

## A Facile Approach to the Preparation of Bis-Crown Ethers Based on SET-Promoted Photomacrocyclization Reactions

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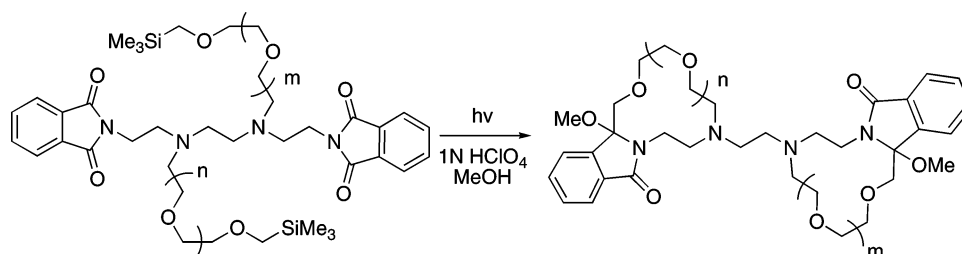
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A novel methodology for the synthesis of bis-crown ethers has been developed. The preparative route takes advantage of an efficient single electron transfer promoted photomacrocyclization reaction of polyether branched bisphthalimides which contain  $\alpha$ -trimethylsilylmethyl groups at terminal positions. The generality of the methodology was demonstrated by its application to the synthesis of symmetric and unsymmetric bis-crown ethers of various ring sizes. Finally, the metal cation binding and fluorescence emission properties of the bis-crowns, prepared by using the developed procedure, were briefly explored.

### Introduction

Since the time of the pioneering studies by Pederson,<sup>1</sup> an intense effort has been given to the design, synthesis, and application of crown ethers and their aza and thia derivatives.<sup>2</sup> Owing to their strong and often selective metal cation binding properties, these substances have been used as key components of photoresponsive metal ion sensors,<sup>3</sup> ion selective electrodes,<sup>4</sup> and ion transport systems.<sup>5</sup> In investigations aimed at developing substances with unique properties and ion binding characteristics, a large number of families comprising differently substi-

tuted and structured crown ethers have been devised. Examples are found in the lariat crown ether<sup>6</sup> and cryptands,<sup>7</sup> which contain additional ligand binding sites in flexible side chains and rigid bridges. Additional interactions associated with these ligand sites typically bring about stronger metal ion binding.

Bis-crown ethers,<sup>8</sup> which possess two macrocyclic polyether rings linked by a connecting unit, also display unique binding profiles. Starting with initial observations made by Smid<sup>9</sup> that bis-crown ethers form sandwich-type complexes with metal cations (Scheme 1), extensive studies have been carried out on these substances and related spiro-bis-crowns<sup>10</sup> and oligo-benzo-crown ethers.<sup>11</sup> Methods used for the preparation of bis-crown ethers have relied on traditional procedures, which most

(1) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.

(2) (a) Parker, D. *Macrocyclic Synthesis*; Oxford University Press: New York, 1996; p 49. (b) Kellogg, R. M. In *Crown Compounds*; Cooper, S. R., Ed.; VCH: New York, 1992; p 261. (c) Yordanov, A. T.; Roundhill, D. M. *New J. Chem.* **1996**, *20*, 447.

(3) (a) Gokel, G. W.; Leevey, W. M.; Weber, M. E. *Chem. Rev.* **2004**, *104*, 2723. (b) de Silva, A. P.; Fox, D. B.; Huxley, A. J. M.; Moody, T. S. *Coord. Chem. Rev.* **2000**, *205*, 41.

(4) Kimura, K.; Shono, T. In *Cation Binding by Macrocycles*; Inoue, Y., Gokel, G. W., Eds.; Marcel Dekker: New York, 1990; p 429.

(5) Ernesto, A.; Maguire, G. E. M.; Murillo, O.; Suzuki, I.; De Wall, S. L.; Gokel, G. W. *J. Am. Chem. Soc.* **1999**, *121*, 9043.

(6) Dishong, D. M.; Diamond, C. J.; Inoman, M. I.; Gokel, G. W. *J. Am. Chem. Soc.* **1983**, *105*, 586.

(7) Lehn, J. M. *Acc. Chem. Res.* **1978**, *11*, 49.

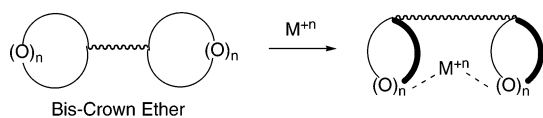
(8) An, H.; Bradshaw, J. S.; Izatt, R. M.; Yan, Z. *Chem. Rev.* **1994**, *94*, 939.

(9) Bourgoin, M.; Wong, K. H.; Hui, J. Y.; Smid, J. *J. Am. Chem. Soc.* **1975**, *97*, 3462.

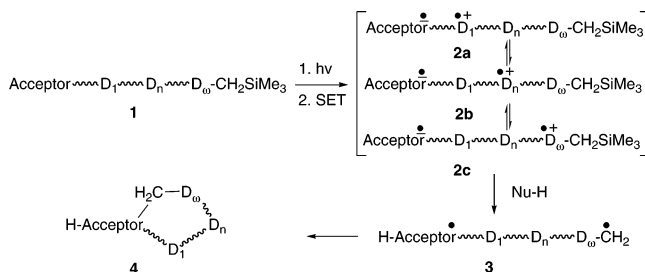
(10) Weber, E. *J. Org. Chem.* **1982**, *47*, 3478.

(11) Sarigul, S.; Bekaroglu, O. *Chem. Ber.* **1989**, *122*, 291.

