, Na, K, Mg, Ca, Sr, and Ba) into the solution of (a) subP-ACE$_{meso}$ **4** and **5**, and (b) subP-ACE$_{axial}$ **7** and **8**. (λ_{ex}: peak-top-wavelengths of the Soret-like bands, Concentration of subporphyrins: 1×10^{-6} M, Concentration of metal ions: 1×10^{-2} M (K$^+$), 2×10^{-2} M (others)).

Finally, the fluorescence enhancement factor (FEF), which is usually used for evaluation of the degree of changes in fluorescence intensity, was determined (Figure 5) based on the absolute fluorescence quantum yields in Table 1 (FEF $= \Phi/\Phi^0$). The FEF of subP-(aza-18-c-6)$_{meso}$ **5** is 0.30 for Ba, suggesting the potential use in turn-off-type chemosensor for Ba-selective detection. On the other hand, axially-ACE-appended subP **7** and **8** exhibited larger FEFs for group IIA metal ions (*i.e.* Mg, Ca, Sr, and Ba) compared to those for Li and Na. It is worth noting that **8** showed larger FEF values (FEF > 10) than **7**, indicating that **8** would be suitable for the turn-on-type fluorescence probe for metal ions, especially for Sr (FEF = 45) and Ba (FEF = 45).

In summary, we have developed two types of aza-crown-ether-attached subPs, *meso*- and axial-substitutions. We revealed that (1) subPs with aza-18-c-6 unit respond more sensitively upon addition of metal ions, (2) the fluorescence intensity of subP-(aza-18-c-6)$_{meso}$ **5** decreases by *ca.* 70% upon the addition of Ba^{2+}, thus serving as a turn-off-type fluorescent probe, and (3) the fluorescence enhancement of subP-(aza-18-c-6)$_{axial}$ **8** is large and the FEF values are 45 for both Sr^{2+} and Ba^{2+}, showing the potential as a turn-on fluorescent probe. This work provides not only a new entry of subP-based fluorescence probes but also unique characteristics of subPs whose scaffolds can be used for the control of photoexcitation-induced electron transfer and fluorescence responses toward metal ions.

[1] Crown-ethers: a) C. J. Pedersen, *J. Am. Chem. Soc.* **1967**, *89*, 7017; b) C. J. Pedersen, H. K. Frensdorff, *Angew. Chem. Int. Ed.* **1972**, *11*, 16; *Angew. Chem.* **1972**, *84*, 16; c) C. J. Pedersen, *Science* **1988**, *241*, 536; d) D. J. Cram, *Science* **1988**, *240*, 760; e) J.-M. Lehn, *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 89; f) K. E. Krakowiak, J. S. Bradshaw, D. J. Zamecka-Krakowiak, *Chem. Rev.* **1989**, *89*, 929; g) G. W. Gokel, W. M. Leevy, M. E. Weber, *Chem. Rev.* **2004**, *104*, 2723; h) G. W. Gokel, S. Negin, R. Cantwell in *Comprehensive Supramolecular Chemistry II* (Eds.: J. L. Atwood), Elsevier, **2017**, 3.02, pp. 3–48.

[2] Molecular recognition and ion receptors with crown ether: a) D. J. Cram, J. M. Cram, *Science* **1974**, *183*, 803; b) R. M. Izatt, N. E. Izatt, B.E. Rossiter, J. J. Christensen, B. L. Haymore, *Science* **1978**, *199*, 994; c) A. Hamilton, J.-M. Lehn, J. L. Sessler, *J. Am. Chem. Soc.* **1986**, *108*, 5158; d) B. L. Allwood, H. Shahriari-Zavareh, J. F. Stoddart, D. J. Williams, *J. Chem. Soc., Chem. Commun.* **1987**, 1058; e) Y. Han, Z. Meng, Y.-X. Ma, C.-F. Chen, *Acc. Chem. Res.* **2014**, *47*, 2026; f) Q. He, G. I. V.-Zúñiga, S. H. Kim, S. Kuk Kim, J. L. Sessler, *Chem. Rev.* **2019**, *119*, 9753.

