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Fluorinated Microgel Star Polymers as Fluorous Nanocapsules for Encapsulation and Release of Perfluorinated Compounds

Yuta Koda, Takaya Terashima, and Mitsuo Sawamoto

Fluorinated microgel star polymers were designed and synthesized as fluorous nanocapsules for the encapsulation and release of perfluorinated compounds. Five types of these fluorostar polymers were obtained by ruthenium-catalyzed linking reaction of chlorine-capped poly(methyl methacrylate) arms (macroinitiators) with a perfluorinated dimethacrylate linker and a perfluorinated methacrylate (RfMA), so as to tune the in-core fluorous properties depending on the latter structure and fluorous content. $^{19}$F nuclear magnetic resonance and $^{19}$F spin–spin relaxation time ($T_2$) measurements revealed that the mobility of the in-core perfluorinated pendant derived from RfMA decreased with increasing the number of fluorine and carbon atoms, or the pendant length. The cores effectively recognized and encapsulated perfluorinated guest compounds (e.g., perfluoroctane and perfluoromethylcyclohexane), and the encapsulation depended on the fluorous properties of the structures and fluorous nature of RfMA and the guests. For example, encapsulation was promoted with increasing the number of in-core fluorine and CF$_3$ groups, and typically the core with perfluorodecyl pendants successfully captured perfluorinated esters and ketones. In addition, fluorinated star polymers could reversibly capture and thermo-responsive release a perfluorinated guest, indicating the encapsulation is selective but dynamic and stimuli-responsive.

Introduction

“Fluorophilicity” is a key character of perfluorinated compounds and related materials, which are generally immiscible with hydrophobic (lipoiphilic) and hydrophilic solvents and compounds.1–15 Because of this unique feature, perfluorinated materials are widely employed in industry and academic research; e.g., as water/oil repellents, surfactants, and surface coating agents,5,6 as well as key players in catalysis (for facile product separation, etc.).2,4,7 Molecular recognition,8–10,12,13,14 and unique self-assembly,11–13 In particular, the functionalization of perfluorinated polymers with hydrophobic and/or hydrophilic segments is promising in creating globular macromolecules with fluorous inner compartments that are fully solubilized and/or dispersed in common organic solvents and water.8–13 Such fluorous compartments have been created within microgel-core star polymers,8,9 micelles,11–13 and the related self-assembly molecules,10,14 typically applicable to molecular encapsulation vessels.

Microgel-core star polymers possess covalently crosslinked microgels in the center that are solubilized and covered with plenty of linear arm polymers (10 – 100),16–22 in sharp contrast to micelles, vesicles, polymersomes, and nanogels that are based on the physical association of amphiphilic and/or functional polymers.23 The microgel cores of star polymers have large free spaces and lots of cavities24 to afford functional compartments that typically serve as nanocapsules for molecular capture and release and nanoreactors for catalysis.8,9,16,17,24–29 In general, microgel star polymers are obtained from the cross-linking reaction of living linear polymers or macroinitiators (arm) with divinyl monomers (core-forming agent) in living polymerization.30–34 Focusing on the high versatility and functionality tolerance, we have employed ruthenium-catalyzed living radical polymerization30 for the arm-linking reaction with functional linking agents and monomers, to directly produce various core-functionalized star polymers with amide,24 phosphine,25–27 amine,27 hydroxyl,24,27 ionic,28 and perfluorinated groups.8,9 Importantly, the arm-linking method not only gives functionalized microgels but also affords the efficient and local accumulation of functional groups into microgel cores.
In particular, fluorinated microgel star polymers have been recently developed as fluorous compartments soluble in organic solvents and aqueous media to encapsulate and separate perfluorinated guest compounds. The fluorous microgels were created by the accumulation of a perfluorinated alkane methacrylate (13FOMA) and the solubility was controlled by the surrounding arm polymers: i.e., hydrophobic poly(methyl methacrylate) (PMMA) and the molecular recognition and the mobility of the in-core perfluorinated pendants decreased with increasing the number of fluorine atom and CF₃ groups such as ester and keto functions. The fluorous microgels can thus efficiently recognize and tightly encapsulate perfluorinated guest compounds.

Herein, we report the synthesis of various fluorinated microgel star polymers (S1–S5) via living radical polymerization to create fluorous nanocapsules for the capture and stimuli-responsive release of perfluorinated compounds in organic media (Scheme 1). The in-core fluorous properties are effectively controlled with various perfluorinated alkyl methacrylates (R₇MA), affording the efficient recognition of various perfluorinated guest compounds.

**Scheme 1** (a) Synthesis of fluorinated microgel star polymers (S1-S5) via ruthenium-catalyzed living radical polymerization and (b) encapsulation and release of perfluorinated compounds with fluorinated star polymers.