## SCHEME 1



## SCHEME 2



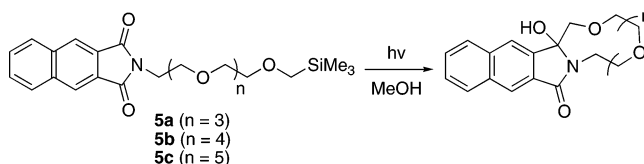
commonly involve formation of mono-crowns by nucleophilic substitution induced macrocyclic ring forming reactions under high dilution conditions and subsequent coupling to form the bis-crown framework.

Results from recent investigations in our laboratories<sup>12</sup> have led to the formulation of a new, potentially efficient strategy for the synthesis of bis-crown ethers. Earlier, we demonstrated that single electron transfer (SET)-induced photochemical reactions of trimethylsilyl-terminated acceptor-polydonor-linked substrates can be used to construct macrocyclic polyether, polythioether, polysulfonamide, and polyamide products.<sup>12</sup> Irradiation of appropriately designed substrates of this type (e.g., **1**, Scheme 2) promotes excited state SET to form interconverting zwitterionic biradicals **2**. Owing to the high reactivity of  $\alpha$ -trimethylsilyl-substituted cation radicals,<sup>13</sup> siliphile-promoted heterolytic fragmentation of the terminal zwitterionic biradicals **2c** takes place selectively to generate  $1,\omega$ -biradicals **3**, which participate in carbon-carbon bond forming reactions to produce macrocyclic products of **4**.

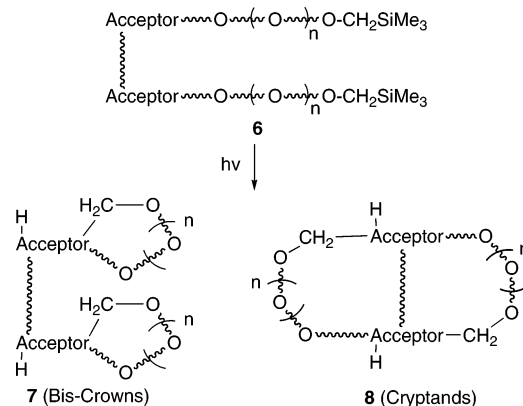
The SET photocyclization approach to the preparation of crown ethers and their heteroatomic analogues has several potential advantages over methods traditionally used for this purpose. For example, by their intrinsic nature, preparative photochemical reactions employ low photon fluxes (i.e., temporally low photon concentrations). Thus, little concern needs to be given to high dilution reaction conditions in order to prevent competitive oligomerizations. Stated in another way, short-lived  $1,\omega$ -biradicals formed in the photomacrocyclization pathway are generated in very low concentrations. Another unique feature of this approach is that it is ideally suited to producing crown ethers at defined times in specific and confined locations. Consequently, the photomacrocyclization procedure would enable the construction of crown ethers in precise patterns and in small volumes.

In continuing efforts in this area, we have shown that SET-promoted photomacrocyclization reactions are a key component of synthetic routes used to prepare crown-ether-based fluorescence sensors for metal cations.<sup>14</sup> In more recent exploratory

## SCHEME 3



## SCHEME 4



investigations, we have probed the effects of polydonor chain length on the efficiencies of SET-induced photomacrocyclization reactions of trimethylsilylmethyl-terminated acceptor-polydonor substrates.<sup>15</sup> A pertinent observation made in the latter effort is that the quantum efficiencies of photomacrocyclization reactions of trimethylsilylmethoxy-terminated polyethylenoxy-linked phthalimides, and naphthalimides (e.g., **5**, Scheme 3) are inversely dependent on the length of the linking polyether chain. This trend is exemplified by the relative quantum efficiencies for photocyclizations of the tri-, tetra-, and pentaethylenoxy naphthalimides (**5a-c**) of 1.0, 0.7, and 0.5, respectively.<sup>15</sup>

The results of these investigations have given rise to the design of a novel photochemical strategy for bis-crown ether synthesis. The methodology relies on the synthesis and selective photocyclization reactions of bis-tethered substrates of general structure **6** (Scheme 4). Irradiation of these substances should result in the production of a number of interconverting zwitterionic biradicals, formed by SET from donor sites in either chain to either acceptor moiety. The implication drawn from the results of the distance-dependence studies, summarized above, is that the most efficient reaction pathways followed by the bis-tethered substrates **6** should involve SET between and biradical formation in the proximal rather than distant acceptor-silyl-terminated polydonor moieties. If this prediction is correct, photomacrocyclization reactions of bis-tethered substrates **6** should selectively produce bis-crown **7** rather than cryptand-like **8** products (Scheme 4).

In order to explore the general strategy for bis-crown synthesis outlined above, the trimethylsilylmethoxy-terminated polyethylenoxy-branched bisphthalimides **13-15** (Scheme 5) and **21** (Scheme 6) were prepared and subjected to photochemical studies. The results of this effort demonstrate that photomacrocyclization reactions of these substrates take place with high efficiencies and high degrees of chemoselectivity to generate interesting bis-crown ethers.

