Surface Functionalization of Polyether Dendrimers Using Palladium-Catalyzed Cross-Coupling Reactions

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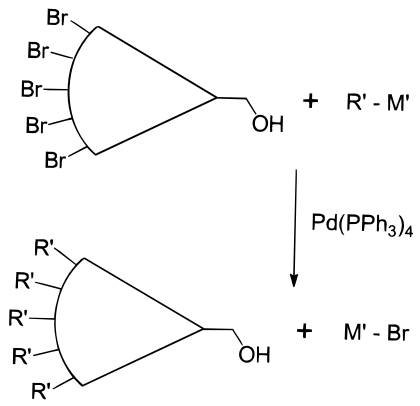
Introduction

Since Tomalia[1a] and Newkome[1b] published their seminal findings on well-defined "Starburst" and "arborol" dendrimers in 1985,[1] dendrimer chemistry has developed into a mature scientific field bridging the gap between organic and polymer chemistry.[2] Until recently, the interest in dendrimers was mainly focused on discovering synthetic routes toward novel members of this unique family of macromolecules. Today, however, scientists working in this field have increasingly shifted their attention to the modification of existing dendrimers in order to explore the material properties of these regular highly branched molecules. Such modifications of the periphery of dendrons or dendrimers[3] can result in tailored materials that are potentially useful in a variety of applications including catalysis,[4] biological recognition,[5] solubilization,[6] and molecular encapsulation.[7]

Herein, we describe the surface modification of polyether dendrons utilizing palladium-catalyzed cross-coupling reactions (Scheme 1).[8] Pd-catalyzed cross-coupling reactions, such as the Suzuki,[9] Negishi,[10] Kumada,[11] Stille,[12] Hiyama,[13] and Heck[14] reactions, have become important tools to facilitate asymmetric C−C bond formation. The reaction between an organometallic reagent (M = B, Zn, Mg, Sn, Si), alkene, or alkyne on one hand, and an organic electrophile (halide or triflate) on the other hand, gives rise to the formation of the asymmetric coupling products via a stepwise cyclic mechanism of Pd-complexed intermediates.[14,15] Today, Pd-catalyzed cross-coupling reactions are frequently applied in organic[16] and oligomer/polymer synthesis,[17] including the synthesis of hyperbranched polymers.[18] In the field of dendrimers, however, there are only two examples in which Pd-catalyzed cross-coupling reactions have been applied to prepare these well-defined molecules. Moore et al. used a Heck reaction for the synthesis of phenylacetylene dendrimers,[19] whereas Miller and Neenan applied the Suzuki reaction to prepare polyphenylene dendrimers.[20]

Scheme 1



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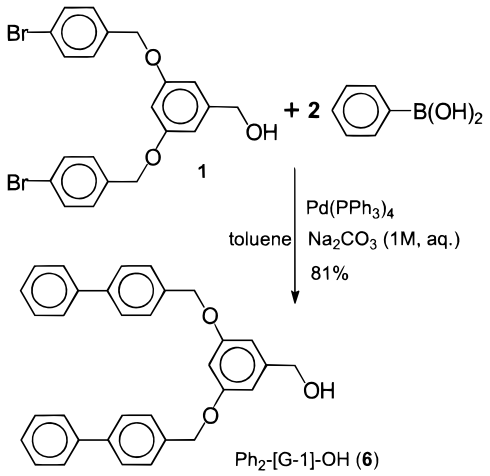
Scheme 2

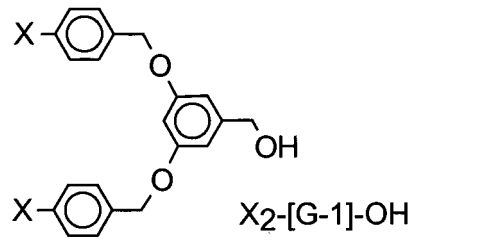


This is the first time that Pd-catalyzed cross-coupling reactions have been utilized to functionalize the surface of dendrons (Scheme 1). To obtain acceptable yields of fully functionalized dendrons of the highest generation, the yield per coupling reaction (*y*/*c*) has to be high. For example, to obtain a fully functionalized [G-3] dendron, a process that requires eight cross-coupling reactions per dendron, in an overall yield of 50%, each coupling reaction must proceed in 92% yield. Utilizing 4-bromophenyl terminated dendrons (Br_{2^n}-[G-*n*]-OH, $n = 1-3$)[21] as the electrophiles, and performing Suzuki[9] coupling reactions with phenylboronic acid, or Stille[12] reactions with 2-trimethylstannylthiophene and 2-trimethyl-stannylpyridine, the periphery of the dendrons has been fully functionalized with phenyl, 2-thienyl, and 2-pyridyl substituents in place of the original 4-bromo moieties.