[3] Ion transporting systems with crown ethers: a) L. Jullien, J. M. Lehn, *Tetrahedron Lett.* **1988**, 3803; b) M. F. M. Roks, R. J. M. Nolte, *Macromolecules* **1992**, *25*, 5398; c) T. M. Fyles, T. D. James, A. Pryhitka, M. Zojaji, *J. Org. Chem.* **1993**, *58*, 7456; d) N. Voyer, M. Robataille, *J. Am. Chem. Soc.* **1995**, *117*, 6599; e) A. D. Pechulis, R. J. Thompson, J. P. Fojtik, H. M. Schwartz, C. A. Lisek, L. L. Frye, *Bioorg. Med. Chem. Lett.* **1997**, *5*, 1893; f) C. D. Hall, G. J. Kirkovits, A. C. Hall, *Chem. Commun.* **1999**, *1897*; g) L. M. Cameron, T. M. Fyles, C. Hu, *J. Org. Chem.* **2002**, *67*, 1548; h) A. C. Hall, C. Suarez, A. Hom-Choudhury, A. N. A. Manu, C. D. Hall, G. J. Kirkovits, I. Ghiriviga, *Org. Biomol. Chem.* **2003**, *1*, 2973.

[4] Phase-transfer catalysts with crown ethers: a) C. L. Liotta, H. P. Harris, *J. Am. Chem. Soc.* **1974**, *96*, 2250; b) D. Landini, A. Maia, F. Montanari, F. M. Pirisi, *J. Chem. Soc., Perkin Trans. 2* **1980**, *46*; c) J. W. Lee, H. Yan, H. B. Jang, H. K. Kim, S.-W. Park, S. Lee, D. Y. Chi, C. E. Song, *Angew. Chem. Int. Ed.* **2009**, *48*, 7683; *Angew. Chem.* **2009**, *121*, 7819; d) N. F. Carvalho, J. R. Pliego, Jr., *J. Org. Chem.* **2016**, *81*, 8455.

[5] Selected reviews on porphyrinoids with crown-ether units: a) N. Kobayashi, *Bull. Chem. Soc. Jpn.* **2002**, *75*, 1; b) P. Even, B. Boitrel, *Coord. Chem. Rev.* **2006**, *250*, 519.

[6] Porphyrinoid-crown-ether dyads: a) V. Thanabal, V. Krishnan, *J. Am. Chem. Soc.* **1982**, *104*, 3643; b) V. Thanabal, V. Krishnan, *Inorg. Chem.* **1982**, *21*, 3606; c) O. E. Sielcken, M. M. v. Tilborg, M. F. M. Roks, R. Hendriks, W. Drenth, R. J. M. Nolte, *J. Am. Chem. Soc.* **1987**, *109*, 4261; d) N. Kobayashi, A. B. P. Lever, *J. Am. Chem. Soc.* **1987**, *109*, 7433; e) S. Yoshimoto, K. Suto, K. Itaya, N. Kobayashi, *Chem. Commun.* **2003**, 2174; f) S. Yoshimoto, K. Suto, A. Tada, N. Kobayashi, K. Itaya, *J. Am. Chem. Soc.* **2006**, *126*, 8020; g) M. Jahan, N. Safari, H. Khosravi, A. Moghimi, B. Notash, *Polyhedron* **2005**, 1682; h) S. Yoshimoto, T. Sawaguchi, W. Su, J. Jiang, N. Kobayashi, *Angew. Chem. Int. Ed.* **2007**, *46*, 1071; *Angew. Chem.* **2007**, *119*, 1089; i) T. Fukuda, I. Sugita, N. Kobayashi, *Chem. Commun.* **2009**, 3449; j) H. Lu, I. Kwak, J. H. Park, K. O'Neill, T. Furuyama, N. Kobayashi, A. Seabaugh, A. Kummel, S. K.

Fullerton-Shirey, *J. Phys. Chem. C* **2015**, *119*, 21992; k) T. Ikeuchi, S. Mori, N. Kobayashi, M. Kimura, *Inorg. Chem.* **2016**, *55*, 5014; l) L. A. Lapkina, V. E. Larchenko, G. A. Kirakosyan, A. Y. Tsivadze, S. I. Troyanov, Y. G. Gorbunova, *Inorg. Chem.* **2018**, *57*, 82.

