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Cylindrical Micelles with “Patchy” Coronas from the Crystallization-Driven Self-Assembly of ABC Triblock Terpolymers with a Crystallizable Central Polyferrocenyldimethylsilane Segment

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ABSTRACT

Solution self-assembly of a series of linear ABC triblock terpolymers with a central crystallizable poly(ferrocenyldimethylsilane) (PFS) core-forming “B” block, and terminal polystyrene (PS) and poly(methylmethacrylate) (PMMA) “A” and “C” blocks has been investigated. Three PS-b-PFS-b-PMMA triblock terpolymers with different block ratios (1: 3.6 : 1.0 : 4.7, 2: 7.0 : 1.0 : 6.9, and 3: 1.1 : 1.0 : 1.6) but with similar degrees of polymerization for the central PFS block were prepared through a combination of living anionic and atom-transfer radical polymerization techniques, together with azide/alkyne “Click” chemistry. Cylindrical micelles with a crystalline PFS core were formed in solvents selective for the terminal PS and PMMA blocks. In ethyl acetate, a slightly more selective solvent for the PS block, cylinders with significant microphase separation within the corona in the dry state were observed based on TEM analysis. The use of acetone, which is slightly more selective for the PMMA block than PS, led to more distinct microphase separation to generate a “patchy” coronal morphology. Living crystallization-driven self-assembly studies in acetone allowed the formation of uniform cylindrical micelles and block comicelles of controlled length with “patchy” coronal segments by seeded growth methods.
INTRODUCTION

Block copolymers (BCPs) have been extensively studied over the past few decades due to their ability to undergo self-assembly both in the solid and solution states to yield a variety of nanoscale functional materials and a range of applications.\textsuperscript{1-8} The use of synthetic protocols, such as anionic and controlled radical polymerization, and “Click” reactions, has permitted access to a wide range of BCP building blocks with tailored segment chemistries. Self-assembly of these materials in block-selective solvents has been used to obtain a wide range of micellar nanoparticle morphologies.\textsuperscript{14, 9} Additional complexity can be introduced by blending two or more block copolymers, which has been shown to facilitate the formation of micelles with phase-separation within either the core, or the corona.\textsuperscript{10-12} Furthermore, self-assembly of multiblock copolymers such as ABC linear terpolymers and multiarm star polymers\textsuperscript{13-14} has allowed the preparation a variety of structures such as Janus particles\textsuperscript{15-16} and nanostructures with either core or corona compartmentalization.\textsuperscript{14, 16-22} Such assemblies have been shown to undergo further hierarchical self-assembly,\textsuperscript{16, 23} and have been used as emulsion stabilisers,\textsuperscript{24} in drug delivery,\textsuperscript{25-27} in catalysis,\textsuperscript{28} and other applications.\textsuperscript{1-3}

Recent work has shown that the incorporation of a crystallizable core-forming block within a BCP provides a promising route to prepare micellar nanoparticles with less common morphologies such as cylinders and platelets via a process known as “crystallization-driven self-assembly” (CDSA).\textsuperscript{29-48} Spherical micelles with crystalline cores are much rarer but have also been prepared.\textsuperscript{42-43} CDSA has been reported for a range of crystallizable BCPs, most extensively for polyferrocenyldimethylsilane (PFS) BCPs.\textsuperscript{45} Significantly, it has also been demonstrated in a growing number of cases that the termini of crystalline micelle cores are active towards the epitaxial growth of further added BCP in a process termed “living CDSA”, by analogy with living covalent polymerization of molecular monomers.\textsuperscript{49-50} This approach allows the preparation of uniform samples of 1D and 2D micelles with considerable complexity and excellent control over their dimensions. Typically living CDSA is implemented in the form of a seeded growth method\textsuperscript{49-50} where a known amount of BCP unimer can be added to preformed “seed” micelles, which are usually prepared by vigorous sonication of polydisperse micelles as a precursor.
These yields monodisperse assemblies of predictable length in both 1D and 2D via the epitaxial growth from the seed micelle termini. This methodology has provided routes to uniform block comicelles in 1D\textsuperscript{32, 49} and 2D,\textsuperscript{51-53} branched structures,\textsuperscript{54} non-centrosymmetric unidirectional micelles\textsuperscript{55,56} and their use as building blocks for hierarchical assembly.\textsuperscript{57} Living CDSA has since been extended to a range of other crystalline core-forming BCP systems, including poly(ferrocenyldimethylgermane),\textsuperscript{32, 58} polyethylene,\textsuperscript{42} polylactide,\textsuperscript{36} poly(3-hexylthiophene),\textsuperscript{40, 59} and molecular species that self-assemble through π-stacking and other non-covalent interactions.\textsuperscript{50-65}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Schematic representations of the living CDSA of (A) a PFS-\textit{b}-PIP BCP with a crystallizable PFS core and a homogeneous PIP corona (PFS = orange, PIP = blue) and (B) a PS-\textit{b}-PE-\textit{b}-PMMA triBCP with a crystallizable PE core and a compartmentalized corona of PS and PMMA (PS = light grey, PE = dark grey, PMMA = purple).}
\end{figure}

