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A novel method for the synthesis of regiospecifically sulfonated porphyrin monomers and dimers

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Abstract—A novel method has been developed to regiospecifically synthesize water-soluble sulfonated porphyrin monomers tetrakis(4′-sulfonatophenyl)porphyrin, tetrakis(3′-sulfonatophenyl)porphyrin, tetrakis(2′-sulfonatophenyl)porphyrin, tetrakis(2′,5′-dimethyl-4′-sulfonatophenyl)porphyrin, the dimers of 1,2-bis[5,10,15-tri(4′-sulfonatophenyl)porphyrinyl]benzene and 1,2-bis[5,10,15-tri(2′,5′-dimethyl-4′-sulfonatophenyl)porphyrinyl]benzene in high yields through introduction of the trimethylsilyl group on the phenyl rings and reaction with trimethylsilyl chlorosulfonate in CCl_4 solvent.

1. Introduction

Sulfonated metalloporphyrins are known to be typical water-soluble ones and have been well investigated,[1] which show applications not only for their anti-HIV activities[2] and tumor localizing properties in photodynamic therapy[3,4] or as contrast-enhancing agent in magnetic resonance imaging,[5] but also for their catalytic activity as ligninase,[6] chloroperoxidase[7] and peroxidase models in biomimetic catalysts for the oxidation of pollutants.[8] In addition, sulfonated porphyrins have also been widely applied in analytical and supramolecular chemistry.[9–14] The Pd^{II} complexes of sulfonated porphyrins have been used to determine O_2 levels in biological systems by phosphorescence quenching[12] and H(β-Br_8-TSPP) [TSPP= tetrakis(4-sulfonatophenyl)porphyrin] to determine the lithium ion in sea water and human serum.[13,14]

Sulfonation of phenyl rings in porphyrin is generally carried out with concentrated sulfuric acid.[15–21] The substitution reaction usually occurs at the *para* position of the phenyl rings. The yields of such reaction are usually not good and the purification procedures are tedious and time-consuming. A convenient and efficient method is therefore desired for the synthesis of water-soluble sulfonated porphyrins. Recently, chlorosulfonic acid was employed to prepare sulfonated porphyrin.[22] The major advantage is that the initially formed chlorosulfonyl compounds are very easily isolated from the reaction medium because they are insoluble in water but soluble in most of organic solvents. The chlorosulfonyl intermediate is conveniently converted into the corresponding sulfonic acids, sulfonate ethers, and sulfonamides. However, this method is only employed to sulfonate the *para* position of the phenyl rings or *meta* position of the *para*-substituent phenyl rings. Furthermore, they are unsuitable to sulfonate phenylene-bridged polyporphyrin due to the problems of sulfonation in indefinite site and tedious chromatographic separation. On the other hand, the trimethylsilylbenzene can react with the sulfonation reagent, $ClSO_3SiMe_3$, to produce the corresponding sulfonated benzene in quantitative yield.[23] Herein, we report a novel method to synthesize regiospecific water-soluble sulfonated porphyrins in high yields through introduction of the trimethylsilyl group on the phenyl rings and successive reaction with trimethylsilyl chlorosulfonate. In addition, we further demonstrated its application to the synthesis of water-soluble sulfonated bisporphyrins. To the best of our knowledge, these are the first examples of the water-soluble sulfonated bisporphyrins.

2. Results and discussion

The syntheses of tetrakis(*p*-sulfonatophenyl)porphyrin have been well investigated.[1] However, *meta*- and *ortho*-sulfonatophenyl porphyrins were not well-documented because the direct sulfonation reaction generally occurs at the *para* position of their phenyl rings.[15–21] This can be overcome by introducing of a trimethylsilyl group to a definite position, which reacts with trimethylsilyl chlorosulfonate and can be converted to the sulfonate quantitatively.[23]

Keywords: sulfonation; regiospecific; water-soluble porphyrin; bisporphyrin; trimethylsilyl chlorosulfonate.

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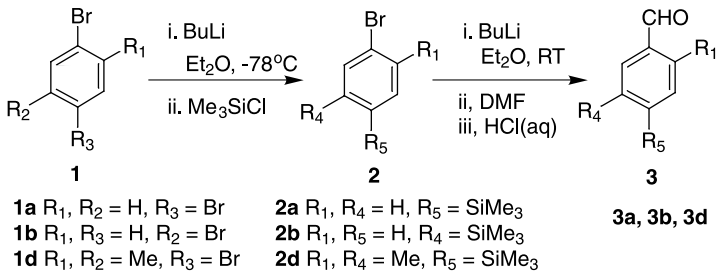
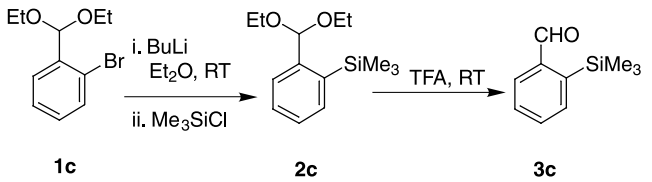


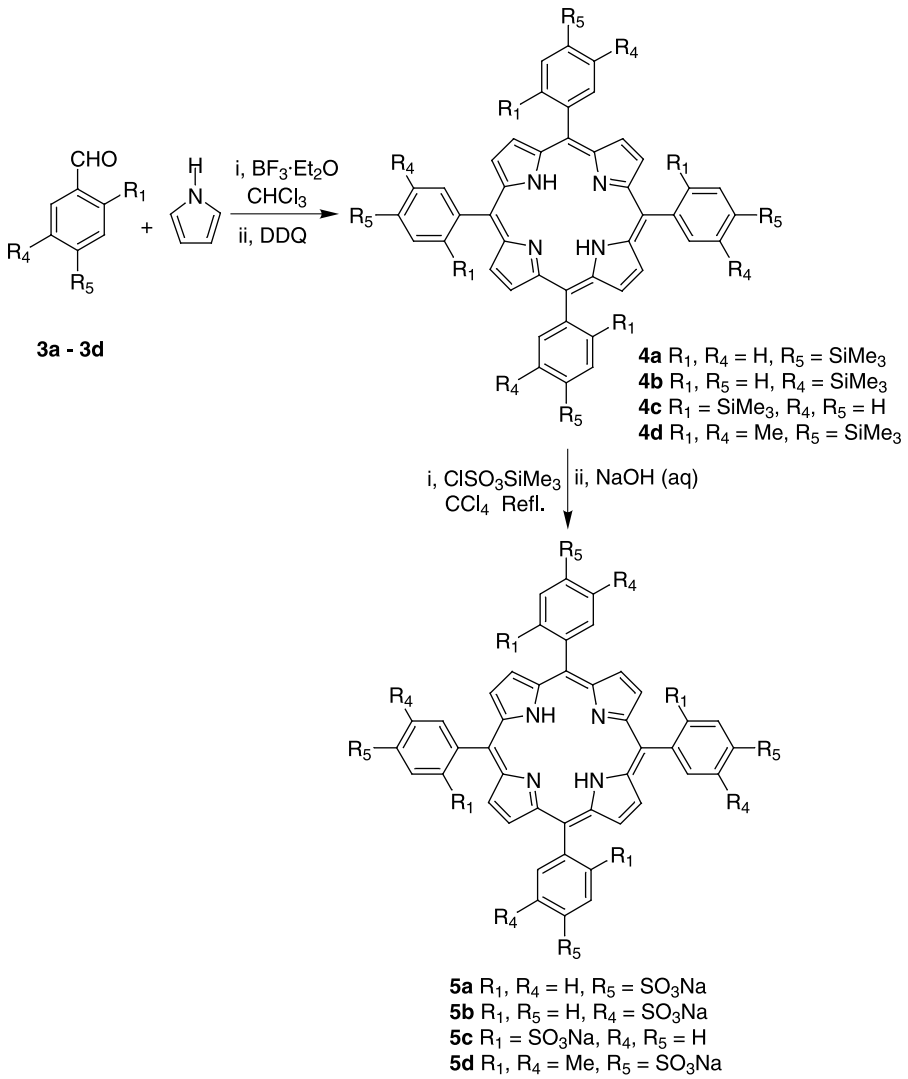
Scheme 1. Synthesis of **3a**, **3b** and **3d**.



