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Supramolecular Reactor in an Aqueous Environment: Aromatic Cross Suzuki Coupling Reaction at Room Temperature

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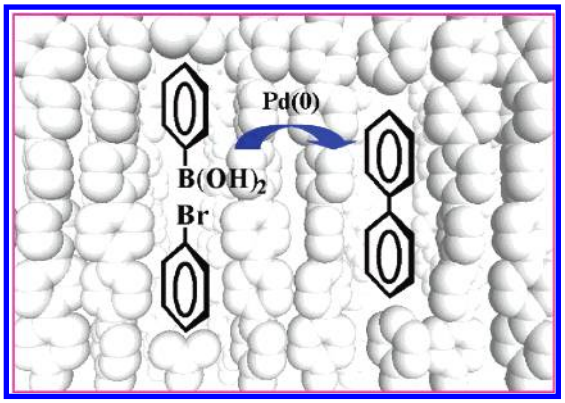

We have investigated supramolecular reactors for the Suzuki coupling reactions of aryl halides with phenyl boronic acids by using self-assembly of amphiphilic rod−coil molecules in aqueous solution at room temperature. All the rod−coil molecules synthesized in this work showed to self-assemble into discrete micelles consisting of aromatic rod bundles encapsulated by hydrophilic poly(ethylene oxide) coils. We present a comparative study of rod−coil molecules' efficiency as supramolecular reactors for Suzuki coupling reaction. The closed-packed aromatic bundles play an efficient role in supramolecular reactors for the coupling reactions at room temperature. The supramolecular reactor based on hexa-*p*-phenylene confers unprecedented activity, allowing reactions to be performed at very low catalyst levels, without conventional heating or microwave.

Introduction

Well-ordered supramolecular materials with nanometer-scale architectures have shown a variety of functionalities in material science, biochemistry, and catalyst science.[1] Rational molecular design can create self-assembled nanostructures through noncovalent intermolecular forces such as hydrogen bonding, coordination bonding, van der Waals interactions, and $\pi-\pi$ interactions.[2] For example, the self-assembly of bowl-shape molecules can lead to a capsule formation with a hollow inner space that has a specific chemical environment different from outside.[3] Some guest molecules are encapsulated in the capsule and, if the guest molecules are chemically active, the chemical reaction is much faster than in general condition. The confinement of the reactant in the hollow capsules makes very high local concentration or the preorganization similar to the product, which provides a microenvironment to enhance chemical reactivity. The encapsulation of reactants within the supramolecular cage realizes the following functionalities such as the stabilization of intermediates,[4] new

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formation of conformational isomers,[5] and templates themselves.[6]

In a rod−coil molecular system, consisting of a flexible coil and a rigid block, the anisotropic orientation of the rod segments and the repulsion between the covalently connected blocks lead to self-organization into a wide variety of aggregation structures.[7] The careful selection of the type and relative length of the respective blocks can give rise to a variety of the well-defined supramolecular structures in nanometer-scale dimensions. Another interesting feature of rod−coil molecules is their amphiphilic characteristic that shows a strong tendency of their lipophilic and lipophobic segments to separate in space into distinct nanodomains.[8] Depending on the solvent content and polarity, rod−coil molecules self-assemble into different aggregated structures via mutual interactions between block segments and solvent.

Amphiphilic rod−coil molecules based on poly(ethylene oxide) (PEO) coils, when dissolved in an aqueous medium, can self-organize into aggregates consisting of a rod bundle surrounded by hydrophilic PEO chains.[9] An important property of the aggregates is the ability to entrap solvophobic aromatic molecules through intermolecular interactions including hydrophobic interactions and $\pi-\pi$ interactions.[10] These secondary forces would provide a nanoenvironment suitable for the confinement of aromatic guest molecules within the rod bundle. Accordingly, micellar aggregates of amphiphilic rod−coil molecules based on poly(ethylene oxide) coils raise the possibility of the use as containers for aromatic coupling reactions in aqueous media.

Recently, we have demonstrated that the aromatic bundle of the micelle can be used as an efficient supramolecular reactor for the Pd-catalyzed Suzuki cross coupling reaction of a wide range of aryl halides with phenyl boronic acids in an aqueous environment.[11] The Suzuki coupling reactions can take place within aromatic bundles in aqueous media at room temperature because this confined environment would lead to a highly concentrated reaction site that lowers the energy barrier for the coupling reaction.[12] The use of water as a solvent for this reaction is expected to have both economical and environmental advantages.[13]

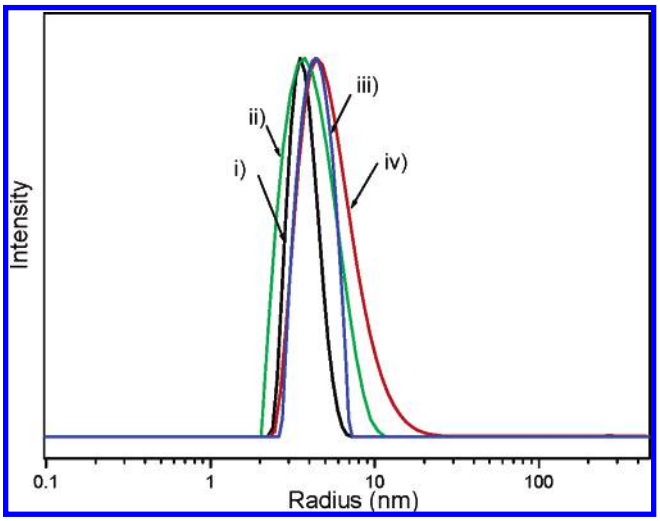

FIGURE 1. CONTIN size distributions of micellar aggregations of **1** (i), **2** (ii), **3** (iii), and **4** (iv) (2×10^{-4} g/mL in H_2O) in water.