The overwhelming majority of examples of living CDSA for BCPs with a crystallizable core-forming block are for simple AB diblock copolymers, which form micelle segments with homogenous coronal structures. However, by using ABC triBCPs, the formation of cylindrical micelles with “patchy” coronas has been recently achieved. Thus, Schmalz and co-workers have previously reported the preparation of “patchy” cylinders with a crystalline PE (PE = polyethylene) core and a compartmentalized corona of
alternating regions of PS (PS = polystyrene) and PMMA (PMMA = polymethylmethacrylate) via the self-assembly of a PS-\textit{b}-PE-\textit{b}-PMMA triBCP (Figure 1B).\textsuperscript{30, 35, 42, 46} This ABC triBCP was also shown to undergo living CDSA and triblock comicelles with a continuous PE core were also reported.\textsuperscript{42} The “patchy” coronal structure was attributed to the immiscibility of the two corona forming PS and PMMA blocks. Moreover, functionalization of the patches has allowed the binding of gold nanoparticles permitting applications as supports in catalysis.\textsuperscript{28, 46}

The preparation of micellar assemblies with a phase-separated corona from BCPs with a crystallizable PFS core-forming block has also been explored. Initial studies in which solution self-assembly of two PFS-containing BCPs, PFS-\textit{b}-PIP (PIP: polyisoprene) and PFS-\textit{b}-PDMS (PDMS: poly(dimethylsiloxane)), were co-assembled surprisingly did not afford micelles with detectable coronal phase separation despite the more significant incompatibility of the two coronal blocks compared to PS and PMMA.\textsuperscript{66} Nevertheless, gradient-type cylindrical micelles with a “patchy” coronal structure were formed through the seeded co-assembly of a linear and \textit{n}-alkyl-functionalized brush PFS-\textit{b}-PMVS (PMVS: poly(methylvinylsiloxane)) BCPs.\textsuperscript{67} In addition, a miktoarm-star PFS-containing terpolymer, PS-\textit{arm}-PI-\textit{arm}-PFS, was shown to form cylinders with a crystalline PFS core and a “patchy” corona consisting of phase-separated PS and PI.\textsuperscript{68} However studies of linear ABC triBCPs with a central PFS block have not been reported. Herein, we report an exploration of the CDSA and coronal microphase separation for a range of PS-\textit{b}-PFS-\textit{b}-PMMA triBCPs which provides a convenient route to uniform micelles with patchy coronas.
EXPERIMENTAL SECTION

Materials

Anhydrous solvents were obtained using a modified Grubbs system of alumina columns manufactured by Anhydrous Engineering. THF was distilled from Na/benzophenone under nitrogen immediately prior to use. Cyclohexane was washed with concentrated sulphuric acid, 10 mol % sodium hydroxide solution, distilled water, and was finally dried over CaH₂ before distillation. Dichlorodimethylsilane was purchased from Aldrich, distilled under nitrogen and freeze-pump-thawed three times prior to use. Styrene was purchased from Acros, dried over CaH₂ and distilled twice under reduced pressure. Methyl methacrylate was purchased from Aldrich and passed through a basic alumina column prior to use. 4-((trimethylsilyl)ethynyl)benzaldehyde was sublimed onto a cold finger and stored under nitrogen. sec-butyllithium (s-BuLi) (1.4M in THF) were purchased from Aldrich and used as received. All other reagents were used as received.

Synthesis of alkyne-functionalized polystyrene-block-polyferrocenylsilane (PS-b-PFS) diblock copolymers

The method outlined below for 4a was used for the preparation of all PS-b-PFS diblock copolymers. Styrene (1.20 mL, 12 mmol) in cyclohexane (6 mL) was initiated with sec-butyllithium (42.8 µL, 60 µmol) at room temperature and a colour change from colourless to orange was observed. After 2 h, an aliquot for analysis was taken and subsequently dimethylsil[a]ferrocenophane (262 mg, 1.08 mmol) in THF was rapidly added and this reacted for a further 1 h, noting a colour change from orange to amber. 4-((trimethylsilyl)ethynyl)benzaldehyde (61 mg, 0.3 mmol) in THF (1 mL) was added and allowed to quench the reaction for 1 h to ensure complete end-capping. The diblock copolymer was precipitated three times into methanol and dried in a vacuum oven overnight, affording a pale orange powder. The diblock copolymer was then dissolved in in THF/MeOH (10:1 v/v, 25 mL total) and to this was added sodium methoxide (50 mg). The reaction mixture was allowed to stir overnight at room temperature. The material was purified by precipitation three times into methanol and dried overnight in a vacuum oven (1.129 g, 93 %). ¹H NMR (400 MHz, CD₂Cl₂): 0.56 (s, 6H, SiMe₂), 1.44-2.48 (br, 1H, CH₂CH(Ph)), 4.12 (m, 4H, Cp),
4.28 (m, 4H, \(Cp\)), 6.41-7.21 (br, 5H, CH\(_2\)CH(Ph)); \(M_n\) (GPC) = 24.7 kg/mol, \(M_w/M_n\) = 1.04; block ratio = 3.6 : 1.0.