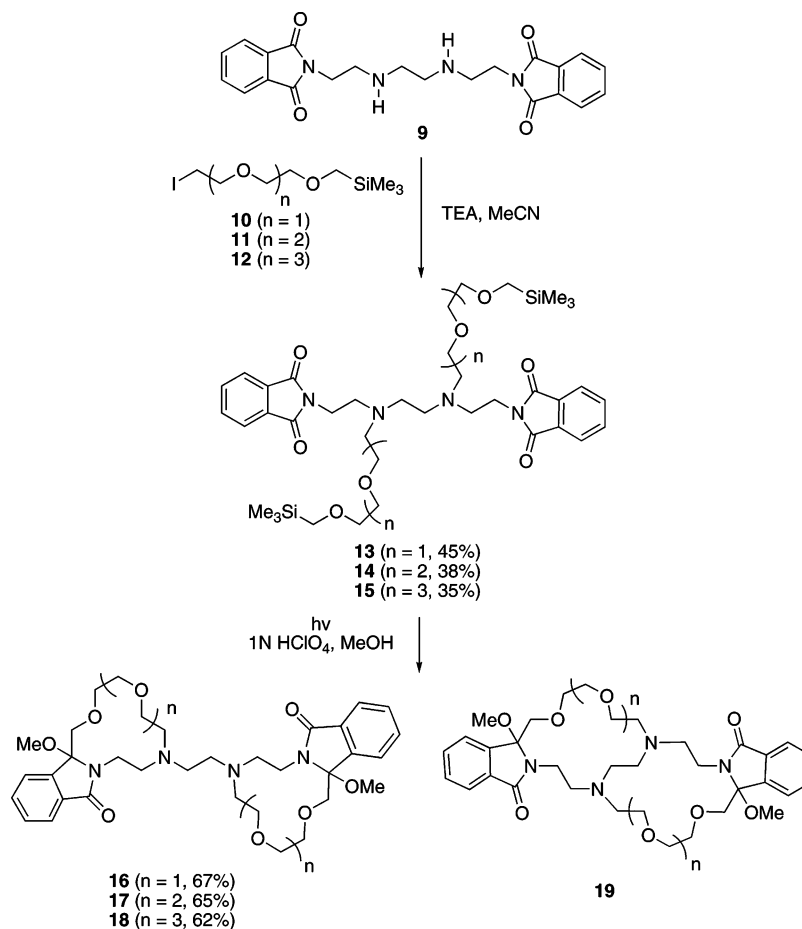
(12) (a) Yoon, U. C.; Oh, S. W.; Lee, C. W.; Park, J. H.; Kang, K. T.; Mariano, P. S. *J. Org. Chem.* **2001**, *66*, 939. (b) Yoon, U. C.; Jin, Y. X.; Oh, S. W.; Park, C. H.; Park, J. H.; Campana, C. F.; Cai, X.; Duesler, E. N.; Mariano, P. S. *J. Am. Chem. Soc.* **2003**, *125*, 10664.

(13) (a) Su, Z.; Falvey, D. E.; Yoon, U. C.; Oh, S. W.; Mariano, P. S. *J. Am. Chem. Soc.* **1997**, *120*, 10676. (b) Yoon, U. C.; Kwon, H. C.; Hyung, T. G.; Choi, K. H.; Oh, S. W.; Yang, S.; Zhao, Z.; Mariano, P. S. *J. Am. Chem. Soc.* **2004**, *126*, 1110.

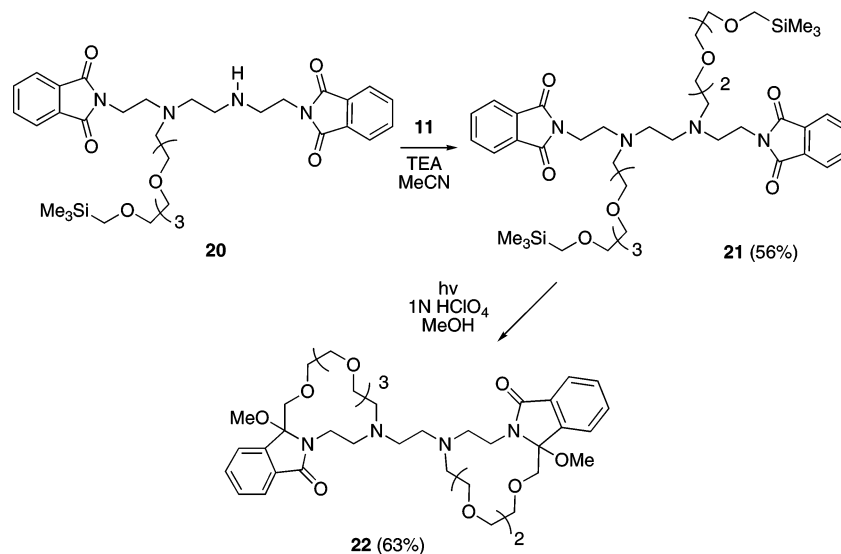
(14) Wang, R.; Zhao, Z.; Mariano, P. S.; Choi, K. H.; Kim, S. H.; Yoon, U. C. *J. Photochem. Photobiol. A* **2005**, *175*, 232.

(15) Unpublished results from studies of Yoon, U. C. and Mariano, P. S. and co-workers.

SCHEME 5



SCHEME 6



## Results and Discussion

**Preparation of Bis-Crowns.** The general procedure used to prepare bis-tethered phthalimides **13–15** involves N-alkylation of the known<sup>16</sup> bis-phthalimido diamine **9** (Scheme 5), prepared by condensation of *N*-carboethoxyphthalimide with triethylene-tetraamine. Reactions of **9** with the known<sup>17</sup> silyl polyethylenoxy

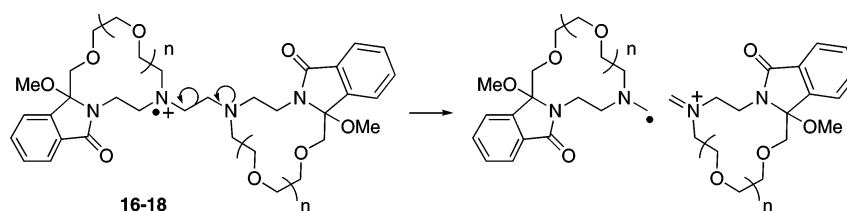
iodides **10–12** in the presence of TEA lead to the generation for the symmetrically substituted bisphthalimides **13–15** in modest yields.

The reaction of diamine **9** with iodide **12** produces the mono-N-alkylated product **20** (35%) in addition to the bis-adduct **15**. As a result, this protocol can be used to prepare unsymmetric

(16) Nefkens, G. H. L. *Nature* **1960**, *185*, 309.

(17) Yoon, U. C.; Oh, S. W.; Lee, C. W. *Heterocycles* **1995**, *41*, 2665.