In this article, we report room-temperature Suzuki coupling reactions of aryl halides with aryl boronic acids in an aqueous environment by using a variety of the aromatic rod bundles as supramolecular reactors. The amphiphilic rod−coil molecules consist of poly(ethylene oxide) with the number of repeating units of 17 as coil segments and rigid rods based on hexa-*p*-phenylene (**1**), hexa-*p*-phenylene with dimethyl group (**2**), tetra-*p*-phenylene (**3**), and perylene (**4**).

Results and Discussion

Synthesis and Characterization of Rod−Coil Molecules (1−4). The synthesis of the rod−coil molecules consisting of poly(ethylene oxide) with the number of repeating units of 17 and aromatic blocks is outlined in Scheme 1. **1** and **2**, with hexa-*p*-phenylene rod, were synthesized from cross coupling of **7** with corresponding boronic acids respectively and **3** was from homo coupling of **7**.[11] Poly(ethylene oxide) was attached to the perylene to give rise to compound **4**. All of the resulting rod−coil molecules were purified by silica gel column chromatography and subsequent prep-HPLC until the polydipersity index remained constant as described in the Experimental Section. The rod−coil molecules were characterized by ^{1}H and ^{13}C NMR spectroscopies, elemental analysis, MALDI-TOF mass spectroscopy, and gel-permeation chromatography (GPC) and shown to be in full agreement with the structures presented.

The amphiphilic molecules based on elongated rods display aggregation behavior in aqueous media. Dynamic light scattering study in aqueous solutions showed that all the rod−coil molecules self-assemble into micellar

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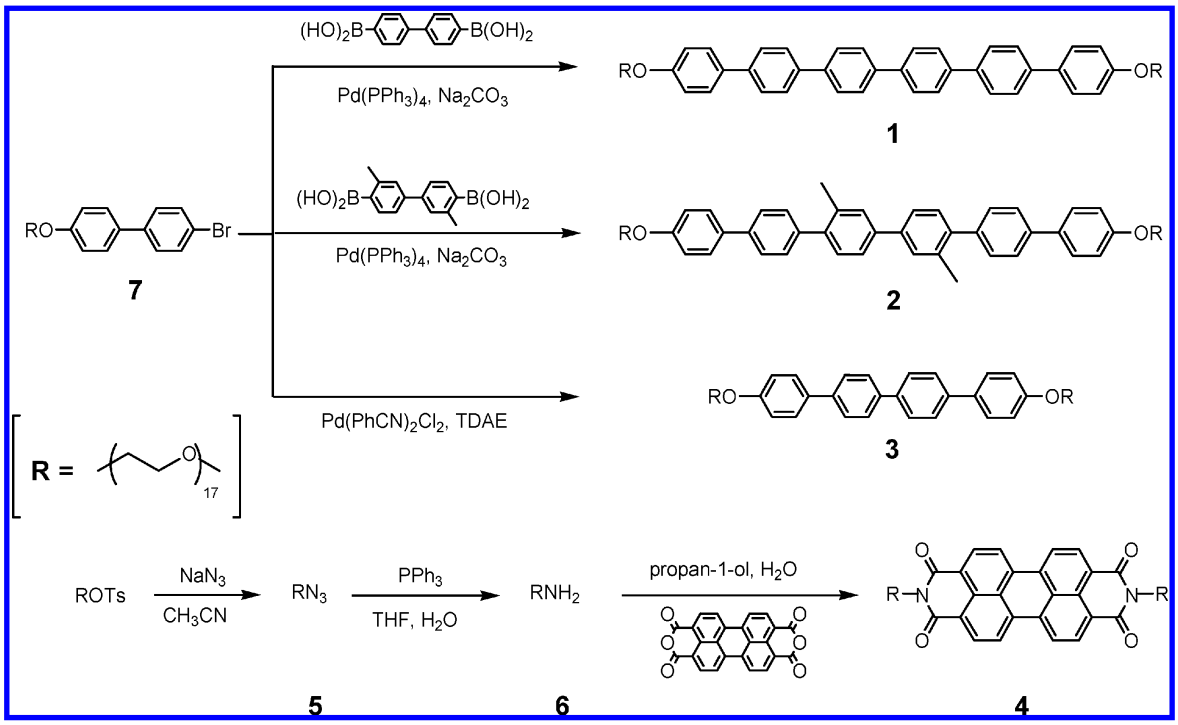
SCHEME 1. Synthesis of Rod−Coil Molecules 1−4

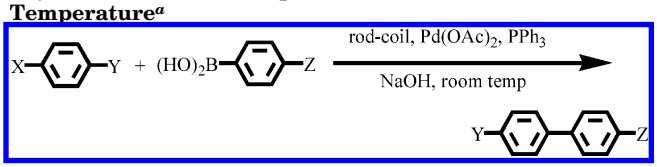


aggregates (Figure 1). The average hydrodynamic radii (R_H) of the aggregates were observed to be approximately 4−6 nm, suggesting that the micelles consist of hydrophobic disklike rod bundles encapsulated by hydrophilic poly(ethylene oxide) coils, as proposed by rod−coil theories.[14] The formation of micellar aggregates was also confirmed by transmission electron microscopy (TEM) experiment, which shows spherical entities (see Supporting Information). The micrographs show the spherical aggregates that are roughly 10−15 nm in diameter. These values are consistent with those from dynamic light scattering experiments.