**Synthesis of azide-terminated poly(methyl)methacrylate (PMMA) homopolymers**

The method outlined below for \(5a\) was used for the preparation of all PMMA homopolymers. Methyl methacrylate (2.66 mL, 25.0 mmol), 2-azidoethyl-2-bromoisorbutyrate (8.20 \(\mu\)L, 0.05 mmol) \(N,N,N',N',N''\)-pentamethyldiethylenetriamine (PMDETA) (5.22 \(\mu\)L, 0.025 mmol) and dry toluene (2.5 mL) were added to a dried Young’s tube fitted with a stirrer bar. The mixture was freeze-pump-thawed three times to remove oxygen. The reaction vessel was transferred to a glovebox and copper (I) bromide (3.58 mg, 0.025 mmol) was added to the mixture. The polymerisation was carried out at 80 °C for 2 h. To terminate the polymerisation, the reaction vessel was rapidly cooled to room temperature and immediately exposed to air. Copper salts were removed by passing the mixture through a short basic alumina column and the material was purified by precipitation three times into methanol (693 mg, 28 %). \(^1\)H NMR (400 MHz, CDCl\(_3\)): 0.73-1.28 (br, 3H, \(\alpha\)-CCH\(_3\)), 1.34-2.10 (br, 2H, \(\alpha\)-CCH\(_2\)), 3.59 (s, 3H, -OCH\(_3\)); \(M_n\) (GPC) = 38.1 kg/mol, \(M_w/M_n\) = 1.09.

**Preparation of PS-b-PFS-b-PMMA triblock terpolymers via CuAAC “Click” Reaction**

The procedure for all the coupling reactions for the preparation of all PS-b-PFS-b-PMMA triblock terpolymers follow the same protocol, which is outlined below for \(1\). Alkyne-functionalized PS-b-PFS (100 mg, 1.88 \(\mu\)mol) and azide-functionalized PMMA (121 mg, 2.82 mmol) were dissolved in dry THF (10 mL) in a dried Young’s tube fitted with a stirrer bar. The reaction vessel was transferred to a glovebox and PMDETA (3.93 \(\mu\)L, 18.8 mmol) was added to the mixture, followed by copper (I) bromide (2.70 mg, 18.8 mmol). The reaction had a molar ratio of [PS-b-PFS]:[PMMA]:[PMDETA]:[CuBr] of [1]:[1.5]:[10]:[10] and was allowed to proceed at 50 °C for 48 h. The reaction was stopped by cooling to room temperature and exposing to air. Copper salts were removed by passing the reaction mixture through a basic alumina column. The material was purified by precipitation into methanol three times and by size exclusion chromatography (SEC) to remove unreacted PMMA, yielding a pale orange powder (68 mg, 38 %). \(^1\)H NMR (400 MHz, CDCl\(_3\)): 0.56 (s, 6H, SiMe\(_2\)), 0.73-1.28 (br, 3H, \(\alpha\)-CCH\(_3\)), 1.34-2.48 (br,
1H, CH₂CH(Ph); 2H, α-CCH₂), 3.59 (s, 3H, -OCH₃), 4.12 (m, 4H, Cp), 4.28 (m, 4H, Cp), 6.41-7.21 (br, 5H, CH₂CH(Ph)); Mₙ (GPC) = 88.1 kg/mol, Mₘ/Mₙ = 1.13; block ratio = 7.0 : 1.0 : 6.9.

**Self-Assembly of PS-b-PFS-b-PMMA Triblock Terpolymers**

Direct dissolution studies were performed by making up a 0.1 mg/mL suspension of the PS-b-PFS-b-PMMA triblock terpolymer in the desired solvent. The mixture was heated up to 55 °C (in acetone), 75 °C (in EtOAc), or 100 °C (in DMAA) for 1 h, and subsequently cooled slowly to room temperature (23°C), before allowing the samples to age for a minimum of 24 h. The samples were analyzed by TEM and DLS.

**Living CDSA of PS-b-PFS-b-PMMA Triblock Terpolymers**

Seed micelles of PS-b-PFS-b-PMMA triblock terpolymers were prepared by sonicating a 0.1 mg/mL solution of polydisperse micelles in a sonic bath at 0 °C for 2 h. The seed micelles were characterized by TEM by drop-casting an aliquot of the seed solution onto a carbon-coated copper grid.

Seeded growth studies were undertaken by adding a known amount of PS-b-PFS-b-PMMA triblock terpolymer unimer in THF (5 mg/mL, between 1 and 20 µL) to a colloidal solution of seed micelles (50 µL, 0.1 mg/mL) diluted in acetone (200 µL). The sample was gently stirred for 2 s and then left to age for 24 h. The samples were analyzed by TEM. Multiple TEM images were obtained and the contour lengths were measured for a minimum of 200 micelles.