## SCHEME 7



bisphthalimides, demonstrated by the formation of the mixed adduct **21** by reaction of **20** with iodide **11** (Scheme 6).

Photoreactions of the bis-tethered phthalimides **13–15** and **21** were carried out under conditions which promote facile desilylation of key cation radical intermediates and that block competitive SET from the tertiary amine donor groups. Accordingly, irradiation of these substances in MeOH containing 1.0 M HClO<sub>4</sub> leads to chemically efficient (62–67%) formation of bis-cyclization products (Schemes 5 and 6).<sup>13b</sup> Monitoring the progress of each photoreaction by UV spectroscopy shows that the phthalimide chromophores with wavelength maxima at 295 nm disappear during the course of the reactions with concurrent formation of a shoulder at ca. 253 nm corresponding to the benzamide chromophore in the bis-crown product.

High-resolution mass spectrometric and NMR analyses show that the products obtained upon chromatographic separation of the crude photolysates contain amido ether moieties. As observed in early studies,<sup>13b</sup> the amido alcohol to amido ether exchange process is typical for cyclic amido alcohols formed in methanol solutions containing HClO<sub>4</sub>. Detailed analyses of their spectroscopic properties and comparisons with those of closely related monocyclic analogues demonstrate that the photoproducts generated in these reactions possess either bis-crowns **16–18** and **22** or corresponding cryptand-type structures **19** (Scheme 5). Moreover, NMR analysis strongly suggests that each photoproduct is produced as a single diastereomer. This conclusion is based on the finding that the <sup>13</sup>C NMR spectra of **16–18** contain half the number of carbons present in their structures, indicating the presence of internal elements (plane or axis) of symmetry that would exist in either bis-crowns **16–18** or cryptand-type structures **19**.

Owing to the noncrystalline nature of the photoproducts and to potential ambiguities associated with interpretations of their NMR properties, alternative methods to assign structures were sought. Important information in this regard came from implementation of the old, but well-tested, technique of electron impact (EI) mass spectrometry. The 1,2-diamine moieties in the photoproducts, independent of whether they possess bis-crown or cryptand-like structures, serve as centers at which highly efficient C–C bond fragmentation reactions of the corresponding amine cation radicals typically take place (Scheme 7).<sup>18</sup> However, only in the cases of bis-crown-type photoproducts would these fragmentation processes lead to positively charged and neutral fragments with one-half the mass-to-charge ratios of the parent ions. Thus, if **16–18** are bis-crowns, their respective EI mass spectra would be expected to contain major peaks at *m/z* 319, 363, and 407, which are one-half that of the corresponding parent ions at *m/z* 638, 726, and 814. It is important to note that, since loss of methanol from the parent ions of related cyclic amido ethers is well-documented,<sup>13b</sup> the

**TABLE 1.** Summary of Electron Impact Mass Spectrometric Data of Bis-Crown Ethers **16–18**

crown	Bis-Crown		EI Mass Spec Fragments	
	molecular formula	mol wt	<i>m/z</i> (%)	molecular formula
<b>16</b>	C <sub>34</sub> H <sub>46</sub> N <sub>4</sub> O <sub>8</sub>	638	287.1389 (100)	C <sub>16</sub> H <sub>19</sub> N <sub>2</sub> O <sub>3</sub>
			319.1667 (22)	C <sub>17</sub> H <sub>23</sub> N <sub>2</sub> O <sub>4</sub>
<b>17</b>	C <sub>38</sub> H <sub>54</sub> N <sub>4</sub> O <sub>10</sub>	726	331.1670 (100)	C <sub>18</sub> H <sub>23</sub> N <sub>2</sub> O <sub>4</sub>
			363.1922 (63)	C <sub>19</sub> H <sub>27</sub> N <sub>2</sub> O <sub>5</sub>
<b>18</b>	C <sub>42</sub> H <sub>62</sub> N <sub>4</sub> O <sub>12</sub>	814	375.1917 (60)	C <sub>20</sub> H <sub>27</sub> N <sub>2</sub> O <sub>5</sub>
			407.2175 (100)	C <sub>21</sub> H <sub>31</sub> N <sub>2</sub> O <sub>6</sub>
<b>22</b>	C <sub>40</sub> H <sub>58</sub> N <sub>4</sub> O <sub>11</sub>	770	331.1669 (100)	C <sub>18</sub> H <sub>23</sub> N <sub>2</sub> O <sub>4</sub>
			363.1881 (12)	C <sub>19</sub> H <sub>27</sub> N <sub>2</sub> O <sub>5</sub>
			375.1918 (94)	C <sub>20</sub> H <sub>27</sub> N <sub>2</sub> O <sub>5</sub>
			407.2182 (20)	C <sub>21</sub> H <sub>31</sub> N <sub>2</sub> O <sub>6</sub>

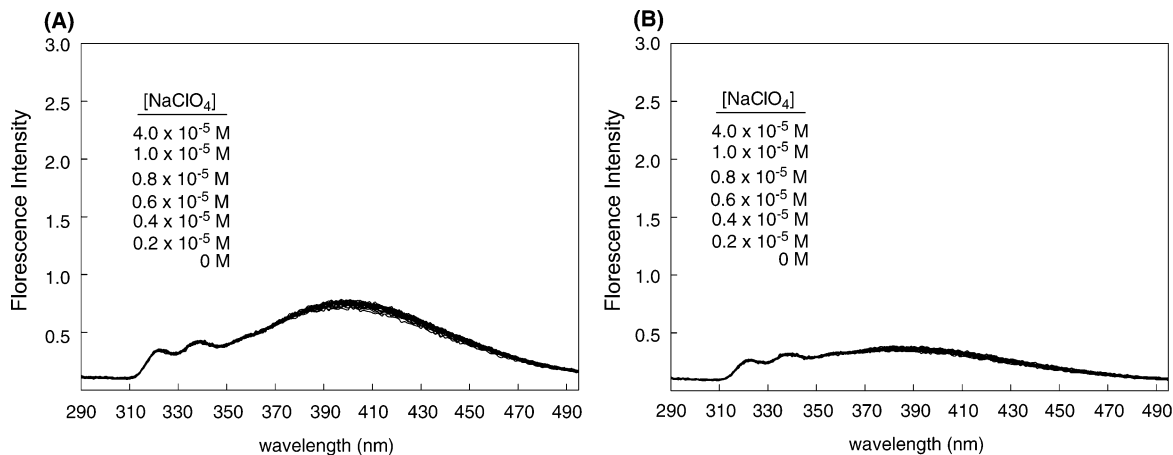
EI mass spectra of **16–18** should also contain intense peaks for fragment ions at *m/z* 287, 331, and 375, respectively.