[7] Fluorescence probes with crown ethers: a) H.-G. Löhr, F. Vögtle, *Acc. Chem. Res.* **1985**, *18*, 65; b) C. Hou, A. M. Urbanec, H. Cao, *Tetrahedron Lett.* **2011**, *52*, 4903; c) M. Işık, R. Guliyev, S. Kolemen, Y. Altay, B. Senturk, T. Tekinay, E. U. Akkaya, *Org. Lett.* **2014**, *16*, 3260; d) M. Taki, H. Ogasawara, H. Osaki, A. Fukazawa, Y. Sato, K. Ogasawara, T. Higashiyama, S. Yamaguchi, *Chem. Commun.* **2015**, *51*, 11880; e) J. Li, D. Yim, W.-D. Jang, J. Yoon, *Chem. Soc. Rev.* **2017**, *46*, 2437; f) S. Ast, H. Müller, R. Flehr, T. Klamroth, B. Walz, H.-J. Holdt, *Chem. Commun.* **2011**, *47*, 4685; g) S. Ast, T. Schwarze, H. Müller, A. Sukhanov, S. Michaelis, J. Wegener, O. S. Wolfbeis, T. Körzdörfer, A. Dürkop, H. J. Holdt, *Chem.–Eur. J.* **2013**, *19*, 14911.

[8] Pioneering studies on chelation-enhanced fluorescence: a) L. R. Sousa, J. M. Larson, *J. Am. Chem. Soc.* **1977**, *99*, 307; b) A. P. d. Silva, S. A. d. Silva, *J. Chem. Soc., Chem. Commun.* **1986**, 1709; c) M. E. Huston, K. W. Haider, A. W. Czarnik, *J. Am. Chem. Soc.* **1988**, *110*, 4460.

[9] Porphyrinoid-aza-crown-ether dyads: a) V. Ahsen, A. Gürek, E. Musluoğlu, Ö. Bekāroğlu, *Chem. Ber.* **1989**, *122*, 1073; b) E. A. Mikhalitsyna, V. S. Tyurin, I. A. Zamylatskov, V. N. Khrustalev, I. P. Beletskaya, *Dalton Trans.* **2012**, *41*, 7642; c) V. Novakova, L. Lochman, I. Zajícová, K. Kopecky, K. Miletin, K. Lang, K. Kirakci, P. Zimcik, *Chem.–Eur. J.* **2013**, *19*, 5025; d) X.-W.Chen, M.-R. Ke, X.-S. Li, W.-L. Lan, M.-F. Zhang, J.-D. Huang, *Chem.–Asian J.* **2013**, *8*, 3063; e) L. Lochman, J. Svec, J. Roh, V. Novakova, *Dyes Pigments* **2015**, *121*, 178.

[10] Seminal works and review articles of subporphyrins: a) Y. Inokuma, J. H. Kwon, T. K. Ahn, M.-C. Yoo, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.*, **2006**, *45*, 961; *Angew. Chem.* **2006**, *118*, 975; b) T. Torres, *Angew. Chem. Int. Ed.*, **2006**, *45*, 2834; *Angew. Chem.* **2006**, *118*, 2900; c) R. Myśliborski, L. Latos-Grażyński, L. Szterenberg, T. Lis, *Angew. Chem. Int. Ed.* **2006**, *45*, 3670; *Angew. Chem.* **2006**, *118*, 3752; d) A. Osuka, E. Tsurumaki, T. Tanaka, *Bull. Chem. Soc. Jpn.* **2011**, *84*, 679; e) C. G. Claessens, D. González-Rodríguez, M. S. Rodríguez-Morgade, A. Medina, T. Torres, *Chem. Rev.* **2014**, *114*, 2192; f) S. Shimizu, *Chem. Rev.* **2017**, *117*, 2730.

[11] a) Y. Inokuma, Z. S. Yoon, D. Kim, A. Osuka, *J. Am. Chem. Soc.* **2007**, *129*, 4747; b) E. A. Makarova, S. Shimizu, A. Matsuda, E. A. Luk'yanets, N. Kobayashi, *Chem. Commun.* **2008**, 2109.

[12] Functionalization of *meso*-free subporphyins: a) M. Kitano, S.-y. Hayashi, T. Tanaka, H. Yorimitsu, N. Aratani, A. Osuka, *Angew. Chem. Int. Ed.* **2012**, *51*, 5593; *Angew. Chem.* **2012**, *124*, 5691; b) M. Kitano, S.-y. Hayashi, T. Tanaka, N. Aratani, A. Osuka, *Chem.–Eur. J.* **2012**, *18*, 8929; c) M. Kitano, D. Shimizu, T. Tanaka, H. Yorimitsu, A. Osuka, *J. Porphyrins Phthalocyanines* **2014**, *18*, 659; d) D. Shimizu, H. Mori, M. Kitano, W.-Y. Cha, J. Oh, T. Tanaka, D. Kim, A. Osuka, *Chem.–Eur. J.* **2014**, *20*, 16194.