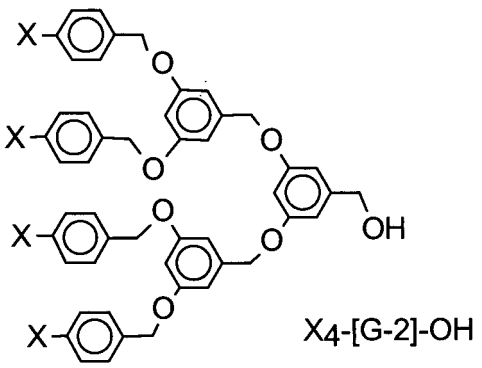
Results and Discussion

Suzuki Reactions. A Suzuki reaction between Br_2-[G-1]-OH (**1**)[21] and 2.4 equiv of phenylboronic acid was performed in a two-phase system consisting of toluene and aqueous Na_2CO_3 (1 M), using $Pd(PPh_3)_4$ as the catalyst. Following workup and purification, the desired product Ph_2-[G-1]-OH (**6**) was isolated in 81% yield (Scheme 2). Similarly, the second and third generation 4-bromophenyl substituted dendrons, Br_4-[G-2]-OH (**2**) and Br_8-[G-3]-OH (**3**),[21] were fully functionalized using excess phenylboronic acid (yields: 71% and 49% for Ph_4-[G-2]-OH (**7**) and Ph_8-[G-3]-OH (**8**), respectively). Although the overall yields of the Suzuki reactions decrease with increasing dendron generation, the yield per coupling (*y*/*c*; 2, 4, and 8 couplings/dendron, respectively) is constant: 90%, 92%, and 91%, respectively (Figure 1).

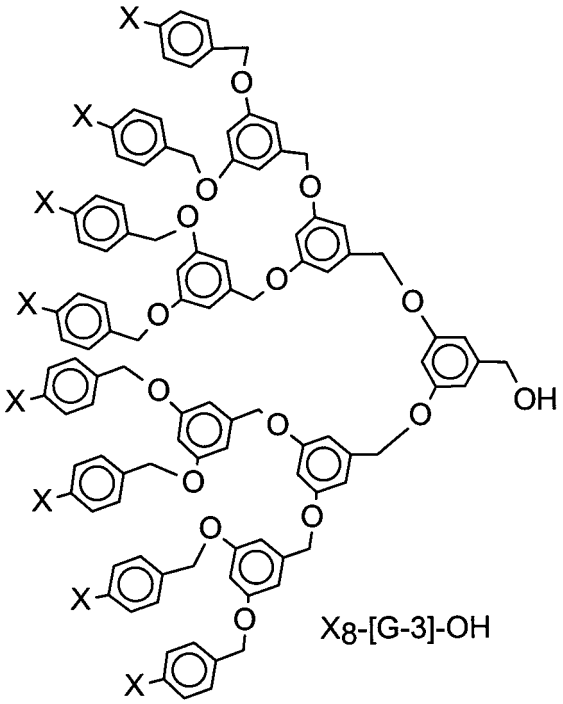
Stille Reactions. Initially, studies were performed to optimize the conditions for the Stille reaction between Br_2-[G-1]-OH (**1**) and 2-trialkylstannylthiophene. By varying the solvent (toluene, toluene/aqueous Na_2CO_3 (1 M), THF), the catalyst ($Pd(PPh_3)_4$, $Pd(PPh_3)_2Cl_2$) and the stannane (2-trimethylstannyl-thiophene (**4**),[22] 2-tributyl-stannylthiophene), the highest yield for th_2-[G-1]-OH (**9**) was obtained in the case of toluene/$Pd(PPh_3)_4$ using 2.3



X = phenyl (**6**, y = 81%, y/c = 90%)
X = 2-thienyl (**9**, y = 78%, y/c = 88%)
X = 2-pyridinyl (**12**, y = 53%, y/c = 73%)



X = phenyl (**7**, y = 71%, y/c = 92%)
X = 2-thienyl (**10**, y = 86%, y/c = 96%)
X = 2-pyridinyl (**13**, y = 43%, y/c = 81%)



X = phenyl (**8**, y = 49%, y/c = 91%)
X = 2-thienyl (**11**, y = 46%, y/c = 91%)
X = 2-pyridinyl (**14**, y = 31%, y/c = 87%)

Figure 1. Functionalized dendrons **6**−**14** as prepared by the Suzuki or Stille reaction.