The results of EI mass spectrometric analysis provide strong support for assignments of bis-crown-type structures to the photomacrocyclization products **16–18** generated upon irradiation of the corresponding bis-tethered phthalimides **13–15**. As can be seen by viewing the data summarized in Table 1, the EI mass spectra of the photoproducts contain pairs of exceptionally intense peaks at *m/z* values that are exactly one-half that of the parent ions and of fragments corresponding to loss of methanol. In the case of the mixed bis-crown **22**, EI ionization promotes C–C bond fragmentation to produce iminium ions corresponding to both macrocyclic components either before or after loss of methanol (Table 1). Exact mass measurements made on these peaks demonstrate that they have atomic compositions that match those of fragments produced by cleavage of the central C–C bonds of radical cations produced by EI ionization of bis-crown structures.

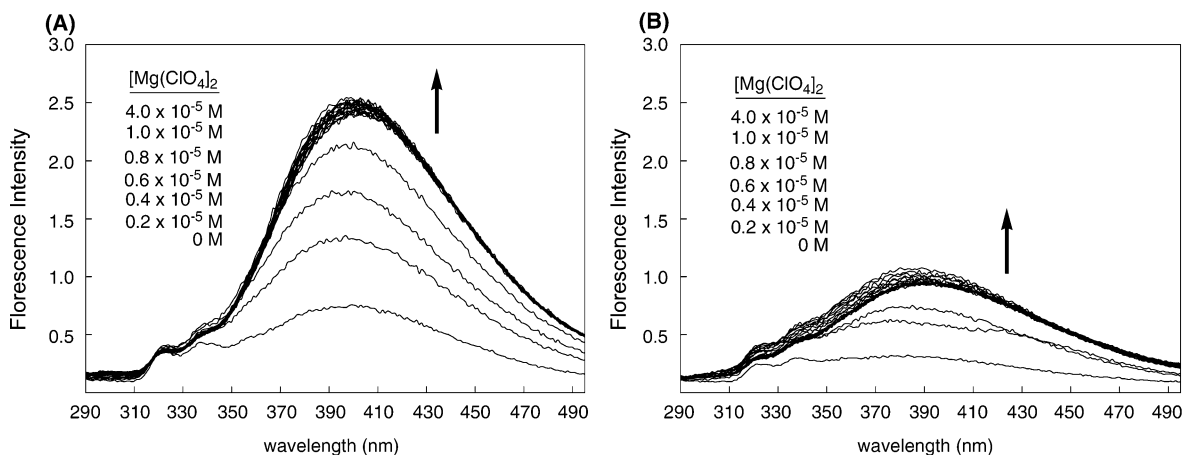
Further support for the assignment of bis-crown rather than cryptand-like structures to the products of the photomacrocyclization reactions has come from the results of chemical degradation studies with **16**. An alternative procedure for promoting cation radical formation and C–C bond fragmentation of the 1,2-diamine group found in the bis-crowns involves the use of SET oxidants,<sup>18b</sup> such as ceric ammonium nitrate (CAN). In these cases, the  $\alpha$ -amino radical, generated along with its iminium ion partner (Scheme 7), undergoes secondary SET oxidation to form an iminium ion. Aqueous workup of the reaction mixture then transforms the iminium ions into two equivalents of formaldehyde and the secondary amine. In accord with this prediction and its bis-crown structure, treatment of **16** with CAN in MeCN followed by aqueous NaHCO<sub>3</sub> workup cleanly yields the secondary amine **23** (Scheme 8).

**Metal Cation Binding Properties of Bis-Crowns.** The metal cation binding properties of selected members of the bis-crown ether family, prepared by using the methodology described above, were briefly explored. Extraction constants<sup>19</sup> are typically used to express binding affinities of substances that coordinate metal cations. To obtain these constants, a water-soluble metal

(18) (a) Bouchoux, G.; Choret, N.; Milliet, A.; Rempp, M.; Terlouw, J. K. *Int. J. Mass Spectrom.* **1998**, 179/180, 337. (b) Lucia, L. A.; Wang, X.; Nafisi, K.; Netzel, T. L.; Schanze, K. S. *J. Phys. Chem.* **1995**, 99, 11801.

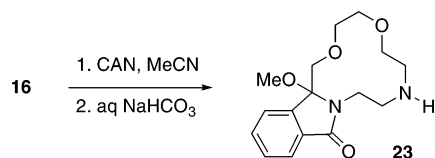


**FIGURE 1.** Fluorescence spectra of bis-crowns **16** (A) and **17** (B) in MeCN ( $1.0 \times 10^{-5}$  M) at 25 °C with an excitation wavelength of 270 nm as a function of the NaClO<sub>4</sub> concentration.



**FIGURE 2.** Fluorescence spectra of bis-crowns **16** (A) and **17** (B) in MeCN ( $1.0 \times 10^{-5}$  M) at 25 °C with an excitation wavelength of 270 nm as a function of the Mg(ClO<sub>4</sub>)<sub>2</sub> concentration.