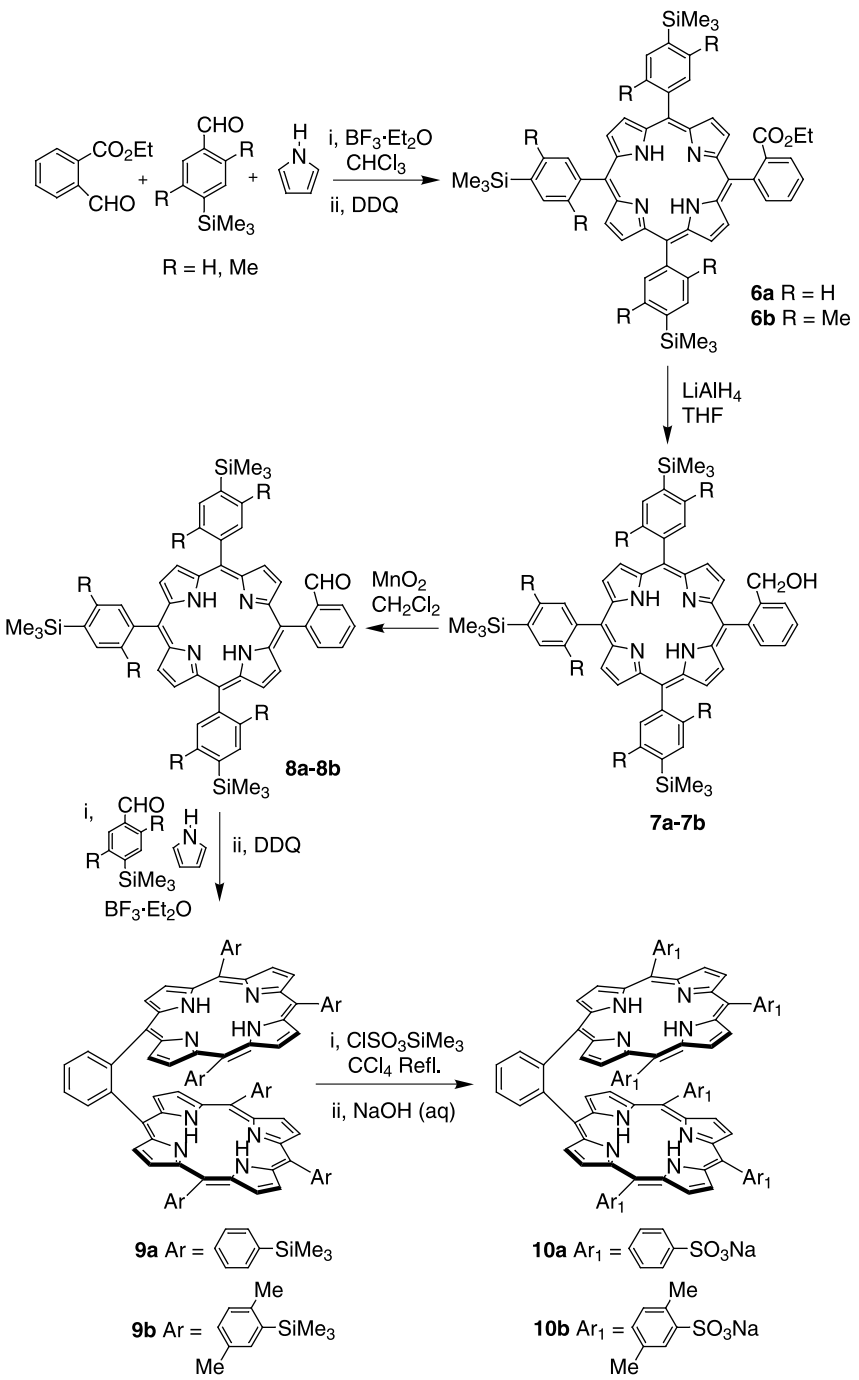
Scheme 2. Synthesis of **3c**.

2.1. Synthesis of monomer porphyrins

The synthesis of trimethylsilylbenzaldehydes is outlined in Scheme 1. Reaction of 1,4-dibromobenzene (**1a**) with an equivalent of *n*-BuLi in Et_2O at −78°C gave the monolithiated intermediate, which further reacted with chlorotrimethylsilane affording the corresponding 1-bromo-4-(trimethylsilyl)benzene (**2a**) in 88% yield.[24] 4-Trimethylsilylbenzaldehyde (**3a**) was obtained in 75% by treatment of **2a** with 1 equiv. *n*-BuLi in Et_2O at room temperature in the presence of dry DMF followed by hydrolysis of the



Scheme 3. Synthesis of sulfonated porphyrins.



Scheme 4. Synthesis of sulfonated porphyrin dimers.

intermediate with aqueous HCl. The other trimethylsilylbenzaldehydes, **3b** and **3d**, were also synthesized by the similar procedures in 60% yield based on **1b** and **1d**.

2-Trimethylsilylbenzaldehyde (**3c**) was prepared in 68% yield by reaction of protected 2-bromobenzaldehyde with an equivalent of *n*-BuLi in the presence of chlorotrimethylsilane, and then deprotection by trifluoroacetic acid (Scheme 2). We had also tried in vain to prepare **3c** by a similar procedure as that for **3a**. Only a trace amount of 1-bromo-(2-trimethylsilyl)benzene was obtained in the reaction of 1,2-dibromobenzene with 1 equiv. *n*-BuLi and then with chlorotrimethylsilane at −130°C, though lithiation/phosphorylation of 1,2-dibromobenzene had been reported.[27] Trimethylsilylphenylporphyrins (**4**) have been synthesized by Lindsey's method[25,26] and purified on Al_2O_3 and silica gel columns in 40–48% yields. The compounds were identified by elemental analysis, NMR and ESI-MS spectra.