(21) Wooley, K. L.; Hawker, C. J.; Fréchet, J. M. J. *J. Chem. Soc., Perkin Trans. 1* **1991**, 1059.
(22) For stannylation of thiophenes see: Bao, Z.; Chan, W.; Yu, L. *Chem. Mater.* **1993**, *5*, 2.

equiv of stannane **4** (78% after workup and purification). These conditions were subsequently applied to modify the second and third generation of 4-bromophenyl substituted dendrons, resulting in the fully 2-thienyl functionalized species th_4-[G-2]-OH (**10**) and th_8-[G-3]-OH (**11**) in 86% and 46% yield, respectively. The yield per coupling (*y*/*c*) for all three generations is 88%, 96%, and 91%, respectively. In a similar fashion, the 4-bromophenyl substituted dendrons were modified with 2-pyridyl units. Using excess 2-trimethylstannylpyridine (**5**)[23] as the stannane, and again performing the reactions in toluene/$Pd(PPh_3)_4$, the dendrons pyr_2-[G-1]-OH (**12**), pyr_4-[G-2]-OH (**13**), and pyr_8-[G-3]-OH (**14**) were obtained in yields of 53%, 43%, and 31%, respectively (yield per coupling is 73%, 81%, and 87%, respectively; Figure 1).

Although the yield per coupling (*y*/*c*) remains essentially constant (~91%) for the phenyl and 2-thienyl functionalization reactions, this value is somewhat lower in case of the 2-pyridyl modifications. This finding is related to difficulties encountered in the purification of the pyridyl-modified dendrons. During the functionalization reaction, homo-coupling of the stannane occurs, which leads to the formation of 2,2′-bipyridine. Since this compound has almost the same R_f value as that of the desired Stille product, purification is difficult and the yields, and thus the *y*/*c*, are significantly lower than is the case for the phenyl or the 2-thienyl derivatives.

Examination of pyr_2-[G-1]-OH (**12**) by ^1H NMR spectroscopy revealed an interesting feature of this compound. The resonance attributed to the OH proton was observed downfield at 2.69 ppm instead of the chemical shift of 1.7−1.9 ppm normally expected for such a structure. Similar observations were made in the cases of pyr_4-[G-2]-OH (**13**) and pyr_8-[G-3]-OH (**14**). These results suggest the occurrence of intermolecular hydrogen bonding between the nitrogen of the pyridyl unit at the periphery of the dendron and the OH group at the focal point of the dendron. In the case of dendron **12**, we were able to obtain crystals suitable for X-ray crystallography by recrystallization from CH_2Cl_2/cyclohexane.[24] The X-ray crystal structure shown in Figure 2 confirms clearly the existence of strong H-bonds between the nitrogen of the pyridyl unit at the periphery of the dendron and the OH group at the focal point of the dendron, resulting in a unit cell consisting of dimers formed through two intermolecular H-bonds. Unfortunately, neither dendron **13** nor dendron **14** was crystalline material.

In conclusion, we have shown that both Suzuki and the Stille coupling reactions can be applied to functionalize the periphery of polyether dendrons. Starting from 4-bromo-substituted dendrons Br_{2^n}-[G-*n*]-OH ($n = 1-3$) and applying Pd-catalyzed cross-coupling reactions, the surfaces of these species have been fully functionalized with phenyl, 2-thienyl, and 2-pyridyl substituents in moderate to good yields using phenylboronic acid, 2-trimethylstannylthiophene, and 2-trimethylstannylpyridine, respectively. Although the overall yields of the coupling reactions decrease with increasing generation, the yield per coupling (*y*/*c*) is relatively constant (91% for phenyl and 2-thienyl substitution, and 80% for 2-pyridyl substitution). Currently, we are attempting to modify the periphery of polyether dendrons with a variety of other substituents using Suzuki, Stille, as well as Heck reactions. In the latter case, further studies are required since the bis-stilbene product obtained by reaction between Br_2-[G-1]-OH (**1**) and 4-acetoxystyrene ($Pd(OAc)_2$, $(o\text{-tol})_3P$, Bu_3N, DMF; 82% yield after purification) is only slightly soluble in common organic solvents.