#### SCHEME 8



picrate is partitioned between a water layer and an organic layer containing the water-insoluble complexing agent. The percentage of the metal picrate extracted into the organic layer is then determined by using absorption spectroscopy. The results of experiments conducted by using reported procedures<sup>20</sup> demonstrate that the small macrocyclic ring containing bis-crowns **16** and **17** has lower and less selective alkali metal cation extraction constants than 18-crown-6 (Table 2).

Another interesting observation made in studies with the bis-crowns concerns the metal cation dependence of their fluorescence properties. Owing to the presence of the benzamide chromophore and tertiary amine SET donor sites, bis-crowns **16** and **17** are only weakly fluorescent. Moreover, complexation

**TABLE 2.** Extraction Constants of Bis-Crown Ethers **16** and **17** and 18-Crown-6

compound	Extraction Constant (%) <sup>a</sup>			
	Na <sup>+</sup>	K <sup>+</sup>	Rb <sup>+</sup>	Cs <sup>+</sup>
18-crown-6 <sup>b</sup>	5	86	73	32
<b>16</b>	10	10	15	12
<b>17</b>	16	14	17	15

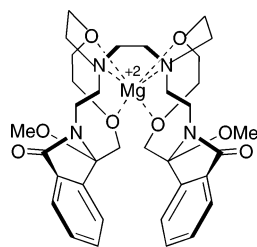
<sup>a</sup> The procedure described by Ouchi et al.<sup>20</sup> was used. <sup>b</sup> The data for 18-crown-6 closely match those reported by Ouchi et al.<sup>20</sup>

of these substances to alkali metal cations does not perturb the character of their singlet excited state emission (Figure 1). In contrast, a dramatic change takes place when magnesium perchlorate is added to MeCN solutions of **16** and **17**. As can be seen by viewing the spectra displayed in Figure 2, in each case increasing concentrations of Mg(ClO<sub>4</sub>)<sub>2</sub> causes a dramatic growth of a broad exciplex emission band between ca. 425 and 440 nm. The increase in the exciplex emission intensity plateaus after approximately 1 molar equiv of magnesium is added. We believe that this unusual behavior is a consequence of several factors. First, sandwich-type binding of magnesium (shown in Scheme 9 for the meso-diastereomer of **16**) could result in close facial approach of the benzamide aromatic rings in **16** and **17**, which would favor exciplex formation. Second, magnesium complexation involving the tertiary amine groups as ligands

(19) Gokel, G. W. *Crown Ethers and Cryptands*; Royal Society of Chemistry: Oxford, 1991.

(20) (a) Ouchi, M.; Inoue, Y.; Sakamoto, H.; Yamahira, A.; Yoshinaga, M.; Hakushi, T. *J. Org. Chem.* **1983**, *48*, 3168. (b) Ouchi, M.; Inoue, Y.; Kanzaki, T.; Hakushi, T. *J. Org. Chem.* **1984**, *49*, 1408.

## SCHEME 9



would block the ability of the amines to serve as SET quenchers of benzamide singlet excited states. The 1:1 stoichiometric nature of the response suggests that the fluorescence enhancements are associated with formation of sandwich complexes involving both amine nitrogens. Finally, the differential magnitudes of the magnesium-promoted fluorescence enhancements of **16** and **17** might be due to differences in the relative orientations of the benzamide rings in their magnesium complexes.

## Experimental Section

**Preparation of Bis-Phthalimido Diamine 9.** This substance was prepared by using a modification of the reported procedure.<sup>16</sup> To a solution of *N*-carboethoxyphthalimide (5.0 g, 22.8 mmol) and triethylamine (6.35 mL, 45.6 mmol) in 50 mL of MeCN was added a solution of triethylenetetraamine hydrate (1.33 g, 9.12 mmol) in 10 mL of MeCN. The mixture was stirred for 2 h at room temperature and concentrated in vacuo to afford the bisphthalimide **9** (2.51 g, 68%): <sup>1</sup>H NMR δ 2.73 (s, 4H), 2.90 (t, 4H, *J* = 6.3 Hz), 3.76 (t, 4H, *J* = 6.3 Hz), 7.69–7.66 (m, 4H), 7.81–7.78 (m, 4H); <sup>13</sup>C NMR δ 37.7, 47.6, 48.6, 123.0, 131.8, 133.6, 168.12; HRMS *m/z* (*M* + Na) 407.1736 (C<sub>22</sub>H<sub>22</sub>N<sub>4</sub>O<sub>4</sub>Na<sup>+</sup> requires 429.1533).

**Preparation of (*N,N'*-Bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)ethylenediamines 13–15.** Independent solutions of *N,N'*-(bisphthalimidoethyl)ethylenediamine **9** (2.0 g, 4.92 mmol) and triethylamine (2.74 mL, 19.7 mmol) in 50 mL of MeCN containing the known<sup>17</sup> ω-(trimethylsilylmethoxy)-polyethylenoxy iodides **10**–**12** (14.8 mmol, 4.46 g of **10**, 5.11 g of **11**, 5.76 g of **12**) were stirred for 4 days at 80 °C. Concentration of each solution in vacuo gave a residue which was diluted with chloroform and extracted with 10% aq NaHCO<sub>3</sub>. The extracts were washed with water, dried, and concentrated to afford residues which were subjected to silica gel column chromatography (1:1 ethyl acetate–hexane) to afford **13** (1.49 g, 41%), **14** (1.57 g, 38%), and **15** (1.60 g, 35%).