Suzuki Coupling Reactions Dependent on Bulkiness of Rod Building Block. The use of each aggregate of different rods as supramolecular reactors in aqueous media was investigated with a Suzuki cross coupling reaction of aryl halides and aryl boronic acids at ambient temperature.[15] As shown in Table 1, the cross coupling reactions of iodobenzenes with 1.2 equiv of phenylboronic acids took place in the presence of 0.5 mol % palladium catalyst and 2 equiv of NaOH in a 2.5×10^{-3} M aqueous solution of rod−coil molecules to give the corresponding products with nearly quantitative conversion after 12 h, in both **1** and **2** (Table 1, entries 1−3). Under similar conditions, the coupling reactions of bromobenzenes including electron-rich and electron-deficient substrates also underwent quantitative conversion (Table 1, entries 4−6), clearly demonstrating that the cross coupling reaction in the presence of **1** is highly effective and allows for the room-temperature cross coupling reaction in aqueous media.

In the case of **2** based on a bulkier rod segment,[16] however, the coupling reaction of bromobenzenes showed much lower conversions. The cross coupling reaction of electron-poor aryl chlorides, which is generally unreactive under the conditions employed to couple aryl bromides and aryl iodides,[17,18] also proceeded under similar conditions to afford the corresponding biphenyl in 72% yield

TABLE 1. Suzuki Cross Coupling of Aryl Halides with Aryl Boronic Acids in Aqueous Solution at Room Temperature[a]



entry	X	Y	Z	yield (%)[b] rod−coil **1**	yield (%)[b] rod−coil **2**
1	I	NO_2	H	99	99
2	I	H	OCH_3	99	97
3	I	OCH_3	H	99	99
4	Br	NO_2	H	99	30
5	Br	H	OCH_3	99	47
6	Br	OCH_3	H	99	34
7	Cl	NO_2	H	72	0
8	Cl	H	OCH_3	17	0
9	Cl	OCH_3	H	15	0

[a] Reaction conditions: aryl halide (0.1 mmol), aryl boronic acid (0.12 mmol), $Pd(OAc)_2$ (0.5 mol %), PPh_3 (1.0 mol %), NaOH (0.2 mmol), rod−coil (0.025 mmol), H_2O (10 mL), stirring at room temperature for 12 h. [b] Percent yields are calculated on the basis of GC analysis using xylene as the internal standard.

(14) (a) Williams, D. R. M.; Fredrickson, G. H. *Macromolecules* **1992**, *25*, 3561−3568. (b) Halperin, A. *Macromolecules* **1990**, *23*, 2724−2731.
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(16) The difference in packing of **1** and **2** was investigated by using the wide-angle X-ray scattering (WAXS) experiment (see Supporting Information). The WAXS pattern of **1** shows the inter-rod distance peak at $q = 14.7$ nm^{-1}, while that of **2** at $q = 13.5$ nm^{-1}, indicating that the distance between rod building blocks of **2** is longer that that of **1** in bulk. Therefore, the packing of the rod of **2** seems to be also looser than that of **1** in solution.
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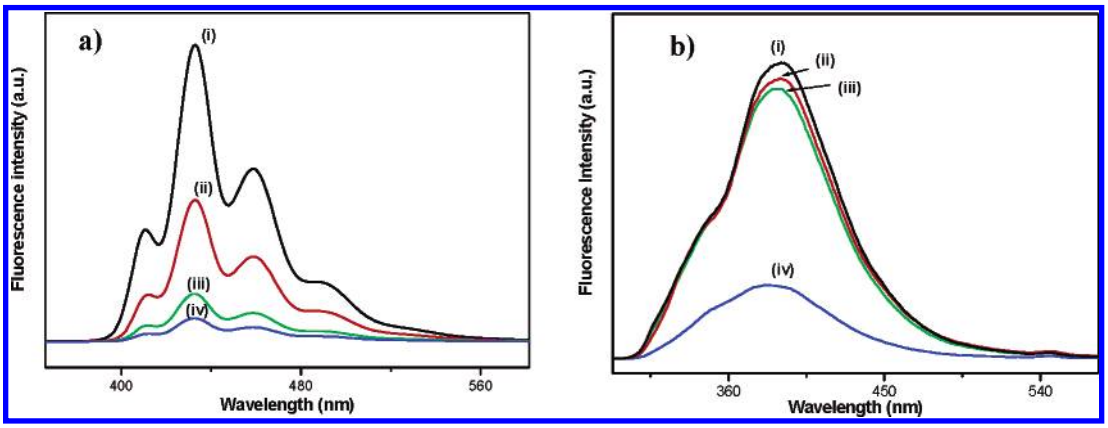

FIGURE 2. Emission spectra of (a) **1** and (b) **2** (2×10^{-4} g/mL in H_2O) by separately adding (i) nothing, (ii) phenyl boronic acid (0.4 mg), (iii) triphenyl phosphine (0.4 mg), and (iv) 1-bromo-4-nitrobenzene (0.4 mg). Excitation wavelength, 333 and 282 nm for **1** and **2**, respectively.