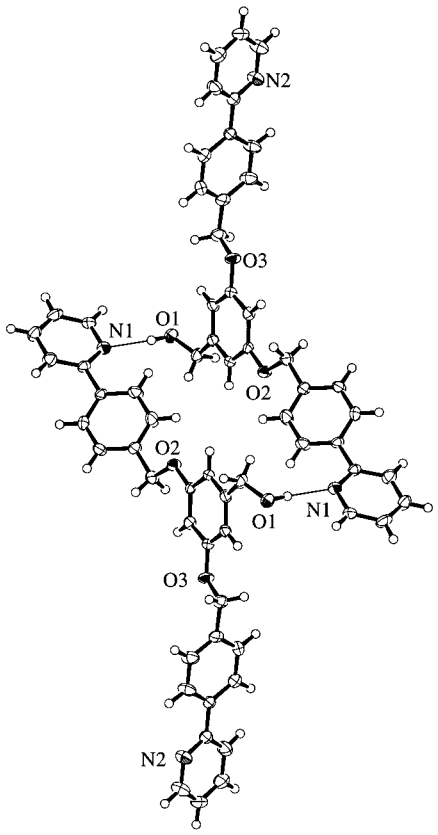


Figure 2. Dimers, as formed by two intermolecular H-bonds, within the crystal structure of pyr_2-[G-1]-OH (**12**).

Experimental Section

All chemicals were reagent grade and used without further purification. The 4-bromine-substituted dendrons **1**, **2**, and **3** were prepared according to a procedure reported by Fréchet et al.[21] 2-Trimethylstannylthiophene (**4**)[22] and 2-trimethylstannylpyridine (**5**)[23] were prepared from 2-bromothiophene and 2-bromopyridine, respectively, applying a standard Br−Li exchange (*n*-BuLi)/stannylation ($(CH_3)_3SnCl$) sequence. Thin-layer chromatography was performed on Whatman TLC plates (Al Sil G/UV_{254} (250 μm)). Chromatographic separations were performed on silica gel 60 (SiO_2, 0.040−0.063 mm, 230−400 mesh). Melting points are uncorrected. ^1H and ^{13}C NMR data were recorded on a 400 MHz spectrometer using TMS as internal standard. Mass spectrometry data were obtained using EI-MS, FAB-MS, or MALDI-TOF MS (operated in delayed extraction mode using *trans*-3-indoleacrylic acid or α-cyano-4-hydroxycinnamic acid as the matrix). MALDI-TOF data are reported using relative masses since the (relatively) broad peaks obtained reflect all isotopic compositions and the mass given represents the value measured at the top of the peak. Elemental analyses were conducted by MHW Laboratories, Phoenix, AZ.

Ph_2-[G-1]-OH (6) (General procedure for a Suzuki reaction). A 100 mL flask with gas-inlet was charged with Br_2-[G-1]-OH (**1**, 738 mg, 1.542 mmol), toluene (6 mL), aqueous Na_2CO_3 (6 mL, 1 M), and phenylboronic acid (457 mg, 3.748 mmol). The mixture was stirred under argon atmosphere for 10 min, after which it was deaerated 7 times, each time saturating with argon. Then $Pd(PPh_3)_4$ (2 mol %) was added and the yellow mixture

(23) For stannylation of pyridines see: Cárdenas, D. J.; Sauvage, J.-P. *Synlett* **1996**, 916.

(24) Colorless platelike crystals: 0.08 × 0.24 × 0.35 mm; O1···N1, 2.827 Å; O1−H1, 0.95 Å; N1···H1, 1.93 Å; O1−H1···N1, 185°. For more details, refer to the corresponding author.

was refluxed for 20 h. The brown organic phase was separated, and the aqueous Na_2CO_3 phase was extracted with CH_2Cl_2. The combined organic fractions were washed with H_2O, dried ($MgSO_4$), and filtered, and the solvent was evaporated. Recrystallization from CH_2Cl_2/cyclohexane finally resulted in **6** as a white solid (589 mg, 1.25 mmol, 81%): mp 136.5−138.0 °C. ^{1}H NMR ($CDCl_3$): δ 7.58 (2 × d, J = 8.2 Hz, 8H), 7.50−7.41 (m, 8H), 7.35 (t, J = 7.3 Hz, 2H), 6.66 (d, J = 2.1 Hz, 2H), 6.59 (t, J = 2.1 Hz, 1H), 5.08 (s, 4H), 4.64 (d, J = 5.7 Hz, 2H), 1.73 (t, J = 5.9 Hz, 1H) ppm ^{13}C NMR ($CDCl_3$): δ 160.2, 143.5, 141.0, 140.7, 135.8, 128.8, 128.0, 127.3, 127.1, 105.8, 101.3, 69.8, 65.3 ppm FT-IR (KBr): ν 3294, 3054, 3031, 2908, 2865, 1592, 1163, 1059, 1006, 828, 757, 695 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 256 nm; EI-MS m/z 472 (M^+), 333, 305, 167; FAB-MS m/z 473 ($M + H^+$), 455, 167. Anal calcd for $C_{33}H_{28}O_3$: C, 83.87; H, 5.97. Found: C, 83.60; H, 5.97.