The syntheses of sulfonated porphyrins are shown in Scheme 3. First, the sulfonation reaction at the *para* position of the phenyl rings of **4a** was performed. Tetrakis(4′-sulfonatophenyl)porphyrin (**5a**) was smoothly synthesized through sulfonation of **4a** with $ClSO_3SiMe_3$ in refluxing CCl_4 solution for 4 h and then hydrolysis of the intermediate

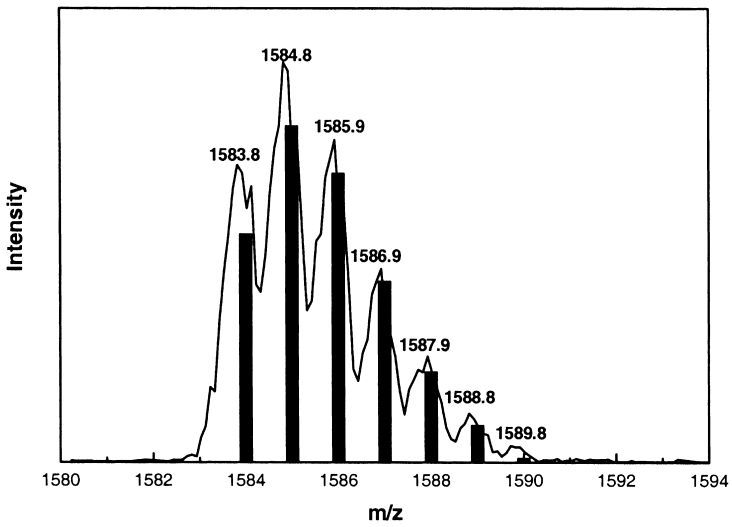


Figure 1. Comparison of experimental ESI-MS of **9a** (solid line) and calculated for $C_{100}H_{103}N_8Si_6$ (bar).

with aqueous NaOH.[23] The reaction was monitored by NMR spectroscopy and terminated when the peak of trimethylsilyl had disappeared. The product was purified by dialysis with cellulose dialysis membranes and confirmed by NMR and ESI-MS spectra. In the course of the synthesis of water-soluble sulfonated porphyrin, the purification procedures are tedious and time-consuming though a few methods, including a low-pressure reverse-phase silica gel column,[19] a Sephadex G-10 column,[28] a celite column,[29] and recrystallization[15,30,31] have been developed. The dialysis method is convenient and easily controlled, but is dependent on the molecular weight.[20,32] In our case, the sulfonation reaction proceeded to completion and produced only inorganic salt as a by-product. Therefore, the dialysis method was the choice for purification. Furthermore, the sulfonation of tetrakis(2′,5′-dimethyl-4′-trimethylsilyphenyl)porphyrin (**4d**), which bears two methyl groups on each phenyl ring, was also successful under these reaction conditions. In the mean time, we found that the sulfonation reaction did not proceed completely when CH_2Cl_2 was used in place of CCl_4. A mixture of mono-, di-, tri-, and tetra-substituted porphyrins was produced. This suggests that the reaction temperature greatly affect this electrophilic substitution.

Secondly, the sulfonation for *meta*-substituted porphyrin was also successfully carried out. Indeed, treatment of tetrakis(3′-trimethylsilylphenyl)porphyrin (**4b**) with $ClSO_3SiMe_3$ afforded the corresponding tetrakis(3′-sulfonatophenyl)porphyrin (**5b**) in a high yield of 90%. We had also tried to exploit this method to synthesize the previously unknown tetrakis(2′-sulfonatophenyl)porphyrin (**5c**). Thus, treatment of tetrakis(2′-trimethylsilylphenyl)porphyrin (**4c**) with $ClSO_3SiMe_3$ under the same reaction conditions as those of **4a** gave only a trace amount of product **5c** in 4 h. After extending the reaction to 4 days, **5c** was obtained in 82% yield. As compared with the preparation of the **4a**, **4b** and **4d**, **4c** needed longer reaction time, which is likely due to the steric hindrance of the bulky *ortho*-substituent. In order to shorten the reaction time, increase in the reaction temperature with 1,1,2,2-tetrachloroethane (TCE) as a solvent made the reaction time shortened to 2 days under refluxing condition to afford **5c** in 85% yield.

2.2. Synthesis of porphyrin dimers

Although several 1,2-phenylene-bridged cofacial porphyrin dimers have been synthesized,[33–36] the cofacial porphyrin dimer bearing trimethylsilyl groups have not been reported. In order to synthesize the water-soluble sulfonate porphyrins, the trimethylsilyl-substituted porphyrin dimers linked by an *o*-phenylene bridge were synthesized by the stepwise method[37] outlined in Scheme 4.

The porphyrin **6a** was synthesized by Lindsey's method.[25] Cross-condensation of the methyl 2-formylbenzoate and **3a** (3 equiv.) and pyrrole (4 equiv.) in the presence of $BF_3{\cdot}Et_2O$ as catalyst in $CHCl_3$ followed by oxidation with DDQ gave the asymmetric porphyrin **6a** in 18%. In the mean time, the symmetric porphyrin **4a** was obtained as the by-product in about 12% yield. Subsequent reduction of **6a** by $LiAlH_4$ in THF at room temperature afforded **7a** in 88% yield. Further oxidation of **7a** by active MnO_2 afforded formylphenyl-porphyrin **8a** in 95% yield. The porphyrin dimer **9a** was synthesized by condensation of **8a** (1 equiv.) and **4a** (11 equiv.) and pyrrole (12 equiv.) in the presence of $BF_3{\cdot}Et_2O$ as catalyst in $CHCl_3$. The subsequent oxidation with DDQ and separation by silica gel flash column chromatography gave the porphyrin dimer **9a** in 23% yield based on **8a**. The symmetric porphyrin **5a** was obtained in 15% yield. The product was identified by NMR and ESI-MS spectra. The ESI-MS spectrum gave a very clear and strong isotopic cluster peaks centered at m/z=1584.8 for **9a** (Fig. 1). The mass spectrum of these clusters and the intensity ratio of the different isotope peaks are in excellent agreement with the calculated isotope pattern for the excepted molecules, $[M+H]^+$. The porphyrin dimer **9b** was also synthesized in a similar way as that of **9a** and identified by NMR and ESI-MS spectra.

The sulfonated porphyrin dimers, **10a** and **10b**, were obtained in 96 and 90% yield, respectively, by sulfonation

Table 1. Sulfonation of porphyrins

Compound	Solvent	Time	Yield (%)[a]
5a	CCl_4	4 h	95
5b	CCl_4	4 h	90
5c	TCE	2 days	85
5d	CCl_4	4 h	90
10a	CCl_4	5 h	96
10b	CCl_4	5 h	90

[a] Isolated yields based on porphyrins.

of **9a** and **9b** with $ClSO_3SiMe_3$ in refluxing CCl_4 for 5 h followed by hydrolysis of the intermediate with aqueous NaOH (Table 1). Compounds **10a** and **10b** were also successfully purified by dialysis with cellulose dialysis membranes.