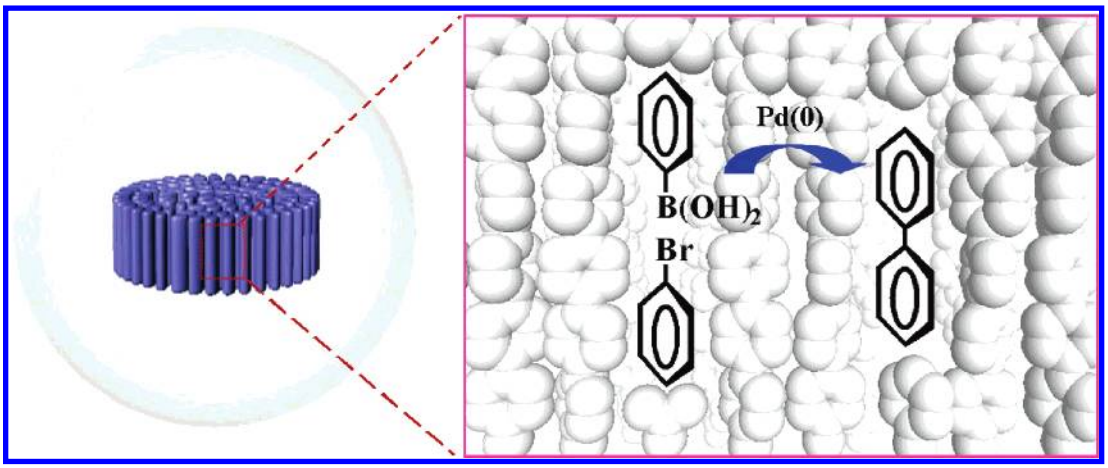

FIGURE 3. Schematic representation of supramolecular reactors.

in the presence of **1**, but no reactions took place in the solution of **2** (Table 1, entries 7−9). These results indicate that the packing of bundle-like aromatic cores within the aggregates is likely to play a key role in the room-temperature coupling reaction in an aqueous environment. To investigate the extent of confinement of the aromatic substrates within the aromatic bundles, entrapment was confirmed with aryl halides, boronic acids, and triphenyl phosphine, respectively, in aqueous solution of **1** and **2** by using fluorescence spectroscopy (Figure 2).

Emission spectra of the rod−coil molecules in aqueous solution, in the absence of the aromatic substrates, showed a strong fluorescence with a maximum at 432 and 390 nm for **1** and **2**, respectively. In great contrast, the fluorescence intensities of the aqueous rod−coil **1** solutions containing the aromatic substrates showed to be remarkably suppressed, demonstrating that they are effectively entrapped within the aromatic bundle of the micelle composed of rod−coil building blocks.[19] **2** solutions, however, showed to be much less suppressed (Figure 2b). This implies that the packing of the rod building block in **1** is much denser than that of **2** in aqueous solution. As a result, self-assembly of amphiphilic rod−coil molecule **1** seems to give rise to a more efficient supramolecular reactor for the aromatic coupling reaction (Figure 3).

Suzuki Coupling Reactions with Rods of Different Lengths and Shapes as Supramolecular Reactors. To obtain more experimental details on the influence of inter-rod interactions in supramolecular reactors, the coupling reactions in aqueous **3** and **4** solutions are compared with those in aqueous **1** solution. Rod−coil molecule **3** consisting of tetra-*p*-phenylene rod might lead to fewer inter-rod interactions than rod−coil molecule **1** consisting of hexa-*p*-phenylene rod. As shown in Table 2, both iodonitrobenzene and bromonitrobenzene with phenyl boronic acid in aqueous solutions of **1** and **3** showed very high reactivity (Table 1, entries 1 and 4, and Table 2, entries 1 and 3). However, the coupling reaction of chloronitrobenzene showed quiet different results. Molecule **1** showed a good yield, 72%; however, molecule **3** based on a shorter rod than **1** showed only 23% yield (Table 1, entry 7, and Table 2, entry 5).

The fluorescence quenching of the rod−coil molecules by adding an aryl halide showed to be consistent with these results. In Figure 4, the quenching of molecule **1** consisting of a longer rod is higher than that of molecule **3**. This result suggests that the longer the rod length, the higher the extent of confinement of the substrates. Besides rod length, the extent of confinement of the substrates can be varied by rod shape. Rod−coil molecule

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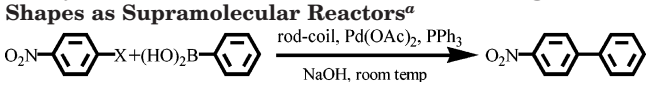
TABLE 2. Suzuki Coupling of Aryl Halide with Phenylboronic Acid with Rods of Different Lengths and Shapes as Supramolecular Reactors[a]



entry	X	rod−coil	yield (%)[b]	entry	X	rod−coil	yield (%)[b]
1	I	3	99	4	Br	4	99
2	I	4	99	5	Cl	3	23
3	Br	3	99	6	Cl	4	70

[a] Reaction conditions: aryl halide (0.1 mmol), aryl boronic acid (0.12 mmol), $Pd(OAc)_2$ (0.5 mol %), PPh_3 (1.0 mol %), NaOH (0.2 mmol), rod−coil (0.025 mmol), H_2O (10 mL), stirring at room temperature for 12 h. [b] Percent yields are calculated on the basis of GC analysis using xylene as the internal standard.