S1–S5 were directly prepared by ruthenium-catalyzed linking reaction of a chlorine-capped poly(methyl methacrylate) (PMMA-CI) with a perfluorinated alkyl spacer dimethacrylate (12FODMA) in the presence of R₇MA. The star polymers were characterized by size exclusion chromatography coupled with multi-angle laser light scattering (SEC-MALLS) and ¹H and ¹⁹F NMR spectroscopy. Confirmed by ¹⁹F T₂ measurements, the mobility of in-core perfluorinated pendants decreased with increasing the number of fluorine atom and CF₃ end-group in R₇MA. Fluorinated star polymers efficiently encapsulated perfluorinated alkanes and the derivatives with functional groups such as ester and ketone, where the fluorous recognition is dependent on in-core R₇MA species. The key was to increase fluorous interaction between the perfluorinated pendants and guest molecules.
Experimental Section

Materials  
*For Monomer Synthesis and Perfluorinated Guests.* 1H,1H,2H,2H-nonafluoro-1-hexanol (TCI, purity > 97%), 1H,1H,7H-dodecafluoro-1-heptanol (TCI, purity > 97%), 1H,1H,2H,2H-perfluoro-7-methyloctan-1-ol (Wako), 1H,1H,2H,2H-heptadecafluoro-1-decanol (TCI, purity > 96%), perfluoromethylcyclohexane (PFMCH: TCI, purity > 95%), perfluoroctane (PFO: Aldrich, purity > 98%), perfluorohexane (PFH: TCI, purity > 95%), methyl perfluorooctanoate (PFO-ester: TCI, purity > 97%), methyl perfluorohexyl ketone (PFHp-ketone: TCI, purity > 95%), and 1H,1H-perfluorooctanol (PFO-OH: Aldrich, purity > 98%) were used as received. Methacryloyl chloride (TCI, purity > 80.0%) and triethylamine (TCI, purity > 99.0%) were purified by distillation before use. Tetrahydrofuran (Wako, dehydrated), dichloromethane (Wako, dehydrated), triethylamine (TCI, purity > 97%), methyl methacrylate (MMA: TCI, purity > 99.0%), ethyl acrylate (ECA: Aldrich), and 1,8,7,4-heptadecafluoro-1,2,3,4-heptanol (TCI, purity > 97%), 1,8-dodecafluorooctanol (Wako), decanol (TCI, purity > 96%), 1H,1H,7H-dodecafluoro-1,8-octanediol dimethacrylate (12FODMA) was prepared according to the previous literature8 and degassed before use. 1H,1H,2H,2H-Perfluorohexyl methacrylate (9FHxMA), 1H,1H,7H-perfluoro-1-heptyl methacrylate (12FHPMA), 1H,1H,2H,2H-perfluoro-7-methyloctyl methacrylate (15FOMOA), and 1H,1H,2H,2H-perfluorodecyl methacrylate (17FDeMA) were prepared as shown below and degassed before use. Ethyl-2-chloro-2-phenylacetate (ECPA: Aldrich, purity > 97%) was purified by distillation under reduced pressure before use. Ru(Ind)Cl2(PPh3)2 (Ind: indenyl, Aldrich) was handled in a grove box under a moisture- and oxygen-free argon atmosphere (H2O < 1 ppm, O2 < 1 ppm). n-Bu4N+ (TCI, purity > 98%) was purged by argon before use. Tetralin (1,2,3,4-tetrahydrophthalene; TCI, purity > 98%), as an internal standard for the conversion of 12FODMA and perfluorinated monomers determined by 1H NMR, was dried over calcium chloride overnight and distilled from calcium hydride. Toluene (Kishida Chemical, purity > 99%) was purified by passing it through a purification column (Solvent Dispensing System, glass contour, HANSEN&CO., LTD) before use.

Characterization  
Molecular weight distribution curves, number-average molecular weight ($M_n$), and dispersity ($M_w/M_n$) of the polymers were measured by SEC (shodex GPC-104) in THF at 40 °C (flow rate: 0.3 mL/min) on three polystyrene gel columns (shodex LF-404: exclusion limit = 2 × 10^6 g/mol; particle size = 6 μm; pore size = 3000 Å; 0.46 cm i.d. × 25 cm) that were connected to a shodex DU-H2000 pump, a shodex RI-74 refractive index detector, and a shodex UV-41 UV detector set at 250 nm. The columns were calibrated against 13 standard poly(MMA) samples (Polymer Laboratories; $M_n = 620 – 1200000$; $M_w/M_n = 1.02 – 1.30$). 1H and 13C NMR spectra were recorded in CDCl3, CD2Cl2, and DMF-d7 at room temperature or 30 °C on a JEOL JNM-ECA500 spectrometer, operating at 500.16 (1H) or 470.62 (13C) MHz. For characterization and molecular encapsulation experiments, polymers were purified by preparative SEC in CHCl3 at room temperature (flow rate: 10 mL/min) on a polystyrene gel column (K-5003: exclusion limit = 7 × 10^4 g/mol; particle size = 15 μm; 5.0 cm i.d. × 30 cm) that was connected to a Jasco PU-2086 precision pump, a Jasco RI-2031 refractive index detector, and a Jasco UV-2075 UV/vis detector set at 250 nm. Absolute weight-average molecular weight ($M_w$) and radius of gyration ($R_g$) of star polymers were determined by multi-angle laser light scattering (MALLS) equipped with SEC on a Dawn E instrument (Wyatt Technology, Ga-As laser, $λ = 690$ nm). The SEC was performed in DMF containing 10 mM LiBr at 40 °C (flow rate: 1 mL/min) on three linear-type polystyrene gel columns (shodex KF-805L: exclusion limit = 4 × 10^5 g/mol; particle size = 10 μm; pore size = 5000 Å; 0.8 cm i.d. × 30 cm) that were connected to a Jasco PU-2080 precision pump, a Jasco RI-1530 refractive index detector, and a Jasco UV-1570 UV/vis detector set at 270 nm. The refractive index increment (dn/dc) was measured in DMF at 40 °C on an Optilab DSP refractometer (Wyatt Technology, $λ = 690$ nm, $c < 3.3$ mg/mL).