3. Conclusion

In conclusion, we have developed a novel method for the regiospecific synthesis of water-soluble sulfonated porphyrin monomers and 1,2-phenylene-bridged dimers in high yields through the introduction of the trimethylsilyl group on the phenyl rings and reaction with $ClSO_3SiMe_3$. This method can also be applied to synthesize mono-, di- and tri-substituted sulfonated porphyrins in a regiospecific manner.

4. Experimental

4.1. General

All reagents and solvent were of the commercial reagent grade and were used without further purification unless otherwise noted. Chlorotrimethylsilane was distilled under a nitrogen atmosphere prior to use. *N*,*N*-dimethylformamide (DMF) was treated with BaO overnight, then distilled from calcium hydride under reduced pressure and stored over 4 Å molecular sieves. Pyrrole was purchased from Tokyo Kasei, distilled under reduced pressure and stored in sealed ampoules. Active MnO_2 was prepared by Attenburrow's method.[38] Reagent grade diethyl ether was treated with $CaCl_2$, then distilled under nitrogen from sodium benzophenone ketyl. CH_2Cl_2 was treated successively with H_2SO_4 and K_2CO_3, then distilled from CaH_2. THF was treated with KOH, then distilled from sodium benzophenone ketyl. Reagent grade chloroform (for the synthesis of porphyrin ligands) was fractionally distilled from K_2CO_3 before use. Carbon tetrachloride was treated with standard method and distilled from P_2O_5, then stored over 4 Å molecular sieves. For dialysis, cellulose membrane (Viskase, 27/32, fractionating MW range: 12000–14000) was used. Thin layer chromatography (TLC) was performed on Merck silica gel 60 pre-coated aluminum sheets and visualized using visible or UV light (254 and 365 nm). Column chromatography was carried out under a positive nitrogen pressure using Merck silica gel (200–400 mesh) or neutral Al_2O_3.

Dialysis was carried out in a 2-L beaker. A 12×2.1$^{\varnothing}$ cm piece of cellulose dialysis membrane tubes were rinsed with distilled water for 4 h, and then one end was sealed with a clump. The porphyrin sample was dissolved in a minimum amount of distilled water, and the resulting solution was transferred into the tubing; the other end of the tubing was then closed with string. The dialysis tubing was hung on the wall of beaker containing distilled water (1.8 L). The water outside the dialysis tubes was replaced by distilled water and the dialysis was continued for 4 days. After which the solution in the tubing was evaporated to dryness.

NMR spectra were recorded on either a JEOL JMX-GX400 or a Varian INOVA 500 spectrometer using solvent as an internal standard. Chemical shifts are reported as parts per million (ppm) with respect to tetramethylsilane (TMS). IR spectra were recorded on a Bruker VECTOR 22 spectrometer. A Shimadzu UV 2500-PC spectrophotometer was used for measuring electronic absorption spectra at room temperature. Electrospray ionization mass spectra (ESI-MS) were obtained on a Perkin–Elmer Sciex API 300 spectrometer. Elemental analyses (C, H and N) were performed on an Elementar Vario EL Elemental analyzer.

4.1.1. 1-Bromo-4-(trimethylsilyl)benzene (2a).[24] To a stirring solution of 1,4-dibromobenzene (9.44 g, 40 mmol) in diethyl ether (80 mL) was added *n*-BuLi (26.7 mL, 40 mmol, 1.5 M in hexane) over 1 h under nitrogen atmosphere at −78°C. The solution was stirred at this temperature until the reaction was completed (monitored by TLC, about 30 min). Then, chlorotrimethylsilane (5.33 mL, 42 mmol) was added over about 10 min. The solution was allowed to warm to room temperature and stirred until the reaction completed (monitored by TLC, about 1.5 h). Water (15 mL) was added to the above solution. The organic layer was separated and washed with brine, then dried over magnesium sulfate. Filtration and removal of the solvent gave a colorless oil, which was purified by column chromatography (silica gel, hexane) and dried in vacuo (yield 8.1 g, 88%, colorless oil). δ_H (400 MHz, $CDCl_3$) 7.48 (2H, d, J=8.3 Hz, ph–H_2), 7.37 (2H, d, J=8.3 Hz, ph–H_3), 0.26 (9H, s, Me); δ_C (400 MHz, $CDCl_3$) 140.8, 133.5 129.7, 128.3, −1.4.

4.1.2. 1-Bromo-3-(trimethylsilyl)benzene (2b).[24] The same procedure as for **2a** afforded **2b** as a colorless oil in 85% yield. δ_H (400 MHz, $CDCl_3$) 7.54 (1H, s, ph–H_2), 7.39 (1H, d, J=7.6 Hz, ph–H_4), 7.34 (1H, d, J=7.3 Hz, ph–H_6), 7.14 (1H, t, ph–H_5), 0.195 (9H, s, Me); δ_C (400 MHz, $CDCl_3$) 143.7, 135.9, 131.8, 131.6, 129.5, 122.9, −1.3.

4.1.3. 2-Trimethylsilylbenzaldehyde diethyl acetal (2c).[39] The procedure is similar to the synthesis of **2a**, using 2-bromobenzaldehyde diethyl acetal in place of 1,4-dibromobenzene and the reaction was carried out at room temperature, affording **2c** as a colorless oil in 75% yield. δ_H (400 MHz, $CDCl_3$) 7.71 (1H, d, J=7.8 Hz, ph–H_3), 7.58 (1H, d, J=7.8 Hz, ph–H_6), 7.37 (1H, t, ph–H_4), 7.29 (1H, t, ph–H_5), 5.61 (1H, s, ph$CH(OEt)_2$), 3.60–3.66 (2H, m, OCH_2Me), 3.45–3.51 (2H, m, OCH_2Me), 1.23 (6H, t, OCH_2Me), 0.370 (9H, s, $SiMe_3$).

4.1.4. 1-Bromo-2,5-dimethyl-4-(trimethylsilyl)benzene (2d).[24] The same procedure as for **2a** afforded **2d** as a colorless oil in 86% yield. δ_H (400 MHz, $CDCl_3$) 7.34 (1H,

s, ph−H_6), 7.27 (1H, s, ph−H_3), 2.39 (3H, s, ph−*Me*), 2.36 (3H, s, ph−*Me*), 0.31 (9H, s, $SiMe_3$).