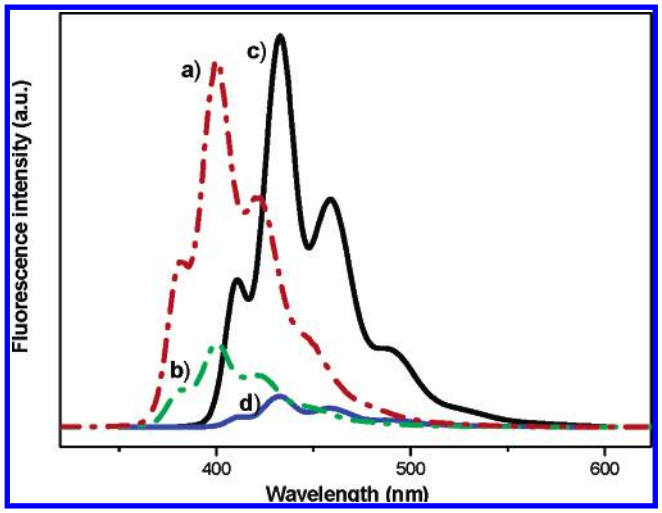
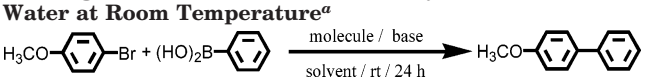


FIGURE 4. Emission spectra of **3** and **1** (2×10^{-4} g/mL in H_2O) by adding (a) and (b) none and (c) and (d) 1-bromo-4-nitrobenzene (0.4 mg), respectively. Excitation wavelength, 308 and 333 nm for **3** and **1**, respectively.

4 consisting of a perylene rod that enabled strong rod-to-rod interaction showed good yields for the coupling reaction of chloronitrobezene as well as iodonitrobenzene and bromonitrobenzene with phenyl boronic acid (Table 2, entries 2, 4, and 6)

Suzuki Coupling Reactions at Very Low Catalyst Loadings. The coupling reaction with loading of low catalytic amount has advantages not only to reduce costs but also to minimize the effort required for the removal of catalytic metal from the final product. Leadbeater and Marco reported a Suzuki-type coupling of a range of aryl halides with phenylboronic acid in water in the presence of tetrabutylammonium bromide (TBAB) without transition-metal catalyst, by using microwave heating.[20] However, their work was reassessed in their recent paper that commercially available Na_2CO_3 used as a base of the coupling reaction includes a small amount of palladium.[21] This observation together with our previous result motivated us to envisage that Suzuki coupling reactions can take place within aromatic bundles in aqueous media at very low catalyst loading. Within the confined environment of the aromatic core of the micelle, the aromatic substrates might be held in enforced proximity to each other. As a result, this constrained environment would lead to a highly concentrated reaction site that lowers the energy barrier for the Suzuki aromatic coupling reaction as described earlier. In consideration of these facts, the use of the aggregate as a supramolecular reactor in aqueous media at very low catalyst loading was investigated with a Suzuki cross coupling reaction of aryl halides and aryl boronic acids at ambient temperature. Remarkably, the cross coupling reaction of 4-bromoanisole with 1.3 equiv of aryl boronic acid took place in the presence of 4 equiv of Na_2CO_3 and 2 wt % of aqueous solution of **1** with 200 ppb Pd catalyst to give the corresponding product with nearly quantitative conversion after 24 h (Table 3, entry 2). However, sodium carbonate in the concentrations used in our experiments included palladium with a concentration of about 50 ppb (induced coupled plasma mass (ICP-mass) spectroscopy result), and then instead of Na_2CO_3, potassium carbonate without Pd trace was used as a base to yield 78% (Table 3, entry 3). When a variety of bases, of the group 1 metal carbonates, were screened, only Na_2CO_3 and K_2CO_3 resulted in acceptable yields of product (Table 3, entries 2 and 3), and Li_2CO_3 and Cs_2CO_3 showed moderate yields (Table 3, entries 1 and 4). Group 2 metal carbonates also showed moderate yield (Table 3, entries 5 and 6), but organic carbonate NH_4CO_3 showed to be inactive (Table 3, entry 7). These results suggest that the cation of the base is important in this reaction, sodium and potassium being particularly good. To investigate this effect more, we performed the reaction by using other sodium- or potassium-containing bases. In the presence of NaOH (Table 3, entry 10), reaction did not occur, different from the 0.5 mol % Pd-catalyzed coupling reaction in a supramolecular reactor,[11] and $NaHCO_3$, NaOAc, and KF showed low yields (Table 3, entries 8, 9, and 11), indicating that anion also is critical in the reaction. In the case of CsF, which has similar basicity, we also

TABLE 3. Suzuki Coupling at Very Low Pd Catalyst Loadings of 4-Bromoanisole and Phenylboronic Acid in Water at Room Temperature[a]