Ph$_4$-[G-2]-OH (7). A Suzuki reaction between Br$_4$-[G-2]-OH (**2**, 258 mg, 0.243 mmol) and phenylboronic acid (151 mg, 1.238 mmol) in toluene (3.5 mL) and aqueous Na_2CO_3(3.5 mL, 1 M) with Pd^0(PPh$_3$)$_4$ as the catalyst was performed as described for **6**. After 20 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a solid that was purified by column chromatography (25 g of SiO_2, CH_2Cl_2, $R_f \gg 0.39$). Subsequent recrystallization (CH_2Cl_2/cyclohexane) resulted in **7** as a fine, white powder (182 mg, 0.173 mmol, 71%). ^{1}H NMR ($CDCl_3$): δ 7.61 (m, 16H), 7.47 (m, 16H), 7.36 (t, J = 7.4 Hz, 4H), 6.72 (d, J = 2.2 Hz, 4H), 6.62 (m, 4H), 6.56 (t, J = 2.2 Hz, 1H), 5.08 (s, 8H), 5.00 (s, 4H), 4.61 (d, J = 6.0 Hz, 2H), 1.71 (t, J = 6.1 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 160.15, 160.03, 143.4, 140.9, 140.7, 139.4, 135.7, 128.8, 128.0, 127.3, 127.1, 106.4, 105.7, 101.6, 101.3, 69.90, 69.85, 65.2 ppm. FT-IR (KBr): ν 3560, 3056, 3029, 2912, 2868, 1595, 1163, 1050, 827, 760, 697 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 254 nm. MALDI-TOF MS m/z calcd for $C_{73}H_{60}O_7$: 1049.3 (M^+), 1072.3 ($M + Na^+$), 1088.4 ($M + K^+$). Found: 1049.0 (M^+), 1071.6 ($M + Na^+$), 1087.8 ($M + K^+$). Anal calcd for $C_{73}H_{60}O_7$: C, 83.56; H, 5.76. Found: C, 83.38; H, 5.84.

Ph$_8$-[G-3]-OH (8). A Suzuki reaction between Br$_8$-[G-3]-OH (**3**, 267 mg, 0.120 mmol) and phenylboronic acid (157 mg, 1.29 mmol) in toluene (5 mL) and aqueous Na_2CO_3 (5 mL, 1 M) with Pd^0(PPh$_3$)$_4$ as the catalyst was performed as described for **6**. After 48 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction ($CHCl_3/H_2O$) gave a solid that was purified by column chromatography (25 g of SiO_2, $CHCl_3$ as eluent, $R_f \gg 0.20$). The latter resulted in pure **8** as a white foam (129 mg, 0.059 mmol, 49%). ^{1}H NMR ($CDCl_3$): δ 7.58 (m, 32H), 7.44 (m, 32H), 7.36 (t, J = 7.3 Hz, 8H), 6.71 (d, J = 2.1 Hz, 8H), 6.68 (d, J = 2.0 Hz, 4H), 6.62 (t, J = 2.1 Hz, 4H), 6.59 (d, J = 2.0 Hz, 2H), 6.57 (t, J = 2.0 Hz, 2H), 6.53 (t, J = 2.0 Hz, 1H), 5.01 (s, 16H), 4.92 (s, 8H), 4.91 (s, 4H), 4.53 (d, J = 6.0 Hz, 2H), 1.70 (t, J = 6.1 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 160.14, 160.03, 143.5, 140.9, 140.7, 139.37, 139.30, 135.7, 128.8, 128.0, 127.3, 127.1, 106.4, 105.8, 101.64, 101.60, 101.25, 69.93, 69.83, 65.2 ppm. FT-IR (KBr): ν 3570, 3054, 3029, 2926, 2871, 1595, 1157, 1052, 829, 760, 697 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 254 nm. MALDI-TOF MS m/z calcd for $C_{153}H_{124}O_{15}$: 2225.7 ($M + Na^+$), 2241.8 ($M + K^+$). Found: 2226.1 ($M + Na^+$), 2242.3 ($M + K^+$). Anal calcd for $C_{153}H_{124}O_{15}$: C, 83.43; H, 5.67. Found: C, 83.13; H, 5.47.