Further self-assembly experimental procedures are outlined in the Supporting Information.
RESULTS AND DISCUSSION

1. Synthesis and Characterization of PS-b-PFS-b-PMMA Triblock Terpolymers (1-3)

A series of linear PS-b-PFS-b-PMMA triBCPs (1 - 3, see Table 1) with different degrees of polymerization (DP$_n$) and block ratios were prepared through a combination of living anionic polymerization, living radical polymerization and “Click” chemistry (Scheme S1). The central PFS “B” block was maintained at a similar length (DP$_n$ ca. 50), whilst the lengths of the two corona forming blocks were varied. Initially, PS-b-PFS diblock copolymers were synthesized by sequential living anionic polymerization of styrene and dimethylsila[1]ferrocenophane (Scheme S1A). The reaction was terminated by the addition of a protected alkyne moiety, 4-[(trimethylsilyl)ethynyl]benzaldehyde, and the resulting polymer was subsequently deprotected post-polymerization to yield alkyne-terminated BCPs in good yield (90 - 94%) (4a - 4c, see Table S1 and Scheme S1B). Separately, PMMA homopolymers were prepared by atom-transfer radical polymerization using an azide-functionalized initiator, 2-azidoethyl-2-bromoisobutyrate in moderate yield (31 - 58%), yielding polymer chains with a terminal azide group (5a - 5c, see Table S1 and Scheme S1C). Azide-capped PMMA and alkyne-functionalized PS-b-PFS BCP were reacted together by a Cu(I)-catalyzed azide/alkyne Huisgen cycloaddition (Scheme S1D), followed by purification by size-exclusion chromatography to give the desired pure triBCPs 1-3 as pale orange powders (33 - 43% yield).

Characterization was achieved by gel permeation chromatography (GPC), $^1$H NMR spectroscopy, and matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry. GPC analysis showed all prepared materials possessed narrow molecular weight distributions (PDI < 1.13) (see Figures S1-S3). The block ratios of the synthesized triBCPs were determined by $^1$H NMR through comparative integration of the phenyl peaks on PS (δ = 6.41 - 7.21), the cyclopentadienyl protons of PFS (δ = 4.12, 4.28) and the methoxy peaks on PMMA (δ = 3.59). This data was used in conjunction with the absolute molecular weights of the PS block as determined by GPC using a triple detector array (6a - 6c), and corroborated with MALDI-TOF, to give the composition of the final materials. Analytical data for all the polymers prepared are outlined in Table 1 and Table S1.
Table 1. Characterization data of PS-b-PFS-b-PMMA triBCPs prepared, including number-average molecular weight ($M_n$), degree of polymerisation (DP$_n$), block ratio and polydispersities (PDI).

<table>
<thead>
<tr>
<th>Composition $^{a,b}$</th>
<th>Material</th>
<th>Block Ratio PS / PFS / PMMA$^a$</th>
<th>Total Core : Corona Ratio $^{a,c}$</th>
<th>$M_n$ / kg.mol$^{-1}$$^{a,b}$</th>
<th>PDI$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS$<em>{143}$-b-PFS$</em>{40}$-b-PMMA$_{188}$</td>
<td>1</td>
<td>3.6 : 1.0 : 4.7</td>
<td>1.0 : 8.3</td>
<td>60.5</td>
<td>1.13</td>
</tr>
<tr>
<td>PS$<em>{384}$-b-PFS$</em>{55}$-b-PMMA$_{381}$</td>
<td>2</td>
<td>7.0 : 1.0 : 6.9</td>
<td>1.0 : 13.9</td>
<td>88.1</td>
<td>1.13</td>
</tr>
<tr>
<td>PS$<em>{53}$-b-PFS$</em>{49}$-b-PMMA$_{70}$</td>
<td>3</td>
<td>1.1 : 1.0 : 1.6</td>
<td>1.0 : 2.7</td>
<td>24.2</td>
<td>1.05</td>
</tr>
</tbody>
</table>

$^a$ Determined by $^1$H NMR through comparative integration of aromatic protons (5H) of PS, methyl protons (6H) of PFS and methoxy protons (3H) of PMMA, $^b$ Determined by GPC with a triple-detector array, $^c$ Molar ratio.

2. Self-Assembly of PS-b-PFS-b-PMMA Triblock Terpolymers (1-3)

a. Self-Assembly of PS$_{143}$-b-PFS$_{40}$-b-PMMA$_{188}$ (1)

The first material to be studied was PS$_{143}$-b-PFS$_{40}$-b-PMMA$_{188}$, 1, (subscripts denote DP$_n$ for each block) with a core (B) to total coronal (A and C) block ratio of 1.0 : 8.3. Based on the differences in the solubility parameters of the three blocks (see Table S2), and also the differences in the solubility behaviour of samples of the homopolymers PS$_{143}$ and PMMA$_{188}$ corresponding to the corona-forming segments, different solvents that were all poor solvents for PFS were selected for self-assembly studies. Dimethylacetamide (DMAA, a good solvent for the PS block), ethyl acetate (EtOAc, a good solvent for both the PS and PMMA blocks, but slightly more favourable for PS) and acetone (a solvent that is slightly more selective for the PMMA block than the PS segment) were chosen to explore how differences in the solvent selectivity would affect the self-assembly behavior (see Table S2 for reference). In a typical self-assembly experiment, samples were made by a direct dissolution method, whereby a 0.1 mg/mL suspension of 1 in each selective solvent was prepared. The mixture was heated to slightly below the boiling point of the solvent (DMAA = 100 °C, EtOAc = 75 °C, acetone = 55 °C) for 1 h to dissolve the samples, and then was left to cool slowly (rate = 1 °C/min) to room temperature (23 °C). The samples were aged for a minimum of 24 h and the resulting micelles were analyzed by transmission electron
microscopy (TEM) by drop-casting and subsequent solvent evaporation of the colloidal micelle solution onto a carbon-coated copper grid.