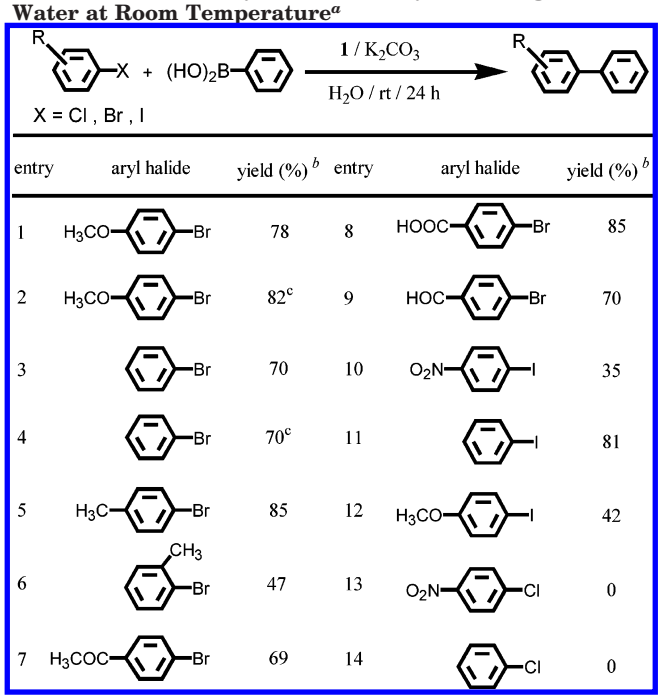
entry	molecule	base	solvent	yield (%)[b]
1	1	Li_2CO_3	H_2O	51
2	1	Na_2CO_3	H_2O	95
3	1	K_2CO_3	H_2O	78
4	1	Cs_2CO_3	H_2O	31
5	1	$MgCO_3$	H_2O	45
6	1	$CaCO_3$	H_2O	45
7	1	NH_4CO_3	H_2O	0
8	1	$NaHCO_3$	H_2O	60
9	1	NaOAc	H_2O	32
10	1	NaOH	H_2O	0
11	1	KF	H_2O	33
12	1	CsF	H_2O	35
13		K_2CO_3	H_2O	0
14	nonionic surfactant[c]	K_2CO_3	H_2O	0
15	1	K_2CO_3	THF	0

[a] Reaction conditions: 4-bromoanisole (0.2 mmol), phenyl boronic acid (0.24 mmol), base (0.8 mmol), molecule (0.05 mol), $Pd(PPh_3)_4$ (200 ppb), and solvent (7 mL), stirred at room temperature for 24 h. [b] Percent yields are calculated on the basis of GC analysis using xylene as the internal standard. [c] Polyethylene-*block*-poly(ethylene glycol) (M_n = 920, 50 wt % ethylene oxide).

(20) (a) Leadbeater, N. E.; Marco, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 1407−1409. (b) Leadbeater, N. E.; Macro, M. *J. Org. Chem.* **2003**, *68*, 5660−5667.

(21) Arvela, R. K.; Leadbeater, N. E.; Sangi, M. S.; Williams, V. A.; Granados, P.; Singer, R. D. *J. Org. Chem.* **2005**, *70*, 161−168.

TABLE 4. Suzuki Coupling of Aryl Halides and Aryl Boronic Acids at Very Low Pd Catalyst Loadings in Water at Room Temperature[a]



entry	aryl halide	yield (%)[b]	entry	aryl halide	yield (%)[b]
1	H_3CO–C$_6$H$_4$–Br	78	8	HOOC–C$_6$H$_4$–Br	85
2	H_3CO–C$_6$H$_4$–Br	82[c]	9	HOC–C$_6$H$_4$–Br	70
3	C$_6$H$_4$–Br	70	10	O_2N–C$_6$H$_4$–I	35
4	C$_6$H$_4$–Br	70[c]	11	C$_6$H$_4$–I	81
5	H_3C–C$_6$H$_4$–Br	85	12	H_3CO–C$_6$H$_4$–I	42
6	CH_3–C$_6$H$_4$–Br	47	13	O_2N–C$_6$H$_4$–Cl	0
7	H_3COC–C$_6$H$_4$–Br	69	14	C$_6$H$_4$–Cl	0

[a] Reaction conditions: aryl halide (0.2 mmol), aryl boronic acid (0.24 mmol), K_2CO_3 (0.8 mmol), **1** (0.05 mmol), $Pd(PPh_3)_4$ (200 ppb), and H_2O (7 mL), stirred at room temperature for 24 h. [b] Percent yields are calculated on the basis of GC analysis using xylene as the internal standard. [c] Reaction using 4-methoxy benzeneboronic acid as the coupling partner.

obtained a low yield (Table 3, entry 12). These effects of base species are well matched with the results reported previously.[20] However, no reaction took place under the aforementioned reaction conditions without **1** (Table 3, entry 13) or in the presence of a conventional nonionic surfactant (Table 3, entry 14). In addition, the reaction did not proceed with the use of tetrahydrofuran (THF) as a solvent (Table 3, entry 15) in which **1** showed a lack of aggregation behavior. Based on these results, it can be concluded that the presence of a bundle-like aromatic core of the aggregates plays a key role in the room-temperature cross coupling reaction with very low transition-metal catalysts in an aqueous environment.

The representative results of the room-temperature cross coupling reaction with a wide range of aryl halides at very low palladium catalyst loading in water are summarized in Table 4. K_2CO_3 with Pd free was used as a base. The reactions of various aryl bromides including electron-rich and electron-deficient substrates proceeded readily and a variety of functional groups were tolerated in the reaction (Table 4, entries 1−9). To show that the reaction is regiospecific with respect to both the aryl bromide and the boronic acid, we screened the reaction of aryl bromides with 4-methoxybenzeneboronic acid and obtained the corresponding product in good yields (Table 4, entries 2 and 4). Furthermore, sterically demanding 2-bromotoluene could be coupled with phenylboronic acid to give moderate yield of product compared with 4-bromotoluene (Table 4, entry 6). The coupling reaction of iodobenzene also proceeded under the same reaction condition to afford the corresponding biphenyl in 81% yield (Table 4, entry 11). Interestingly, aryl iodides with a para-substituent provided lower yields compared with their bromo counterparts (Table 4, entries 10 and 12). Aryl chlorides were not coupled with phenyl boronic acids (Table 4, entries 13−14), which is consistent with the results reported previously.[20] These results indicate clearly that amphiphilic rod−coil systems are well-suited as a supramolecular reactor for aromatic coupling in an aqueous environment at room temperature even in the presence of only trace amounts of Pd.