**13:** <sup>1</sup>H NMR δ 0.01 (s, 18H), 2.50 (s, 4H), 2.61 (t, 4H, *J* = 4.4 Hz), 2.72 (t, 4H, *J* = 6.0 Hz), 3.03 (s, 2H), 3.42–3.36 (m, 12H), 3.65 (t, 4H, *J* = 4.4 Hz), 7.62–7.58 (m, 4H), 7.76–7.72 (m, 4H); <sup>13</sup>C NMR δ –2.8, 36.3, 52.4, 52.8, 53.9, 65.4, 69.8, 70.2, 74.4, 123.1, 132.3, 133.7, 168.2; HRMS *m/z* (*M* + Na) 777.3505 (C<sub>38</sub>H<sub>58</sub>N<sub>4</sub>O<sub>8</sub> Si<sub>2</sub>Na<sup>+</sup> requires 777.3585).

**14:** <sup>1</sup>H NMR δ 0.01 (s, 18H), 2.57 (s, 4H), 2.71 (t, 4H, *J* = 5.8 Hz), 2.76 (t, 4H, *J* = 6 Hz), 3.11 (s, 2H), 3.42 (t, 4H, *J* = 6.0 Hz), 3.61–3.46 (m, 16H), 3.72 (t, 4H, *J* = 5.8 Hz), 7.69–7.65 (m, 4H), 7.83–7.79 (m, 4H); <sup>13</sup>C NMR δ –3.1, 36.1, 52.3, 52.6, 53.8, 65.3, 69.6, 70.2, 70.3, 70.4, 74.6, 123.1, 132.1, 133.7, 168.2; HRMS *m/z* (*M* + Na) 865.4215 (C<sub>42</sub>H<sub>66</sub> N<sub>4</sub>O<sub>10</sub>Si<sub>2</sub>Na<sup>+</sup> requires 865.4210).

**15:** <sup>1</sup>H NMR δ 0.01 (s, 18H), 2.58 (s, 4H), 2.69 (t, 4H, *J* = 6.4 Hz), 2.77 (t, 4H, *J* = 6.1 Hz), 3.11 (s, 2H), 3.43 (t, 4H, *J* = 6.1 Hz), 3.65–3.47 (m, 24H), 3.72 (t, 4H, *J* = 6.4 Hz), 7.67–7.63 (m, 4H), 7.83–7.79 (m, 4H); <sup>13</sup>C NMR δ –3.1, 36.0, 52.3, 52.6, 53.8, 65.5, 72.6–69.6 (multiple resonances), 74.6, 123.0, 132.1, 133.7, 168.1; HRMS *m/z* (*M* + Na) 953.4738 (C<sub>46</sub>H<sub>74</sub>N<sub>4</sub>O<sub>12</sub>Si<sub>2</sub>Na<sup>+</sup> requires 953.4734).

In the reaction of **9** with **12**, 1.54 g (31%) of the monoalkylated product **20** was also obtained: <sup>1</sup>H NMR δ –0.02 (s, 9H), 2.67 (t, 2H, *J* = 4.5 Hz), 2.85 (t, 2H, *J* = 4.5 Hz), 3.05 (t, 2H, *J* = 4.9

Hz), 3.11 (s, 2H), 3.24 (t, 2H, *J* = 5.9 Hz), 3.28 (t, 2H, *J* = 5.9 Hz), 3.58–3.40 (m, 12H), 3.78 (t, 2H, *J* = 6.0 Hz), 4.21 (t, 2H, *J* = 5.9 Hz), 7.76–7.70 (m, 4H), 7.81–7.77 (m, 4H); <sup>13</sup>C NMR δ –2.9, 34.1, 37.4, 46.0–45.7 (multiple resonances), 51.1, 54.7, 53.9, 65.3, 70.4–69.5 (multiple resonances), 74.5, 123.1, 123.3, 131.5, 131.7, 134.0, 134.1, 168.4, 167.8; HRMS *m/z* 669.3319 (C<sub>34</sub>H<sub>49</sub>N<sub>4</sub>O<sub>8</sub>-Si requires 669.3320).

**Preparation of Unsymmetric (*N,N'*-Bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)-ethylenediamine 21.** A solution of (*N,N'*-bisphthalimidoethyl)-(*N*-ω-trimethylsilylmethoxytetraethylenoxy)ethylenediamine **20** (1.0 g, 1.50 mmol), triethylamine (0.42 mL, 3.0 mmol), and (trimethylsilylmethoxy)polyethylenoxy iodide **11** (1.29 g, 3.74 mmol) in 10 mL of MeCN was stirred for 30 min at 80 °C each day for 4 days and concentrated in vacuo to afford a residue which was diluted with 10% aq NaHCO<sub>3</sub> and extracted with chloroform. The extracts were washed with water, dried, and concentrated in vacuo, giving a residue which was subjected to silica gel column chromatography (1:1 ethyl acetate–hexane) to afford 0.74 g (56%) of the mixed-chain bisphthalimide **21**: <sup>1</sup>H NMR δ 0.01 (s, 18H), 2.56 (s, 4H), 2.67 (t, 4H, *J* = 5.9 Hz), 2.74 (t, 4H, *J* = 6.1 Hz), 3.10 (s, 2H), 3.39 (t, 4H, *J* = 6.1 Hz), 3.61–3.49 (m, 20H), 3.71 (t, 4H, *J* = 5.9 Hz), 7.74–7.65 (m, 4H), 7.82–7.78 (m, 4H); <sup>13</sup>C NMR δ –3.1, 36.0, 52.5, 53.7, 61.5, 65.4, 72.6–69.6 (multiple resonances), 74.6, 123.0, 132.1, 133.7, 168.2; HRMS *m/z* (*M* + Na) 909.4504 (C<sub>44</sub>H<sub>70</sub>N<sub>4</sub>O<sub>11</sub>Si<sub>2</sub>Na<sup>+</sup> requires 909.4472).