In DMAA, mixed micelle morphologies were observed after 48 h comprising both long fibrous bundles of apparent tape-like structures together with spherical micelles (Figure S4A and S4B). In EtOAc, no micelles were observed after 48 h, but after aging for 7 days, cylindrical micelles were detected by TEM together with a film presumably derived from unimer (Figure S4C). The slow self-assembly in this case may be a consequence of the similarity in the solubility parameters for EtOAc and the core-forming PFS block (Table S2).69 Self-assembly in acetone was more rapid and TEM showed the exclusive formation of long polydisperse cylindrical micelles after 48 h (Figure 2A and S4D) and dynamic light scattering (DLS) studies were consistent with their formation in solution rather than on solvent evaporation prior to TEM analysis (see Figure S5). No further changes were detected by TEM after monitoring the solutions over several months.

![Figure 2.](image)

**Figure 2.** (A) TEM micrograph of cylindrical micelles of PS$_{143}$-b-PFS$_{40}$-b-PMMA$_{188}$, 1, prepared in and drop-cast from acetone; (B) TEM micrograph image of cylindrical micelles of 1 drop-cast from EtOAc
and subsequently exposed to RuO₄ to stain PS coronal chains, showing the less distinct compartmentalization of the coronal chains; (C) TEM micrograph images and (D) (inset of (C)) higher magnification TEM image of cylindrical micelles of 1 drop-cast from acetone and subsequently exposed to RuO₄, showing a compartmentalized coronal structure; (E) a schematic representation of “patchy” cylindrical micelle formation. Scale bars are (A) 2000 nm; (B), (D) 100 nm; (C) 200 nm.

To provide further insight, the coronal structure of the micelles formed by the self-assembly of 1 in all three solvents was probed by TEM following selective staining of the PS block with RuO₄ vapour. Stained samples were prepared by exposing a freshly drop-cast sample on a TEM grid to an aqueous RuO₄ solution for ca. 16 h. The irregular ribbon-like micelles prepared in DMAA displayed no discernible phase separation within the corona of the micelles (Figure S6). As DMAA is a selective solvent for the PS block a mixed PFS/PMMA core may be formed in this case and the corona may consist entirely of the PS block. In the case of the cylinders formed in EtOAc (a good solvent for PS and PMMA, but slightly more selective for PS) some microphase separation within the micelle corona was detected, however this is difficult to discern, and there is little regularity to the patch size and location (Figure 2B). However, micelles prepared by the self-assembly of 1 in acetone, which dissolves PMMA and PS but is more selective for the former, showed the formation of distinct alternating patches of PS (dark patches due to staining with RuO₄) and PMMA (light patches) along the backbone of the cylindrical micelles (see Figure 2C, 2D, S6B and S6C). The solvent selectivity of acetone therefore appears to facilitate the formation of patchy coronas (Figure 2E) compared to the case where EtOAc was used.

b. Self-Assembly of PS₃₈₁-b-PFS₅₅-b-PMMA₃₈₈, (2), and PS₅₃-b-PFS₄₉-b-PMMA₇₀, (3)

In order to investigate how altering the coronal block lengths might affect the coronal compartmentalization of the PS and PMMA blocks during micellization, the self-assembly of PS₃₈₁-b-PFS₅₅-b-PMMA₃₈₈, 2, and PS₅₃-b-PFS₄₉-b-PMMA₇₀, 3, was studied. BCP 2 had longer PS and PMMA blocks than in 1, with a core (B) to total coronal (A and C) block ratio of 1.0 : 13.9 (compared to 1.0 : 8.3
for 1). BCP 3, on the other hand, had significantly shorter A and C blocks than the other two materials, with a total block ratio of core- to total corona-forming blocks of 1.0 : 2.7. In a similar manner to the initial studies for 1, DMAA, EtOAc and acetone were investigated as the solvent systems for self-assembly of 2 and 3, and samples were prepared by direct dissolution method as outlined previously. The self-assembly of 2 and 3 was primarily investigated by TEM, but was also monitored by DLS (see Figure S8 and S11 respectively).

**Figure 3.** (A) TEM micrograph image of aggregated cylindrical micelles of PS$_{381}$-b-PFS$_{55}$-b-PMMA$_{388}$, 2, prepared in and drop-cast from acetone; (B) higher magnification TEM micrograph image illustrating the compartmentalized coronal structure in acetone. Scale bars are (A) 2000 nm; (B) 100 nm.

TEM analysis revealed that the self-assembly of 2 in the three solvents was broadly similar to that of 1. When DMAA was used as the selective solvent, spherical micelles were initially observed after 48 h (Figure S7A), which evolved into long fibrous structures over a period of 2 weeks (Figure S7B). Based on similar behaviour for other crystallizable BCPs, this transformation is likely driven by the crystallization
of the PFS core forming block. Cylindrical micelles were observed after 48 h when EtOAc was used as a selective solvent. However significant amounts of unimer were still observable by TEM analysis after several weeks, as small regions of unimer film were shown to be present (Figure S7C). These micelles did not appreciably evolve over time and, unlike in the case of 1, unimer film was still present even after aging for 3 months. It is likely that the longer corona-forming blocks in 2 hinder crystallization of the PFS block. In acetone, morphologically pure cylindrical micelles of 2 were obtained, although these structures formed large aggregates that were several microns in diameter based on analysis by TEM (Figure 3A, S7D). This feature can also be attributed to the increase in length of the PS block as it has been shown for other micellar systems with a PS corona-forming block that aggregation occurs during solvent evaporation, resulting in difficulties in structural analysis. Interrogation of the coronal microstructure along the backbone of assemblies formed from 2 by TEM showed no discernible coronal phase separation in DMAA (Figure S9A), whilst poorly-defined “patchiness” was detected in EtOAc (Figure S9B). In acetone, despite the formation of large aggregates, distinct alternating patches of PS and PMMA were clearly observed along the length of the cylinders (Figure 3B). Staining was unnecessary for these samples due to the greater PS block length, which increased the resolution of the PS patches (dark) compared to those of PMMA patches (light), therefore giving effective contrast between the two compartments by TEM.