Conclusion

We have demonstrated that self-assembly of amphiphilic rod−coil molecules in an aqueous solution can be used as supramolecular reactors for the room-temperature Suzuki coupling of a wide range of aryl halides including even aryl chlorides with phenyl boronic acids, giving rise to an environmentally friendly reaction system. When extended rod segments without side groups are used as a reaction template, the coupling reactions can be conducted in excellent yields, indicating that the packing of aromatic segments within aggregates is likely to play a key role in the room-temperature coupling reaction in an aqueous environment. Therefore, a well-designed rod−coil molecule that enabled strong inter-rod interactions can give rise to an efficient supramolecular reactor. Interestingly, at very low Pd loadings coupling reactions occur, without conventional heating or microwave, at room temperature for a wide range of aryl halides. These observations highlight the ability of supramolecular rod bundles to provide confined space for the aromatic substrates of the Suzuki cross coupling reaction. We believe that this supramolecular approach to a reactor in an aqueous environment will be broadly applicable to a wide variety of catalytic chemical reactions.

Experimental Section

Materials. All starting materials were obtained from commercial suppliers and were used without purification. All atmosphere-sensitive reactions were done under nitrogen. Flash column chromatography was carried out with silica gel (230−400 mesh). Molecules **1** and **7** were synthesized according to a previous procedure.[11] Compounds were synthesized according to the procedure described in Scheme 1 and purified by silica gel column chromatography and then prep-HPLC until the transition temperature and polydispersity index remained constant.

Techniques. Molecular weight distributions (M_w/M_n) were determined by gel permeation chromatography (GPC). Measurements were made by using an UV detector, $CHCl_3$ as a solvent (1.0 mL min^{-1}), and a calibration plot constructed with polystyrene standards. The dynamic laser light scattering experiments were performed with an aqueous solution of rod−coil molecule (2×10^{-4} g/mL) at a scattering angle of 90°. The transmission electron microscope (TEM) was performed at 120 kV. A drop of aqueous solution of rod−coil molecule (2×10^{-4} g/ mL) was placed onto a carbon-coated copper grid and dried at room temperature.

Synthesis. The synthetic procedures used in the preparation of the compounds are described in Scheme 1.

Synthesis of 2. Compound **7** (4.0 g, 4.08 mmol) and 3,3′-dimethyl-4,4′-biphenyldiboronic acid (0.50 g, 1.85 mmol) were dissolved in degassed THF (70 mL). Degassed 2 M aqueous Na_2CO_3 (70 mL) was added to the solution and then tetrakis(triphenylphosphine) palladium(0) (22 mg, 0.018 mmol) was added. The mixture was heated at reflux for 48 h with vigorous

stirring under nitrogen. Cooled to room temperature, the layers were separated, and the aqueous layer was then washed twice with methylene chloride. The combined organic layer was dried over anhydrous magnesium sulfate and filtered. The solvent was removed in a rotary evaporator, and the crude product was purified by column chromatography (silica gel) using methlylene chloride: methanol (8:1 v/v) as eluent to yield 1.8 g (48.6%) of a waxy solid. ^{1}H NMR (250 MHz, $CDCl_3$, ppm): δ 7.75−7.57 (m, 18H), 7.00 (d, 4H, J = 8.7 Hz), 4.18 (t, 4H, J = 4.9 Hz), 3.89−3.52 (m, 132H), 3.36 (s, 6H), 2.43 (s, 6H). ^{13}C NMR (250 MHz, $CDCl_3$, ppm): δ 158.5, 139.8, 139.5, 128.0, 127.4, 127.3, 115.0, 77.6, 77.1, 76.6, 71.9, 70.8, 70.6, 69.7, 67.5, 59.0, 14.6. M_n/M_w = 1.06 (GPC). Anal. Calcd for $C_{108}H_{170}O_{36}$: C, 63.45; H, 8.38. Found: C, 63.44; H, 8.37.

Synthesis of 3. A mixture of compound **7** (4.0 g, 4.0 mmol), TDAE (1.6 g, 8.0 mmol), and $PdCl_2(PhCN)_2$ (0.08 g, 0.2 mmol) in DMF (50 mL) was heated at 50 °C for 4 h. Cooled to room temperature, the layers were separated, and the aqueous layer was then washed twice with methylene chloride. The combined organic layer was dried over anhydrous magnesium sulfate and filtered. The solvent was removed in a rotary evaporator, and the crude product was purified by column chromatography (silica gel) using methylene chloride: methanol (8:1 v/v) as eluent to yield 2.1 g (54.8%) of a white solid. ^{1}H NMR (250 MHz, $CDCl_3$, ppm): δ 7.51−7.67 (m, 12H), 6.93−6.95 (d, 4H, J = 8.5 Hz), 4.12−4.14 (t, 4H, J = 5.0 Hz), 3.53−3.75 (m, 132H), 3.36 (s, 6H). ^{13}C NMR (250 MHz, $CDCl_3$, ppm): δ 158.5, 139.8, 139.5, 128.0, 127.4, 127.3, 115.0, 77.6, 77.1, 76.6, 71.9, 70.8, 70.6, 69.7, 67.5, 59.0. M_n/M_w = 1.07 (GPC). Anal. Calcd for $C_{94}H_{158}O_{36}$: C, 60.56; H, 8.54. Found: C, 60.56; H, 8.50.