**Irradiation of (*N,N'*-Bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)ethylenediamines 13–15. Formation of Bis-Crowns 4a–c.** Independent N<sub>2</sub>-purged solutions of (*N,N'*-bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)ethylenediamines **13** (680 mg, 0.9 mmol), **14** (760 mg, 0.9 mmol), and **15** (840 mg, 0.9 mmol) in 250 mL of MeOH containing 1.0 M HClO<sub>4</sub> were irradiated with Pyrex glass filtered light for 2 h. Each photolysate was neutralized by addition of 10% aq NaHCO<sub>3</sub> and extracted with CHCl<sub>3</sub>. The organic extracts were dried and concentrated in vacuo to give residues which were subjected to silica gel column chromatography (5:1 ethyl acetate–MeOH) to afford **16** (454 mg, 67%), **17** (361 mg, 65%), and **18** (429 mg, 63%).

**16:** <sup>1</sup>H NMR δ 2.75 (s, 6H), 3.11–2.77 (m, 8H), 3.74–3.41 (m, 20H), 4.20, 4.18 (s, 2H), 7.44–7.40 (m, 2H), 7.52–7.47 (m, 4H), 7.72–7.70 (m, 2H); <sup>13</sup>C NMR δ 36.3, 50.1, 51.7, 53.8, 53.9, 70.1, 70.3, 72.0, 74.1, 93.3, 123.0, 123.2, 129.7, 131.8, 132.7, 142.4, 168.2; HRMS *m/z* (*M* – 2MeOH + Na) 633.2800 (C<sub>32</sub>H<sub>42</sub>N<sub>4</sub>O<sub>8</sub>-Na<sup>+</sup> requires 633.3895).

**17:** <sup>1</sup>H NMR δ 2.74 (s, 6H), 3.01–2.77 (m, 8H), 3.76–3.36 (m, 28H), 4.28, 4.24 (s, 2H), 7.42–7.38 (m, 2H), 7.53–7.46 (m, 4H), 7.71–7.69 (m, 2H); <sup>13</sup>C NMR δ 36.6, 50.0, 51.9, 53.6, 53.8, 70.0, 70.1, 70.3, 71.0, 72.0, 74.2, 93.1, 122.7, 123.1, 129.4, 131.4, 132.5, 142.1, 167.8; HRMS *m/z* (*M* + Na) 749.3757 (C<sub>38</sub>H<sub>54</sub>N<sub>4</sub>O<sub>10</sub>Na<sup>+</sup> requires 749.3732).

**18:** <sup>1</sup>H NMR δ 2.76 (s, 6H), 2.90–2.86 (m, 8H), 3.59–3.30 (m, 36H), 3.87 (q, 2H, *J* = 6.0 Hz), 7.43–7.40 (m, 2H), 7.50–7.45 (m, 4H), 7.72–7.70 (m, 2H); <sup>13</sup>C NMR δ 38.0, 50.4, 52.8, 53.8, 54.8, 69.9, 70.9–71.7 (multiple resonances), 73.6, 94.0, 123.0, 123.3, 130.0, 132.0, 133.4, 142.6, 168.6 (C=O); HRMS *m/z* (*M* + Na) 837.4212 (C<sub>42</sub>H<sub>62</sub>N<sub>4</sub>O<sub>12</sub>Na<sup>+</sup> requires 837.4256).

**Irradiation of Mixed-Chain (*N,N'*-Bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)ethylenediamine 21.** A N<sub>2</sub>-purged solution of the mixed-chain (*N,N'*-bisphthalimidoethyl)-(*N,N'*-bistrimethylsilylmethoxypolyethylenoxy)ethylenediamine **21** (700 mg, 0.789 mmol) in 250 mL of MeOH containing 1.0 M HClO<sub>4</sub> was irradiated with Pyrex glass filtered light for 2 h. The photolysate was neutralized by addition of 10% aq NaHCO<sub>3</sub> and extracted with CHCl<sub>3</sub>. The organic extracts were dried and concentrated in vacuo to give a residue which was subjected to silica gel column chromatography (5:1 ethyl acetate–MeOH) to afford bis-crown **22** (365 mg, 63%): <sup>1</sup>H NMR δ 2.76 (s, 6H), 2.90–2.86 (m, 8H), 3.59–3.30 (m, 36H), 3.87 (q, 2H, *J* = 6.0 Hz), 7.43–

7.40 (m, 2H), 7.50–7.45 (m, 4H), 7.72–7.70 (m, 2H);  $^{13}\text{C}$  NMR  $\delta$  35.0, 50.4, 52.8, 53.4, 54.8, 70.1, 70.9–71.7 (multiple resonances), 73.6, 93.60, 122.8, 123.2, 129.2, 130.0, 132.1, 142.06, 168.2; HRMS  $m/z$  793.3986 ( $\text{C}_{40}\text{H}_{58}\text{N}_4\text{O}_{11}\text{Na}^+$  requires 793.3994).

**Oxidative Cleavage of Bis-Crown 16.** A solution of **16** (16 mg, 0.025 mmol) in  $\text{CH}_3\text{CN}$  (25 mL), containing ceric ammonium nitrate (119 mg, 0.217 mmol), was stirred for 6 days at 25 °C and then poured into aq  $\text{NaHCO}_3$ . Extraction of the solution with  $\text{CHCl}_3$  followed by drying of the extract and concentration in vacuo gave the secondary amine **23** in sufficient purity to perform spectroscopic analysis:  $^{13}\text{C}$  NMR  $\delta$  36.3, 45.2, 48.1, 49.6, 63.3, 66.7, 68.0, 69.7, 93.4, 121.7, 123.3, 130.1, 131.6, 132.7, 141.7, 170.1; HRMS (M

+ 1)  $m/z$  307.1644 ( $\text{C}_{16}\text{H}_{23}\text{N}_2\text{O}_4$  requires 307.1658), (M – OMe)  $m/z$  275.1373 ( $\text{C}_{15}\text{H}_{19}\text{N}_2\text{O}_3$  requires 275.1396).

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**Supporting Information Available:** General experimental, NMR spectra, and EI mass spectra are included. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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