For the case of triBCP 3, with shorter corona-forming blocks compared to 1 and 2, large bundles of fiber-like structures with irregular widths were observed after self-assembly in DMAA (Figure S10A), whilst only unimer film was detected in EtOAc (Figure S10B). This persisted over a period of several weeks with no morphological evolution. Short cylindrical micelles were formed in acetone, the majority of which grouped together to form large aggregates (Figure S10C). Upon changing the solvent system to 1 : 1 (v/v) acetone/EtOAc, much longer cylindrical micelles were formed, although these still aggregated extensively. The small number of individual cylinders that were separated from these aggregates showed evidence for regions of larger core diameter, suggesting that the decreased coronal bulk in 3 leads to a situation that is close to the onset of the formation of 2D-type platelet structures (Figure S10D). However,
it is likely that in order to be able to exclusively form 2D platelet-type micelles, the block ratio would need to be reduced even further (a total core- to corona-forming block ratio closer to 1 : 1 would be necessary based on previous work with PFS diBCPs). Unlike the cases of 1 and 2, interrogation of the corona structure by TEM did not show any discernible coronal microphase separation after staining with RuO₄ for any sample derived from 3 (Figure S12A and S12B). This is postulated to be a consequence of the reduced overall coronal block length. It is likely that the coronal chains do not extend very far from the micelle core, reducing the propensity for phase separation and, at the same time, making it more difficult to resolve any coronal compartmentalization. Additionally, a threshold DPₙ of the two corona-forming blocks may need to be attained to allow phase separation to occur as a result of PS and PMMA only being weakly incompatible.

3. Seeded Growth Studies involving PS-b-PFS-b-PMMA triblock terpolymers (1-3)

Living CDSA was initially explored for triBCP 1 (see Figure 4 for schematic representation). Seed micelles of 1 were formed by sonicating a 0.1 mg/mL acetone solution of polydisperse cylinders for 2 h at 0 °C in an ultrasonic bath. This afforded seed micelles with a relatively narrow length distribution (Lₙ = 92 nm, Lₙ/Lₙ = 1.12) (Figure 5A). Subsequently, a known amount of unimer solution of 1 in THF (10 mg/mL) was added to a solution of the seed micelles in acetone at various unimer-to-seed ratios (from 1 : 1 to 20 : 1). The resulting solution was then stirred vigorously for 5 s and left to age for 24 h. An aliquot corresponding to each unimer-to-seed ratio was taken and then analyzed after drying by TEM following solvent evaporation. The resulting solutions showed that the length of the cylindrical micelles grew as the amount of unimer of 1 increased, with micelle lengths varying from 130 nm to 2060 nm with low length dispersities (Lₙ/Lₙ < 1.1, where Lₙ and Lₙ are the weight- and number-average length, respectively) and no visible alteration in the widths of the micelles (ca. 17 nm) (Figures 5B-E). The lengths of the micelles increased linearly with the amount of unimer added, indicating that this was a living CDSA process (Figure 5F and S13). Significantly, the compartmentalization of the coronal structure was preserved for all samples independent of the amount of unimer added. Some aggregation of micelles occurred at higher
unimer-to-seed ratios, presumably caused by the increased PS content of the individual micelles, which has been shown to increase micelle aggregation as noted earlier.\textsuperscript{30, 40} However, this did not greatly affect the analysis of the resulting micelles.

**Figure 4.** Schematic representation of the preparation of monodisperse cylindrical micelles with coronal compartmentalization from PS-$b$-PFS-$b$-PMMA triblock terpolymers.

At the very high unimer-to-seed ratio of 20 : 1, some film, presumably derived from unimer of 1, was detected on the TEM grids. This suggested that the self-assembly was not 100\% complete after the initial 24 h self-assembly period. Upon analyzing samples after ageing for 7 d, the length of the micelles had not altered significantly and the film was still detected (Figure S14). As the lengths of the micelles prepared were close to the expected theoretical values based on the amount of unimer added, this suggests that only a small percentage of triBCP 1 does not add to the seeds over this time period. However, it is still possible that the CDSA of 1 is slower than that of its corresponding BCPs (PS-$b$-PFS and PFS-$b$-PMMA). The increased steric bulk as a consequence of having two separate coronal blocks around the central crystallizable core-forming PFS could inhibit the rate at which free unimer can crystallize on the micelle terminus. Additionally, there may be a preferred orientation in certain solvents which induce the formation of a microphase-separated coronal structure (such as acetone) for the incoming unimer of 1 to add onto the seed micelle, which in turn could influence the speed of self-assembly.
Figure 5. (A) TEM micrograph of seed micelles of 1 prepared by sonication for 2 h at 0 °C \( (L_n = 92 \text{ nm}, \frac{L_w}{L_n} = 1.12) \); inset (A) is a magnified images of the representative seed micelles; (B)-(E) (and insets) TEM micrographs of near monodisperse cylindrical micelles drop-cast from acetone prepared by “living” CDSA by the addition of (B) 1, (C) 2, (D) 8 and (E) 20 equivalents of unimer 1, insets (B)-(E) are higher magnification images of the representative micelles; (F) graph showing the linear dependence of micelle length to the unimer-to-seed ratio of 1. Scale bars are (A)-(E) 2000 nm; (A)-(E) (insets) 250 nm.