4.1.5. 4-Trimethylsilylbenzaldehyde (3a). To a solution of **2a** (4.56 g, 20 mmol) in diethyl ether (30 mL) was added a solution of *n*-BuLi (13.40 mL, 20 mmol, 1.5 M in hexane) by a syringe over a period of 30 min under nitrogen at 0°C. The solution was stirred at this temperature for further a 30 min, then stirred at room temperature for 1.5 h. A solution of DMF (2.46 mL, 32 mmol) in diethyl ether (15 mL) was added to the solution, and the mixture solution was stirred overnight, then treated with 10% hydrochloric acid. The organic layer was separated and the aqueous layer was extracted with chloroform (2×40 mL). The combined organic layer was washed with $NaHCO_3$ and brine, then dried over $MgSO_4$. After filtration and removal of the solvent, the slightly yellowish oil was chromatographed on a silica gel column eluting with hexane–acetone (9:1, v/v) to afford the title compound as a colorless oil in 75% yield (2.7 g). δ_H (400 MHz, $CDCl_3$) 10.02 (1H, s, CHO), 7.83 (2H, d, J=8.3 Hz, ph−H_2), 7.69 (2H, d, J=8.3 Hz, ph−H_3), 0.30 (9H, s, Me); δ_C (100 MHz, $CDCl_3$) 192.6, 149.2, 136.4, 133.8, 128.6, −1.4.

4.1.6. 3-Trimethylsilylbenzaldehyde (3b). The same procedure as for **3a** afforded **3b** as a colorless oil in 70% yield. δ_H (400 MHz, $CDCl_3$) 9.93 (1H, s, CHO), 7.93 (1H, s, ph−H_2), 7.74 (1H, d, J=7.8 Hz, ph−H_6), 7.67 (1H, d, J=7.3 Hz, ph−H_4), 7.40 (1H, t, ph−H_5), 0.216 (9H, s, Me); δ_C (100 MHz, $CDCl_3$) 192.6, 141.6, 139.2, 135.4, 134.5, 130.0, 128.2, −1.4.

4.1.7. 2-Trimethylsilylbenzaldehyde (3c). The **2c** (2.52 g, 1 mmol) was dissolved in a CH_2Cl_2 (40 mL). Trifluoroacetic acid (25 mL) and water (15 mL) were added to the solution. The mixture was stirred at room temperature for 6 h. The organic layer was separated and washed successively with water, aqueous $NaHCO_3$, brine, then dried over Na_2SO_4. After filtration and removal of the solvent, the slightly yellowish oil was chromatographed on silica gel column eluting with hexane–benzene (2:1, v/v) to afford the title compound as a colorless oil in 90% yield (1.6 g). δ_H (400 MHz, $CDCl_3$) 10.17 (1H, s, CHO), 7.89 (1H, d, J= 7.8 Hz, ph−H_6), 7.72 (1H, d, J=7.8 Hz, ph−H_3), 7.53–7.58 (2H, m, ph−H_4 and ph−H_5), 0.36 (9H, s, Me); δ_C (100 MHz, $CDCl_3$) 193.5, 142.7, 141.0, 135.6, 133.0, 132.5, 129.3, 0.04.

4.1.8. 2,5-Dimethyl-4-trimethylsilylbenzaldehyde (3d). The same procedure as for **3a** afforded **3d** as a colorless oil in 70% yield. δ_H (400 MHz, $CDCl_3$) 10.24 (1H, s, CHO), 7.54 (1H, s, ph−H_6), 7.32 (1H, s, ph−H_3), 2.62 (3H, s, ph−*Me*), 2.48 (3H, s, ph−*Me*), 0.34 (9H, s, $SiMe_3$); δ_C (100 MHz, $CDCl_3$) 193.1, 146.2, 141.4, 137.8, 136.2, 134.2, 130.3, 22.3, 19.0, −0.4.

4.1.9. 5,10,15,20-Tetra(4′-trimethylsilylphenyl)porphyrin (4a). This compound was synthesized by Lindsey's method.[25] To a 1-L three-necked round-bottomed flask containing $CHCl_3$ (500 mL) were added **3a** (20.0 mmol) and pyrrole (1.34 g, 20.0 mmol). After the solution was purged with nitrogen for 10 min, $BF_3{\cdot}OEt_2$ (0.25 mL, 2 mmol) was added via a syringe. The mixture was stirred at room temperature under nitrogen atmosphere and monitored by TLC. At the end of 40 min, 2,3-dichloro-5,6-dicycano-1,4-benoquinine (DDQ) (4.08 g, 18 mmol) dissolved in benzene (100 mL) was added and the solution was further stirred at room temperature for 1 h. After the elimination of the insoluble solid by filtration, the filtrate was concentrated and loaded on Al_2O_3 (200 g) column, the crude products were eluted by $CHCl_3$. The porphyrin was further purified on silica gel column (chloroform–hexane, 1:1), then concentrated and dried. Yield, 48%. [Found: C, 74.31; H, 6.60; N, 6.03. $C_{56}H_{62}N_4Si_4$ requires C, 74.53; H, 6.81; N, 6.21%]; ν_{max} (KBr) 3580–3498, 3240–3180, 1595, 1472, 1400, 1248, 1108, 966, 879, 845, 799, 756, 728, 708, 624 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 8.75 (8H, s, pyrrole β-H), 8.09 (8H, d, J=7.32 Hz, ph−H_2), 7.79 (8H, d, J=7.32 Hz, ph−H_3), 0.42 (36H, s, Me) and −2.87 (2H, br, N−H); δ_C (100 MHz, $CDCl_3$) 147.0, 142.5, 138.5, 134.1, 131.6, 131.0, 120.2, −0.8. ESI-MS: found 903 (100%). $C_{56}H_{63}N_4Si_4$ $[M+H]^+$ requires 903. UV–vis: λ_{max}/nm (CH_2Cl_2): 419, 480, 516, 552, 590, 646.

4.1.10. 5,10,15,20-Tetra(3′-trimethylsilylphenyl)porphyrin (4b). The same procedure as for **4a** afforded **4b** as a purple solid in 45% yield. [Found: C, 74.42; H, 6.55; N, 6.14. $C_{56}H_{62}N_4Si_4$ requires C, 74.53; H, 6.81; N, 6.21%]; ν_{max} (KBr) 3540–3488, 1637, 1401, 1248, 1116, 974, 841, 799, 752, 621 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 8.87 (8H, s, pyrrole β-H), 8.37 (4H, d, J=7.8 Hz, ph−H_6), 8.21 (4H, s, ph−H_2), 7.92 (4H, d, J=7.3 Hz, ph−H_4), 7.74 (4H, t, ph−H_5), 0.41 (36H, s, Me) and −2.71 (2H, br, N−H); δ_C (100 MHz, $CDCl_3$) 147.1, 141.5, 139.5, 138.7, 135.0, 132.5, 131.2, 126.0, 120.5, −0.9. ESI-MS: found 903 (100%). $C_{56}H_{63}N_4Si_4$ $[M+H]^+$ requires 903.

4.1.11. 5,10,15,20-Tetra(2′-trimethylsilylphenyl)porphyrin (4c). The same procedure as for **4a** afforded **4c** as a purple solid in 42% yield. [Found: C, 74.29; H, 6.64; N, 6.03. $C_{56}H_{62}N_4Si_4$ requires C, 74.53; H, 6.81; N, 6.21%]; ν_{max} (KBr) 3480–3450, 1637, 1401, 1248, 1122, 966, 836, 802, 746, 622 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 8.57 (8H, s, pyrrole β-H), 7.97 (4H, d, J=7.2 Hz, ph−H_6), 7.92 (4H, d, J=7.6 Hz, ph−H_3), 7.74 (4 h, t, ph−H_4), 7.59 (4H, t, ph−H_5), −0.78 (36H, s, Me) and −2.67 (2H, br, N−H); δ_C (125.7 MHz, $CDCl_3$) 147.7, 143.3, 134.0, 133.8, 132.9, 131.1, 127.2, 126.3, 121.2, −0.2. ESI-MS: found 903 (100%). $C_{56}H_{63}N_4Si_4$ $[M+H]^+$ requires 903.