[13] Exchange of axial substituents of subporphyrins: a) S. Shimizu, A. Matsuda, N. Kobayashi, *Inorg. Chem.* **2009**, *48*, 7885; b) S. Saga, S.-y. Hayashi, K. Yoshida, E. Tsurumaki, P. Kim, Y. M. Sung, J. Sung, T. Tanaka, D. Kim, A. Osuka, *Chem.–Eur. J.* **2013**, *19*, 11158; c) E. Tsurumaki, J. Sung, D. Kim, A. Osuka, *J. Am. Chem. Soc.* **2015**, *137*, 1056; d) E. Tsurumaki, J. Sung, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2016**, *55*, 2596; *Angew. Chem.* **2016**, *128*, 2642; e) R. Kotani, K. Yoshida, E. Tsurumaki A. Osuka, *Chem.–Eur. J.* **2016**, *22*, 3320.

[14] A previous study on subporphyrin–aza-crown-ether dyad: Y. Inokuma, S. Easwaramoorthi, Z. S. Yoon, D. Kim, A. Osuka, *J. Am. Chem. Soc.* **2008**, *130*, 12234.

[15] K. A. Winterfeld, G. Lavarda, K. Yoshida, M. J. Bayerlein, K. Kise, T. Tanaka, A. Osuka, D. M. Guldi, T. Torres, G. Bottari, *J. Am. Chem. Soc.* **2020**, *142*, 7920.

[16] The methoxy group at the axial position was easily exchangeable with a hydroxy group. This axial-exchange reaction proceeds even during rotary evaporation from CH_2Cl_2/MeOH solution due to the small amount of water contained in MeOH.

[17] K. Yoshida, A. Osuka, *Chem.–Eur. J.* **2015**, *21*, 11727.

[18] T. Kinzel, Y. Zhang, S. L. Buchwald, *J. Am. Chem. Soc.* **2010**, *132*, 14073.

[19] Bowl depth is defined by the distance between the boron atom and the mean plane of the peripheral six β-carbons of subporphyrin macrocycle.

[20] The fluorescence quantum yields of **4** and **5** are sensitive to oxygen contaminated in solution whereas those of **7** and **8** are not (Table S4-2). Then, for **4** and **5**, all measurements of fluorescence spectra, fluorescence quantum yields and fluorescence lifetimes were conducted after degassing by nitrogen bubbling for more than 10 min. For more details, see sections 4 and 5 in SI.

[21] The Job's plot for **2** and **7** confirmed their 1:1 complexation behaviors upon addition of Na(ClO$_4$)$_2$ and Ca(ClO$_4$)$_2$, respectively. See Figures S5-31 and S5-32.

[22] Upon addition of metal ions, B–C bonds of B–aryl subporphyrins are maintained and the fluorescence changes are reversible (see Figures S5-25).

COMMUNICATION

Subporphyrins bearing aza-crown ether moieties at the *meso-* and axial-positions were synthesized for turn-off- and turn-on-type fluorescent chemosensors for metal-ion detection. Their spectral changes were investigated by titration experiments with seven kinds of metal ions. The fluorescence responses toward metal ions have been controlled by the substitution position and the size of aza-crown-ethers.

✓ *Meso-substitution*
✓ *'Turn-off'* type FL probes

✓ *axial-substitution*
✓ *'Turn-on'* type FL probes
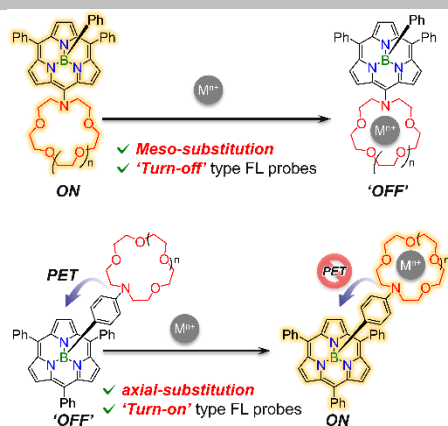
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Axially- and Meso-Substituted Aza-Crown-Ether-Incorporated B^{III} Subporphyrins: Control of Electron-Donating Ability by Metal Ion Chelation