Living CDSA experiments were then repeated with triBCP 2, with longer coronal chains compared to 1. A 0.1 mg/mL solution of polydisperse cylinders of 2 was sonicated in acetone for 2 h at 0 °C using a sonic bath to yield crystallite seed micelles with a narrow length distribution \( (L_n = 101 \text{ nm}, \frac{L_w}{L_n} = 1.14) \) (Figure S15A). The seed micelles were difficult to analyze in terms of their dimensions due to considerable aggregation, presumably caused by the presence of long PS corona chains. Despite this, seeded growth proceeded similarly to the case of 1 (Figure S15G and S16), affording micelles that also
exhibited coronal compartmentalization with lengths ranging from 130 nm to 1080 nm. By this method, the cylinders were prepared with excellent apparent control over the micelle lengths, narrow length distributions and no change in the micelle widths (see Figures S15B-F). Once the unimer-to-seed ratio increased to greater than 10 substantial aggregation was observed, which made length analysis of these micelles challenging as very few single micelles could be identified.

Seeded growth of triBCP 3 was also conducted similarly to the cases of 1 and 2 using seeds (\(L_n = 88\) nm, \(L_w/L_n = 1.09\)) (Figure S17A) which readily aggregated, presumably in this case due to the presence of shorter corona blocks which lower the colloidal stability (Figure S18A). However this was alleviated by dilution of the seed micelles in \(n\)-butyl acetate, a high boiling point solvent that is good for both the corona-forming blocks (Figure S18B). Micelles of controlled length were obtained, with cylinders up to 850 nm (Figure S17B-E) with narrow length dispersities (<1.05) and the micelles formed grew linearly with the addition of known amounts of triBCP unimer (Figure S17F and S19). However, presumably due to the short length of the PS and PMMA corona-forming blocks, it was not possible to discern any “patchiness” for the cylindrical micelles in this case. Additionally, as greater unimer-to-seed ratios were used, noticeable branching of the micelles from regions of larger core thickness was observed (Figure S20A and S20B). This is likely a consequence of the core to overall corona block ratio of the triBCP (1.0 : 2.7) which, as previously noted, may be close to that for the onset of 2D micelle formation.\(^{29, 32, 51}\) Core regions of greater thickness are likely to behave similarly to platelets with respect to living CDSA and cylinder growth from their edges has been well documented.\(^{32, 52-53}\)

4. **Block Comicelle Formation of PS-b-PFS-b-PMMA Triblock Terpolymers (1-2)**

We also explored the preparation of triblock comicelles with patchy coronas using triBCPs 1 and 2. To this end, monodisperse PFS\(_{50}\)-b-P2VP\(_{675}\) (P2VP: poly(2-vinylpyridine)) seed micelles (\(L_n = 150\) nm, \(L_w/L_n = 1.07\)) were selected to allow effective differentiation during imaging between the central block with a homogeneous P2VP corona and the outer blocks that were expected to exhibit a “patchy” corona. The seed micelles were diluted in acetone and a known amount of unimer solution of 1 in THF (10 mg/mL)
was added to the seed solution. The sample was vigorously mixed for 5 s, left to age to for 24 h and analyzed by TEM after solvent evaporation. Although elongation from the termini of the seed micelles was evident, aggregation of the micelles was prominent, although a clear difference in the electron density of the central PFS-\textit{b}-P2VP block and the outer blocks derived from 1 was apparent (Figure S21A). To counter this, EtOAc was then used as the solvent. The micelles formed in EtOAc were much shorter than those in acetone, implying the self-assembly was much slower, a possible consequence of the similarity in solubility parameters between the PFS block and the solvent (Figure S21B). This was corroborated when the lengths of the micelles formed in EtOAc was significantly shorter than expected ($L_n = 738$ nm, predicted length = 2280 nm). Presumably because EtOAc is only a marginal solvent for the P2VP corona, TEM analysis showed that the resulting triblock comicelles stacked together through the central PFS-\textit{b}-P2VP segment, forming short train track-type aggregates. A mixed solvent system of acetone/EtOAc (1 : 1 (v/v)) was therefore used to minimise the two different competing forms of aggregation. This solvent system worked successfully, affording long well-dispersed cylindrical micelles with lengths that correlated well with the predicted length ($L_n = 2330$ nm) (Figure 6A).