4.1.12. 5,10,15,20-Tetra(2′,5′-dimethyl-3′-trimethylsilylphenyl)porphyrin (4d). The same procedure as for **4a** afforded **4d** as a purple solid in 40% yield. [Found: C, 75.47; H, 7.51; N, 5.36. $C_{56}H_{62}N_4Si_4$ requires C, 75.68; H, 7.74; N, 5.52%]; ν_{max} (KBr) 3480–3458, 2953, 1597, 1560, 1472, 1401, 1249, 1227, 1187, 1071, 979, 938, 854, 834, 803, 761, 732, 696, 628, 472 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 8.68 (8H, s, pyrrole β-H), 7.79–7.73 (4H, m, ph−H_6), 7.63 (4H, s, ph−H_3), 2.63–2.60 (12H, q, ph−*Me*), 2.05–1.98 (12H, q, ph−*Me*), 0.55 (36H, s, $SiMe_3$) and −2.64 (2H, br, N−H); δ_C (125.7 MHz, $CDCl_3$) 147.2, 142.2, 141.0, 138.8, 138.2, 135.6, 135.2, 130.2, 118.8, 22.6, 20.8, 0.2. ESI-MS: found 1015 (100%). $C_{64}H_{79}N_4Si_4$ $[M+H]^+$ requires 1015. UV–vis (λ_{max}/nm CH_2Cl_2): 370, 418, 478, 514, 548, 590, 644.

4.1.13. Tetrasodium tetrakis(4′-sulfonatophenyl)porphyrin (5a).[15] To a CCl_4 (20 mL) solution containing **4a**

(0.1 mmol) was added $ClSO_3SiMe_3$ (0.226 g, 1.2 mmol). The mixture solution was refluxed under nitrogen atmosphere for 4 h. Upon cooling to room temperature, NaOH solution (1N, 15 mL) was added to the above solution and stirred for 0.5 h. The solution was separated to two layers. The aqueous layer was washed with $CHCl_3$ three times (3×20 mL), concentrated to 5 mL and purified through membrane for 4 days. The sulfonated porphyrin was obtained by removing the water, then washed with acetone and dried. Yield, 95%. [Found: C, 51.44; H, 2.40; N, 5.33. $C_{44}H_{26}N_4O_{12}S_4Na_4$ requires C, 51.66; H, 2.54; N, 5.48%]; δ_H (400 MHz, DMSO-d_6) 8.92 (8H, s, pyrrole β-H), 8.25 (8H, d, J=7.58 Hz, ph−H_3), 8.12 (8H, d, J=7.58 Hz, ph−H_2), −2.84 (2H, br, N−H). ESI-MS: found 935 (100%). $[C_{44}H_{26}N_4S_4O_{12}+5H]^+$ requires 935.

4.1.14. Tetrasodium tetrakis(3′-sulfonatophenyl)porphyrin (5b). The same procedure as for **5a** afforded **5b** as a purple solid in 90% yield. [Found: C, 51.45; H, 2.30; N, 5.31. $C_{44}H_{26}N_4O_{12}S_4Na_4$ requires C, 51.66; H, 2.54; N, 5.48%]; δ_H (400 MHz, DMSO-d_6) 8.84 (8H, s, pyrrole β-H), 8.40 (4H, d, J=7.8 Hz, ph−H_6), 8.25, (4H, s, ph−H_2), 8.10 (4H, d, J=7.3 Hz, ph−H_4), 7.82 (4H, t, ph−H_5), −2.70 (2H, br, N−H). ESI-MS: found 935 (100%). $[C_{44}H_{26}N_4S_4O_{12}+5H]^+$ requires 935.

4.1.15. Tetrasodium tetrakis(2′-sulfonatophenyl)porphyrin (5c). The similar procedure as for **5a** but using TCE in place of CCl_4 afforded **5c** as a purple solid in 85% yield. [Found: C, 51.51; H, 2.32; N, 5.30. $C_{44}H_{26}N_4O_{12}S_4Na_4$ requires C, 51.66; H, 2.54; N, 5.48%]; δ_H (400 MHz, DMSO-d_6) 8.84 (8H, br, pyrrole β-H), 8.20 (4H, br, ph−H_3), 8.04, (4H, d, ph−H_6), 7.80–7.86 (8H, t, ph−H_4 and ph−H_5), −2.72 (2H, br, N−H). ESI-MS: found 935 (100%). $[C_{44}H_{26}N_4S_4O_{12}+5H]^+$ requires 935.

4.1.16. Tetrasodium tetrakis(2′,5′-dimethyl-4′-sulfonatophenyl)porphyrin (5d). The same procedure as for **5a** afforded **5d** as a purple solid in 90% yield. [Found: C, 54.91; H, 3.42; N, 4.78. $C_{52}H_{42}N_4O_{12}S_4Na_4$ requires C, 55.03; H, 3.70; N, 4.94%]; δ_H (400 MHz, DMSO-d_6) 8.67 (8H, s, pyrrole β-H), 8.04 (4H, s, ph−H_3), 7.83–7.71 (4H, m, ph−H_6), 2.71 (12H, s, ph−Me), 2.01–1.88 (12H, m, ph−Me), −2.78 (2H, br, N−H). ESI-MS: found 1047 (100%). $[C_{52}H_{42}N_4S_4O_{12}+5H]^+$ requires 1047. UV−vis (λ_{max}/nm MeOH): 309, 413, 511, 543, 587, 643.

4.1.17. Methyl 2-formylbenzoate.[39] To a solution of K_2CO_3 (70.0 g) and 2-formylbenzoic acid (24.0 g, 0.16 mol) in acetone (500 mL) was added methyl iodide (23.0 g, 0.16 mol) at room temperature. The mixture was refluxed under nitrogen atmosphere for 4 h. After cooling to room temperature, the mixture was filtrated and concentrated, then, the residue was extracted by $CHCl_3$ and washed by saturated Na_2SO_4 and NaCl. After removing the solvent, the product was distilled under reduced pressure to give 19.0 g in 72.3% yield. δ_H (400 MHz, $CDCl_3$) 10.62 (1H, s, CHO), 7.99–7.93 (2H, m, ph−H), 7.67–7.65 (2H, m, ph−H), 3.98 (3H, s, Me).