th$_2$-[G-1]-OH (9) (General procedure for a Stille reaction). A 100 mL flask with gas-inlet was charged with Br$_2$-[G-1]-OH (**1**, 334 mg, 0.698 mmol), 2-trimethylstannylthiophene (**4**, 392 mg, 1.587 mmol), and toluene (6 mL). The mixture was deaerated 7 times, each times saturating with argon. Then Pd(PPh$_3$)$_4$ (2 mol %) was added and the yellow mixture was refluxed, constantly blanketed by argon. After 2 days the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a dark oil that was subsequently purified by column chromatography (30 g of SiO_2, eluent CH_2Cl_2, $R_f \gg 0.31$). Recrystallization from CH_2Cl_2/cyclohexane finally resulted in pure **9** as a white solid (264 mg, 0.545 mmol, 78%): mp 147.5−149 °C. ^{1}H NMR ($CDCl_3$): δ 7.60 (d, J = 8.3 Hz, 4H), 7.40 (d, J = 8.4 Hz, 4H), 7.30 (dd, J = 3.6 and 1.1 Hz, 2H), 7.26 (dd, J = 5.1 and 1.1 Hz, 2H), 7.07 (dd, J = 5.0 and 3.6 Hz, 2H), 6.62 (d, J = 2.2 Hz, 2H), 6.54 (t, J = 2.2 Hz, 1H), 5.02 (s, 4H), 4.61 (d, J = 4.8 Hz, 2H), 1.78 (t, J = 4.5 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 160.0, 143.9, 143.5, 136.0, 134.1, 128.0, 126.1, 124.9, 123.2, 105.8, 101.3, 69.7, 65.3 ppm. FT-IR (KBr): ν 3385, 3279, 3100, 2904, 2862, 1593, 1445, 1376, 1319, 1163, 812, 692 cm^{-1}; UV−vis 288 nm. EI-MS m/z 484 (M^+), 345, 311, 173. FAB-MS: m/z 485 ($M + H^+$), 467, 441, 173. Anal calcd for $C_{29}H_{24}O_3S_2$: C, 71.87; H, 4.99; S, 13.23. Found: C, 72.04; H, 5.20; S, 13.00.

th$_4$-[G-2]-OH (10). A Stille reaction between Br$_4$-[G-2]-OH (**2**, 368 mg, 0.347 mmol) and 2-trimethylstannylthiophene (**4**, 478 mg, 1.936 mmol) in toluene (6 mL) with Pd(PPh$_3$)$_4$ as the catalyst was performed as described for **9**. After 2 days the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a solid that was purified by column chromatography (20 g of SiO_2, $CHCl_3$ as eluent, $R_f \gg 0.16$). Final recrystallization (CH_2Cl_2/cyclohexane) resulted in **10** as a fine, white powder (320 mg, 0.298 mmol, 86%). ^{1}H NMR ($CDCl_3$): δ 7.60 (d, J = 8.2 Hz, 8H), 7.40 (d, J = 8.2 Hz, 8H), 7.30 (dd, J = 3.6 and 1.1 Hz, 4H), 7.27 (dd, J = 5.1 and 1.1 Hz, 4H), 7.07 (dd, J = 5.1 and 3.6 Hz, 4H), 6.69 (d, J = 2.1 Hz, 4H), 6.60 (d, J = 2.0 Hz, 2H), 6.58 (t, J = 2.1 Hz, 2H), 6.54 (t, J = 2.1 Hz, 1H), 5.01 (s, 8H), 4.96 (s, 4H), 4.57 (d, J = 6.0 Hz, 2H), 1.86 (t, J = 6.1 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 160.0, 159.9, 143.9, 143.5, 139.3, 135.9, 134.0, 128.04, 128.00, 126.0, 124.9, 123.2, 106.3, 105.6, 101.6, 101.2, 69.8, 69.7, 65.1 ppm. FT-IR (KBr): ν 3569, 3456, 3104, 3069, 2923, 2869, 1595, 1448, 1371, 1159, 1051, 811, 699 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 288 nm. MALDI-TOF MS: m/z calcd for $C_{65}H_{52}O_7S_4$: 1073.4 (M^+), 1096.4 ($M + Na^+$), 1112.5 ($M + K^+$). Found: 1073.6 (M^+), 1096.9 ($M + Na^+$), 1113.0 ($M + K^+$). Anal calcd for $C_{65}H_{52}O_7S_4$: C, 72.73; H, 4.88; S, 11.95. Found: C, 72.58; H, 4.92; S, 12.13.