Inspection of the coronal structure of the outer blocks showed clear microphase separation of the PS and PMMA chains, with alternating patches apparent along the length of the outer blocks (Figure 6B and S21C, see Figure 6C for a schematic representation of this). There is some slight tapering of the micelle when grown from the PFS-\textit{b}-P2VP seed (see the top section of 1 grown from the PFS-\textit{b}-P2VP seed micelle in Figure 6B). This can be attributed to the difference in the DP$_n$ of the PFS block; initially the incoming triBCP will add to give the same core width as that of the seed, but this will slowly revert to the preferred core width of 1 as the block comicelle grows, affording the observed tapered structure.$^{54}$
Figure 6. TEM micrographs of block comicelles prepared from PFS-$b$-P2VP seed micelles following the addition of unimer 1 in (A) acetone/EtOAc (1 : 1 (v/v)); (B) magnified TEM micrograph showing the compartmentalization of the coronal chains along the micelle backbone, inset is a schematic of the formation of block comicelles with “patchy” outer blocks off PFS-$b$-P2VP seed micelles; (C) schematic representation of the preparation of monodisperse cylindrical block comicelles micelles with a central PFS-$b$-P2VP block and outer 1 blocks exhibiting coronal compartmentalization. Scale bars are (A) 2000 nm; (B) 200 nm.

Block comicelle formation was also explored for triBCP 2 using PFS-$b$-P2VP seed micelles as the central block. As expected, the longer PS chains led to greater degrees of micellar aggregation during TEM analysis of the block comicelles compared to the case of 1. Stacks of shorter micelles were observed in EtOAc (Figure S22A), whereas very large aggregates of long cylinders were observed in acetone (Figure
S22B). A 1 : 1 (v/v) solvent mixture of acetone/EtOAc was also investigated, although some micelle aggregation still occurred (Figure S22C). For non-aggregated micelles in both acetone and acetone/EtOAc as solvents, compartmentalization of the two coronal blocks was evident from alternating light and dark patches along the micelle outer segments (Figure S22D and S22E).

Block comicelles were also prepared using the two triBCPs 1 and 2 to form the alternating segments. First, to seeds of 1 in acetone was added a unimer solution of 2. TEM images clearly showed the formation of block comicelle structures by comparison of the coronal blocks for the different segments (Figure 7A and S23A, see Figure 7C for a cartoon representation). The much longer chain lengths of the corona-forming block present in the outer blocks derived from 2 is clearly evident. Next, triblock comicelles were prepared using the reverse sequence involving the addition of unimers of 1 to seeds derived from 2. As expected, an inverted coronal structure was observed by TEM, with greater coronal bulk evident within the central segments compared to the outer blocks (Figure 7B and S23B, see Figure 7D for a cartoon representation). Furthermore, in both sets of samples, the compartmentalization of the coronal chains was present throughout all of the segments present in the comicelles.

Figure 7. TEM micrographs of representative triblock comicelles prepared from monodisperse “patchy” seed micelles when drop-cast from acetone; (A) a triblock comicelle with a central seed segment
composed of 1, with outer blocks derived from unimers of 2; (B) a triblock comicelle with a central seed segment composed of 2, with outer blocks derived from unimers of 1; (C) and (D) cartoon representations of structures observed in (A) and (B) respectively, highlighting the different patchy coronal segments. Scale bars are 200 nm.
SUMMARY

PS-\textit{b}-PFS-\textit{b}-PMMA triBCPs 1 – 3 have been prepared through a combination of living anionic polymerization, atom-transfer radical polymerization and “Click” chemistries, and their self-assembly behavior in non-solvents for the crystallizable central PFS core-forming block has been studied. The most distinct coronal phase separation was observed after self-assembly of triBCP 1 in acetone, which is more selective for the PMMA block than PS, and the resulting cylindrical micelles possessed a clear “patchy” corona structure. Self-assembly in EtOAc, a good solvent for both corona-forming blocks and less poor for PFS, was much slower and led to cylinders with a lower degree of coronal segregation. For the triBCP 2 with longer coronal chains, coronal compartmentalization was also detected, but this was not observed for triBCP 3, with shorter coronal chains compared to those of 1. In the latter case, the coronal chains are apparently insufficiently long for phase separation either to take place, or to be detected, within the corona.

Living CDSA seeded growth approaches allowed the preparation of uniform cylindrical micelles and triblock comicelles of controlled length ($L_w/L_m < 1.1$, up to 2000 nm) with coronal compartmentalization in selected segments. The results described also provide some additional insight into CDSA processes for BCPs in general. Self-assembly for triBCPs with a central crystallizable block may be slower than for analogous diBCPs with similar core : corona block ratios. It appears that the presence of a corona-forming block at each terminus of the core-forming segment in the unimer significantly hinders addition to the exposed crystal faces at the seed termini.

As part of our future work, the self-assembly behavior of other triBCPs with a crystallizable core-forming block will be explored. For example, we will target triBCPs corona-forming blocks that can allow post-self-assembly modification to afford micellar structures with functional patches. Additionally, whether the size of the patches can be tuned and if they can be utilized to influence the formation of secondary structures will be interrogated. Development of triBCPs with a core: total corona block ratio closer to 1 : 1 should allow the formation of “patchy” 2D assemblies and this is also currently under investigation.
SUPPORTING INFORMATION

Experimental details for the polymer synthesis, polymer characterization data, figures showing GPC traces, DLS data, TEM images, and histogram plots.
REFERENCES