Synthesis of 5. A solution of ROTs (4.5 g, 0.9 mmol) and sodium azide (2.9 g, 4.5 mmol) in 50 mL of acetonitrile was heated under reflux at 100 °C for 36 h. After cooling to room temperature, 100 mL of water was added and the mixture was extracted with methylene chloride. The organic layer was then dried on $MgSO_4$ and concentrated. A slightly yellow-brown oil was chromatographed on silica gel column and eluted with CH_2Cl_2/MeOH (10:1 v/v). Pure product was obtained as oil, 3.4 g (81% yield). ^{1}H NMR (250 MHz, $CDCl_3$, ppm): δ 3.77−3.59 (m, 66H), 3.40 (t, 2H, J = 5.0 Hz), 3.37 (s, 3H).

Synthesis of 6. 5 (2.7 g, 7.4 mmol), triphenylphosphine (2.3 g, 9.0 mmol), and water (540 mg, 11 mmol) were mixed with 20 mL of THF. After the solution was stirred for 6 h at room temperature, the solvent was eliminated under reduced pressure and the residue was loaded on a silica gel column; the product was eluted with $CHCl_3/CH_3OH/Et_3N$ (3:3:1). The pure product was obtained as oil, 2 g (80% yield). ^{1}H NMR (250 MHz, $CDCl_3$, ppm): δ 3.77−3.59 (m, 66H), 3.40 (s, 3H), 2.82 (t, 2H, J = 5.0 Hz).

Synthesis of 4. 6 (0.7 g, 2.6 mmol) and 3,4,9,10-perylene-tetracarboxylic anhydride (0.39 g, 1.0 mmol) were added to a mixture of 50 mL of propan-1-ol and 25 mL of water. The reaction mixture was stirred under argon at 100 °C for 16 h. After the solution was chilled, a mixture of popan-1-ol and water was removed by distillation and the crude product was purified by column chromatography with CH_2Cl_2/MeOH (20:1 v/v) as an eluent and by preparative HPLC to yield 0.76 g (76%) of a red solid. ^{1}H NMR (250 MHz, $CDCl_3$, ppm): δ 8.56 (d, 4H, J = 8.1 Hz), 8.48 (d, 4H, J = 8.1 Hz), 4.32 (t, J = 5.7 Hz, 4H), 3.77−3.59 (m, 132H), 3.47 (s, 6H). ^{13}C NMR (250 MHz, $CDCl_3$, ppm): δ 162.7, 133.7, 131.2, 123.9, 122.1, 77.6, 77.1, 76.6, 71.9, 70.8, 69.7, 67.5, 59.0. M_n/M_w = 1.04 (GPC). Anal. Calcd for $C_{94}H_{150}N_2O_{38}$: C, 58.92; H, 7.89; N, 1.46. Found: C, 58.91; H, 7.90; N, 1.45.

General Procedure for Cross Coupling Reaction in Water. Aryl halide (0.1 mmol), aryl boronic acid (0.12 mmol), base (0.4 mmol), PPh_3 (0.001 mmol, 1.0 mol %), and $Pd(OAc)_2$ (0.0005 mmol, 0.5 mol %) were added to the solution of rod−coil molecule (50 mg) in water (10 mL). The reaction mixture was stirred at room temperature for 24 h. The product was extracted with methylene chloride, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was then removed in a rotary evaporator, and the residue was filtered by column chromatography (silica gel) using methylene chloride: hexane (1:1 v/v) as eluent. The yield of the reaction was determined by GC-MASS analysis.

General Procedure for Cross Coupling Reaction in Water at Low Pd Loadings. Aryl halide (0.2 mmol), aryl boronic acid (0.24 mmol), base (0.8 mmol), and $Pd(PPh_3)_4$ (200 ppb) were added to the solution of **1** (0.05 mmol) in water (7 mL). The reaction mixture was stirred at room temperature for 24 h. The product was extracted with methylene chloride, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was then removed in a rotary evaporator, and the residue was purified by column chromatography (silica gel) using methylene chloride: hexane (1:1 v/v) as eluent.

GC-MS Analysis. Reference samples of the substrate, product, byproducts, and xylene (internal standard) with known concentrations were injected to identify the retention time and response factor. Individual response factors [area (product) × mg (standard)/area (standard) × mg (product)] were determined for all products by GC analysis. Determination of the ratio of the area of each product to the area of xylene obtained from GC run of the reaction mixture allowed calculation of the percent yields. Temperature program: 100 °C for 3 min and then 30 °C/min to 280 °C. Apart from comparing the product and byproduct peaks to the standard (xylene) peaks under identical conditions, their authenticity was further confirmed by comparing their mass spectra with those of the actual compound in the spectral library.

ICP-Mass Analysis. We screened elements such as Pd, Ni, Co, Cr, Cu, Mn, Pt, Ru, Se, and Zn. The reaction mixture was analyzed three times and averaged.

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Supporting Information Available: General method for fluorescence measurement, TEM data, the wide-angle X-ray scattering data, NMR data, and MALDI-TOF mass data. This material is available free of charge via the Internet at http://pubs.acs.org. This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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