th$_8$-[G-3]-OH (11). A Stille reaction between Br$_8$-[G-3]-OH (**3**, 278 mg, 0.125 mmol) and 2-trimethylstannylthiophene (**4**, 525 mg, 2.13 mmol) in toluene (3 mL) with Pd^0(PPh$_3$)$_4$ as the catalyst was performed as described for **9**. After 48 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a solid that was purified by column chromatography (35 g of SiO_2, $CHCl_3$ as eluent, $R_f \gg 0.12$). The latter resulted in pure **11** as a slightly yellow foam (130 mg, 0.0578 mmol, 46%). ^{1}H NMR ($CDCl_3$): δ 7.52 (d, J = 8.3 Hz, 16H), 7.31 (d, J = 8.3 Hz, 16H), 7.22 (dd, J = 3.6 and 1.1 Hz, 8H), 7.20 (dd, J = 5.1 and 1.1 Hz, 8H), 7.00 (dd, J = 5.1 and 3.6 Hz, 8H), 6.64 (d, J = 2.2 Hz, 8H), 6.62 (d, J = 2.2 Hz, 4H), 6.56 (d, J = 2.1 Hz, 2H), 6.54 (t, J = 2.2 Hz, 4H), 6.51 (t, J = 2.1 Hz, 2H), 6.47 (t, J = 2.1 Hz, 1H), 4.90 (s, 16H), 4.86 (s, 8H), 4.84 (s, 4H), 4.48 (broad s, 2H), 1.86 (broad s, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 159.98, 159.94, 159.91, 143.9, 143.6, 139.34, 139.27, 135.9, 134.0, 128.02, 125.9, 127.98, 124.8, 123.2, 106.3, 105.6, 101.58, 101.49, 101.14, 69.80, 69.76, 69.62, 65.03 ppm. FT-IR (KBr): ν 3570, 3100, 3070, 2923, 2871, 1595, 1449, 1372, 1158, 1048, 811, 699 cm^{-1}; UV−vis ($CHCl_3$): λ_{max} 288 nm. MALDI-TOF MS: m/z calcd for $C_{137}H_{108}O_{15}S_8$: 2273.9 ($M + Na^+$), 2290.0 ($M + K^+$). Found: 2273.3 ($M + Na^+$), 2289.9 ($M + K^+$). Anal calcd for $C_{137}H_{108}O_{15}S_8$: C, 73.10; H, 4.84; S, 11.40. Found: C, 72.97; H, 5.00; S, 11.60.

pyr$_2$-[G-1]-OH (12). A Stille reaction between Br$_2$-[G-1]-OH (**1**, 336 mg, 0.703 mmol) and 2-trimethylstannylpyridine (**5**, 431 mg, 1.782 mmol) in toluene (6 mL) with Pd^0(PPh$_3$)$_4$ as the catalyst was performed as described for **9**. After 48 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a solid that was purified by column chromatography (25 g of SiO_2, 3% methanol in CH_2Cl_2, $R_f \gg 0.36$). Subsequent recrystallization from cyclohexane/CH_2Cl_2 gave pure **12** as colorless platelike crystals (178 mg, 0.375 mmol, 53%): mp 147.5−148.5 °C. ^{1}H NMR (CDCl3): δ 8.67 (m, 2H), 7.97 (d, J = 8.4 Hz, 4H), 7.72 (m, 4H), 7.49 (d, J = 8.4 Hz, 4H), 7.22 (tt, J = 5.9 and 1.7 Hz, 2H), 6.61 (d, J = 2.3 Hz, 2H), 6.55 (t, J = 2.3 Hz, 1H), 5.06 (s, 4H), 4.60 (s, 2H), 2.69 (broad s, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 160.0, 157.0, 149.6, 143.7, 138.9, 137.7, 136.8, 127.7, 127.1, 122.1, 120.5, 105.8, 101.3, 69.7, 65.0 ppm. FT-IR (KBr): ν 3248, 3036, 2924, 2872, 1589, 1470−1295, 1155, 1045, 845, 772 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 252, 280 nm; EI-MS m/z 474 (M^+), 168. Anal calcd for $C_{31}H_{26}N_2O_3$: C, 78.46; H, 5.52; N, 5.90. Found: C, 78.37; H, 5.74; N, 5.71.