4.1.18. 5-(2′-Methylbenzoate)-10,15,20-tri(4″-trimethylsilylphenyl)porphyrin (6a). To a 1-L three-neck round-bottomed flask containing $CHCl_3$ (500 mL) were added **3a** (2.67 g, 15.0 mmol), methyl 2-formylbenzoate (0.82 g, 5.0 mmol) and pyrrole (1.34 g, 20.0 mmol), respectively. After the solution was purged with nitrogen for 10 min, $BF_3{\cdot}OEt_2$ (0.25 mL, 2 mmol) was added via a syringe. The mixture was stirred at room temperature under nitrogen atmosphere and monitored by TLC. At the end of the 40 min reaction, DDQ (4.08 g, 18 mmol) dissolved in benzene (100 mL) was added and the solution was further stirred at room temperature for 1 h. After the elimination of the insoluble solid by filtration, the filtrate was concentrated and loaded on Al_2O_3 (200 g) column, the crude products were eluted by $CHCl_3$. The title porphyrin was purified on silica gel column (chloroform−hexane, 1:1), then concentrated and dried. Yield, 0.78 g, 18%. [Found: C, 74.10; H, 6.25; N, 6.08. $C_{55}H_{56}N_4O_2Si_3$ requires C, 74.28; H, 6.35; N, 6.30%]; ν_{max} (KBr) 3470–3410, 2954, 1733, 1637, 1596, 1472, 1400, 1249, 1107, 1084, 982, 967, 878, 839, 799, 761, 734, 696, 624, 532 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 8.73 (4H, d, J=7.3 Hz), 8.53 (2H, d, J=4.6 Hz), 8.29 (2H, d, J=5.2 Hz), 8.13–8.03 (8H, m), 7.80–7.72 (8H, m), 2.64 (3H, s, OMe), 0.42 (9H, s, $SiMe_3$), 0.41 (18H, s, $SiMe_3$), −2.78 (2H, br, N−H); δ_C (125.7 MHz, $CDCl_3$) 167.9, 142.6, 142.5, 139.5, 136.1, 134.2, 134.1, 131.6, 129.7, 128.3, 120.2, 118.9, 51.5, −0.8. ESI-MS: found 889 (100%). $C_{55}H_{57}N_4O_2Si_3$ $[M+H]^+$ requires 889.

4.1.19. 5-(2′-Methylbenzoate)-10,15,20-tri(2″,5″-dimethyl-4″-trimethylsilylphenyl) porphyrin (6b). The same procedure as for **6a** afforded **6b** as a purple solid in 16% yield. [Found: C, 75.02; H, 6.95; N, 5.54. $C_{61}H_{68}N_4O_2Si_3$ requires C, 75.26; H, 7.04; N, 5.76%]; δ_H (400 MHz, $CDCl_3$) 8.67 (6H, s), 8.62–8.58 (2H, q), 8.39–8.36 (1H, q), 8.12–8.07 (1H, m), 7.86–7.70 (5H, m), 7.65–7.62 (3H, m), 2.79–2.80 (3H, m, OMe), 2.63–2.59 (9H, m, ph−*Me*), 2.07–1.98 (9H, m, ph−*Me*), 0.54 (27H, s, $SiMe_3$), −2.59 (2H, br, N−H). ESI-MS: found 973 (100%). $C_{61}H_{69}N_4O_2Si_3$ $[M+H]^+$ requires 973.

4.1.20. 5-(2′-Benzomethanol)-10,15,20-tri(4″-trimethylsilylphenyl)porphyrin (7a). To a suspension of $LiAlH_4$ (0.443 g, 12 mmol) in dry THF (40 mL) was slowly added a solution of **6a** (0.445 g, 0.5 mmol) dissolved in dry THF (20 mL) at 0°C. The mixture was stirred for 30 min at room temperature under nitrogen atmosphere. After the reaction was completed, methanol (10 mL) was added for quenching at 0°C. Removal of the solvent, the residue was dissolved in CH_2Cl_2 (50 mL) and neutralized (pH=5–7) by 1N HCl. The organic layer was separated and washed with saturated $NaHCO_3$. The solvent was removed and the crude product was purified on silica gel C-200 column (benzene), given purple crystals. Yield, 0.37 g, 88%. [Found: C, 75.12; H, 6.28; N, 6.24. $C_{54}H_{56}N_4OSi_3$ requires C, 75.30; H, 6.55; N, 6.50%]; δ_H (400 MHz, $CDCl_3$) 8.77 (4H, d, J=4.9 Hz), 8.59 (2H, d, J=3.4 Hz), 8.15–8.18 (8H, m), 7.99–7.73 (8H, m), 7.61–7.55 (2H, m), 4.26 (2H, d, J=5.9 Hz, CH_2OH), 0.44 (9H, s, $SiMe_3$), 0.43 (18H, s, $SiMe_3$), −2.80 (2H, br, N−H). ESI-MS: found 861 (100%). $C_{54}H_{57}N_4OSi_3$ $[M+H]^+$ requires 861.

4.1.21. 5-(2′-Benzomethanol)-10,15,20-tri(2″,5″-dimethyl-4″-trimethylsilylphenyl) porphyrin (7b). The same procedure as for **7a** afforded **7b** as a purple solid in 86% yield. [Found: C, 75.98; H, 7.08; N, 5.78.

$C_{60}H_{68}N_4OSi_3$ requires C, 76.22; H, 7.25; N, 5.93%]; δ_H (400 MHz, $CDCl_3$) 8.59 (6H, s), 8.52 (2H, d, J=4.8 Hz), 7.98–7.90 (1H, m), 7.84–7.70 (1H, m), 7.68–7.61 (5H, m), 7.53 (3H, s), 4.25 (2H, d, J=5.9 Hz, CH_2OH), 2.54–2.52 (9H, m, ph–*Me*), 1.96–1.86 (9H, m, ph–*Me*), 0.45 (27H, s, $SiMe_3$), −2.75 (2H, br, N–H). ESI-MS: found 945 (100%). $C_{60}H_{69}N_4OSi_3$ $[M+H]^+$ requires 945.

4.1.22. 5-(2′-Benzoaldehyde)-10,15,20-tri(4″-trimethylsilylphenyl)porphyrin (8a). To a solution of **7a** (0.430 g, 0.5 mmol) in dry CH_2Cl_2 (100 mL) was added MnO_2 (0.88 g, 10 mmol). The mixture was stirred at room temperature for 3 h (monitored by TLC) under nitrogen atmosphere. After the elimination of the insoluble MnO_2 by filtration, the filtrate was concentrated. The crude product was purified on silica gel C-200 column (CH_2Cl_2), given purple crystals. Yield, 0.41 g, 96%. [Found: C, 75.24; H, 6.178; N, 6.35. $C_{54}H_{54}N_4OSi_3$ requires C, 75.48; H, 6.33; N, 6.52%]; δ_H (400 MHz, $CDCl_3$) 9.38 (1H, s, CHO), 8.77 (4H, d, J=4.6 Hz), 8.52 (2H, d, J=4.9 Hz), 8.32–8.29 (2H, m), 8.16–8.09 (8H, m), 7.87–7.77 (8H, m), 0.418 (9H, s, $SiMe_3$), 0.412 (18H, s, $SiMe_3$), −2.79 (2H, br, N–H). ESI-MS: found 859 (100%). $C_{54}H_{55}N_4OSi_3$ $[M+H]^+$ requires 859.