pyr$_4$-[G-2]-OH (13). A Stille reaction between Br$_4$-[G-2]-OH (**2**, 323 mg, 0.305 mmol) and 2-trimethylstannylpyridine (**5**, 371 mg, 1.534 mmol) in toluene (5 mL) with Pd^0(PPh$_3$)$_4$ as the

catalyst was performed as described for **9**. After 24 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction (CH_2Cl_2/H_2O) gave a brown oil that was purified by column chromatography (35 g SiO_2, 3% methanol in CH_2Cl_2 as eluent, $R_f \gg 0.35$). Final recrystallization (CH_2Cl_2/cyclohexane) resulted in pure **13** as a fine, white powder (137 mg, 0.130 mmol, 43%). ^{1}H NMR ($CDCl_3$): δ 8.68 (m, 4H), 7.97 (d, J = 8.3 Hz, 8H), 7.71 (m, 8H), 7.47 (d, J = 8.3 Hz, 8H), 7.23 (m, 4H), 6.64 (d, J = 2.2 Hz, 4H), 6.57 (t, J = 2.2 Hz, 2H), 6.48 (d, J = 2.1 Hz, 2H), 6.45 (t, J = 2.2 Hz, 1H), 5.09 (s, 8H), 4.95 (s, 4H), 4.56 (s, 2H), 3.45 (broad s, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 159.9, 159.7, 157.0, 149.6, 144.0, 139.5, 138.9, 137.6, 136.8, 127.7, 127.1, 122.2, 120.6, 106.1, 105.5, 101.7, 101.0, 69.69, 69.61, 64.7 ppm. FT-IR (KBr): ν 3254, 3053, 2922, 2852, 1589, 1467, 1157, 1055, 833, 777 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 252, 282 nm. MALDI-TOF MS: m/z calcd for $C_{69}H_{56}N_4O_7$: 1054.4 (M + H$^+$), 1076.4 (M + Na$^+$); found: 1054.7 (M + H$^+$), 1076.9 (M + Na$^+$). HR-MS m/z calcd for $C_{69}H_{56}N_4O_7$: 1053.4227. Found: 1053.4232.

pyr$_8$-[G-3]-OH (14). A Stille reaction between Br$_8$-[G-3]-OH (**3**, 337 mg, 0.1516 mmol) and 2-trimethylstannylpyridine (**5**, 427 mg, 1.577 mmol) in toluene (6 mL) with $Pd^0(PPh_3)_4$ as the catalyst was performed as described for **9**. After 40 h the reaction was complete and the mixture was allowed to cool to room temperature. Extraction ($CHCl_3/H_2O$) gave a dark spongy material that was purified by column chromatography (60 g of SiO_2, 3−5% methanol in CH_2Cl_2 as eluent, R_f (3%) $\gg$ 0.28). This finally resulted in pure **14** as a white foam (104 mg, 0.047 mmol, 31%). ^{1}H NMR ($CDCl_3$): δ 8.67 (m, 8H), 7.97 (d, J = 8.3 Hz, 16H), 7.68 (m, 8H), 7.48 (d, J = 8.3 Hz, 16H), 7.19 (m, 8H), 6.67 (d, J = 2,2 Hz, 8H), 6.64 (d, J = 2.1 Hz, 8H), 6.57 (m, 6H), 6.53 (t, J = 2.2 Hz, 2H), 6.49 (t, J = 2.2 Hz, 1H), 5.05 (s, 16H), 4.94 (s, 8H), 4.91 (s, 4H), 4.54 (s, 2H), 3.07 (broad s, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ 160.01, 159.95, 159.90, 156.9, 149.6, 143.8, 139.36, 139.30, 138.9, 137.6, 136.7, 127.7, 127.0, 122.1, 120.5, 106.4, 105.7, 101.66, 101.55, 101.08, 69.86, 69.80, 69.70, 64.9 ppm. FT-IR (KBr): ν 3280, 3051, 2923, 2870, 1593, 1467, 1153, 1059, 832, 777 cm^{-1}. UV−vis ($CHCl_3$): λ_{max} 250, 280 nm. MALDI-TOF MS m/z calcd for $C_{145}H_{116}N_8O_{15}$: 2211.6 (M + H$^+$), 2233.6 (M + Na$^+$). Found: 2212.2 (M + H$^+$), 2234.3 (M + Na$^+$). Anal calcd for $C_{145}H_{116}N_8O_{15}$: C, 78.79; H, 5.29; N, 5.07. Found: C, 78.76; H, 5.43; N, 4.84.

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