4.1.23. 5-(2′-Benzoaldehyde)-10,15,20-tri(2″,5″-dimethyl-4″-trimethylsilylphenyl) porphyrin (8b). The same procedure as for **8a** afforded **8b** as a purple solid in 95% yield. [Found: C, 76.13; H, 6.89; N, 5.79. $C_{60}H_{66}N_4OSi_3$ requires C, 76.38; H, 7.05; N, 5.94%]; δ_H (400 MHz, $CDCl_3$) 9.61–9.45 (1H, m, CHO), 8.73–8.71 (6H, m), 8.58–8.56 (2H, m), 8.42–8.39 (1H, m), 7.94–7.89 (1H, m), 779–7.73 (4H, m), 7.64 (4H, s), 2.63–2.61 (9H, m, ph–*Me*), 2.04–1.98 (9H, m, ph–*Me*), 0.554 (27H, s, $SiMe_3$), −2.61 (2H, br, N–H). ESI-MS: found 943 (100%). $C_{60}H_{67}N_4OSi_3$ $[M+H]^+$ requires 943.

4.1.24. 1,2-Bis[5,10,15-tri(4′-trimethylsilylphenyl)porphyrinyl]benzene (9a). To a 300-mL three-neck round-bottomed flask containing $CHCl_3$ (150 mL) were added **8a** (0.429 g, 0.5 mmol), **3a** (0.980 g, 5.5 mmol) and pyrrole (0.420 g, 6.0 mmol). After the solution was purged with nitrogen for 10 min, $BF_3{\cdot}OEt_2$ (0.075 mL) was added via a syringe. The mixture was stirred at room temperature under nitrogen atmosphere and monitored by TLC. After 1 h, DDQ (1.13 g, 5 mmol) dissolved in benzene (50 mL) was added and the solution was further stirred at room temperature for 1.5 h. Elimination of the insoluble solid by filtration, the filtrate was concentrated and loaded on Al_2O_3 (100 g) column, the crude products were eluted by $CHCl_3$. The bisporphyrin was further purified on silica gel column (chloroform–hexane), then concentrated and dried. Yield, 0.18 g, 23%. [Found: C, 75.62; H, 6.23; N, 6.87. $C_{100}H_{102}N_8Si_6$ requires C, 75.81; H, 6.44; N, 7.08%]; ν_{max} (KBr) 3450–3410, 3180, 2953, 1637, 1597, 1559, 1400, 1249, 1108, 981, 966, 839, 798, 755, 731, 696, 624 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 9.16 (4H, d, J=4.9 Hz), 8.84–8.82 (2H, m), 8.37–8.35 (12H, m), 8.27–8.24 (2H, m), 7.99 (2H, d, J=6.8 Hz), 7.77–7.69 (16H, m), 7.56–7.51 (4H, m), 7.43 (2H, d, J=6.3 Hz), 0.496 (36H, s), 0.363 (18H, s), −3.87 (4H, br). ESI-MS: found 1584 (100%). $C_{100}H_{103}N_8Si_6$ $[M+H]^+$ requires 1584. UV–vis: λ_{max}/nm (CH_2Cl_2): 408, 524, 554, 599, 655.

4.1.25. 1,2-Bis[5,10,15-tri(2′,5′-dimethyl-4′-trimethylsilylphenyl)porphyrinyl]benzene (9b). The same procedure as for **9a** afforded **9b** as a purple solid in 22% yield. [Found: C, 76.61; H, 7.02; N, 6.15. $C_{112}H_{126}N_8Si_6$ requires C, 76.75; H, 7.25; N, 6.39%]; ν_{max} (KBr) 3430–3410, 3210, 2953, 1637, 1598, 1400, 1249, 975, 941, 854, 834, 801, 760, 730, 696, 628, 471 cm^{-1}; δ_H (400 MHz, $CDCl_3$) 9.25–9.21 (12H, m), 8.79–8.73 (4H, m), 8.32–8.28 (10H, m), 7.52–7.40 (6H, m), 2.56–2.37 (36H, m), 0.56–0.54 (36H, m), 0.43–0.42 (18H, m) and −3.60 (4H, br). ESI-MS: found 1752 (100%). $C_{112}H_{127}N_8Si_6$ $[M+H]^+$ requires 1752. UV–vis: λ_{max}/nm (CH_2Cl_2): 408, 521, 596, 649.

4.1.26. Sodium 1,2-bis[5,10,15-tri(4′-sulfonatophenyl)-porphyrinyl]benzene (10a). To the CCl_4 (20 mL) solution containing **9a** (0.158 g, 0.1 mmol) was added $ClSO_3SiMe_3$ (0.226 g, 1.2 mmol). The mixture solution was refluxed 5 h under nitrogen atmosphere. After cooling to room temperature, NaOH (1N, 15 mL) was added to the above solution and stirred for 0.5 h. A two layers solution was separated. The aqueous layer was washed with $CHCl_3$ three times (3×20 mL), concentrated to 5 mL and purified through membrane for 4 days. The sulfonated porphyrin was obtained by removing the water, then washed with acetone and dried. Yield, 96%. [Found: C, 55.58; H, 2.48; N, 6.14. $C_{82}H_{48}N_8O_{18}S_6Na_6$ requires C, 55.84; H, 2.74; N, 6.35%]; δ_H (400 MHz, DMSO-d_6) 9.69 (4H, br), 9.18 (2H, s), 8.69–8.71 (14H, m), 8.38 (4H, br), 8.20–8.25 (12H, m), 8.19 (4H, br), 8.06 (4H, t), 7.88 (4H, t), −3.72 (4H, br). ESI-MS: found 816 (100%). $[C_{82}H_{48}N_8S_6O_{18}+8H]^{2+}$ requires 816. UV–vis: λ_{max}/nm (MeOH): 309, 413, 511, 543, 587, 643.

4.1.27. Sodium 1,2-bis[5,10,15-tri(2′,5′-dimethyl-4′-sulponatophenyl)porphyrinyl] benzene (10b). The same procedure as for **10a** afforded **10b** as a purple solid in 90% yield. [Found: C, 58.28; H, 3.48; N, 5.53. $C_{94}H_{72}N_8O_{18}S_6Na_6$ requires C, 58.44; H, 3.75; N, 5.80%]; δ_H (400 MHz, DMSO-d_6) 9.46 (8H, br), 8.92–8.95 (6H, m), 8.30–8.33 (8H, m), 7.93 (4H, br), 7.39–7.42 (6H, m), 2.76–2.42 (18H, m), 1.87–1.32 (18H, m), −3.78 (4H, br). ESI-MS: found 900 (100%). $[C_{94}H_{72}N_8S_6O_{18}+8H]^{2+}$ requires 900. UV–vis: λ_{max}/nm (MeOH): 307, 408, 520, 548, 594, 652.

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