Synthesis of Perfluorinated Monomers  
*9FHxMA.* In 200 mL round-bottomed flask filled with argon, methacryloyl chloride (143.3 mmol, 13.9 mL) was added to a solution of 1H,1H,2H,2H-nonafluoro-1-hexanol (95.5 mmol, 25.2 g) and triethylamine (143.3 mmol, 19.9 mL) in dry THF (50 mL) at 0 °C. The reaction mixture was stirred at 25 °C for 24 h. After the evaporation of the reaction solution, diethyl ether (150 mL) and distilled water (150 mL) were poured into the flask. The aqueous phase was separated and extracted by diethyl ether (150 mL), and the ether extracts were combined with the organic layer. The combined organic phase was washed with water three times. After the ether was removed by evaporation, the crude product was purified by silica gel column chromatography (the bottom and top layers were covered with sodium sulfate) with hexane/ethyl acetate (10/1, v/v) as an eluent. The solution was evaporated in vacuo to dryness to give colorless liquid of 9FHxMA. Yield: 21.9 g (69%). $δ_F$ (500 MHz; CDCl3; chloroform) 6.13 (1H, m), 5.60 (1H, m), 4.45 (2H, $J = 6.6$ Hz), 2.51 (2H, $J = 18.3$, $J_{HF} = 6.6$ Hz) 1.94 (3H, $J = 1.4$ Hz). $δ_C$ (125 MHz; CDCl3; chloroform) 166.9 (C), 136.0 (C), 126.0 (CH2), 117.6 (CH2F2, tt, $J_{CF} = 255.5$, $J_{HF} = 32.4$ Hz), 117.1 (CF3, qt, $J_{CF} = 287.9$, $J_{HF} = 33.6$ Hz), 112.9 – 106.7 (CF2/CF2, m), 56.3 (CH2), 30.5 (CH2, $t, J_{HF} = 22.8$ Hz), 17.9 (CH3). $δ_p$ (470 MHz; CDCl3; chloroform) 4.90 (2H, $J = 7.0$ Hz) 2.51 (2H, $J = 18.3$, $J_{HF} = 6.6$ Hz) 1.94 (3H, $J = 1.4$ Hz). $δ_F$ (500 MHz; CDCl3; chloroform) 6.13 (1H, m), 5.60 (1H, m), 4.45 (2H, $J = 6.6$ Hz), 2.51 (2H, $J = 18.3$, $J_{HF} = 6.6$ Hz) 1.94 (3H, $J = 1.4$ Hz). $δ_C$ (125 MHz; CDCl3; chloroform) 166.9 (C), 136.0 (C), 126.0 (CH2), 117.6 (CH2F2, tt, $J_{CF} = 255.5$, $J_{HF} = 32.4$ Hz), 117.1 (CF3, qt, $J_{CF} = 287.9$, $J_{HF} = 33.6$ Hz), 112.9 – 106.7 (CF2/CF2, m), 56.3 (CH2), 30.5 (CH2, $t, J_{HF} = 22.8$ Hz), 17.9 (CH3). $δ_p$ (470 MHz; CDCl3; chloroform) 4.90 (2H, $J = 7.0$ Hz)
In 300 mL round-bottomed flask filled with argon, methacryloyl chloride (222.7 mmol, 21.5 mL) was added to a solution of 1H,1H,2H,2H-perfluoro-7-methyloctan-1-ol (47.3 mmol, 19.6 g) and triethylamine (71.0 mmol, 9.9 mL) in dry dichloromethane (50 mL) at 0 °C. The reaction mixture was stirred at 25 °C for 24 h. After the evaporation of the reaction solution, diethyl ether (150 mL) and distilled water (150 mL) were poured into the flask. The aqueous phase was separated and extracted by diethyl ether (150 mL), and the ether extracts were combined with the organic layer. The combined organic phase was washed with water three times. After the ether was removed by evaporation, the crude product was purified by silica gel column chromatography (the bottom and top layers were covered with sodium sulfate) with hexane/ethyl acetate (10/1, v/v) as an eluent. The solution was evaporated in vacuo to dryness to give colorless liquid of 15FMOMA. Yield: 22.8 g (80%). 

15FMOMA. In 300 mL round-bottomed flask filled with argon, methacryloyl chloride (71.0 mmol, 6.9 mL) was added to a solution of 1H,1H,2H,2H-perfluoro-7-methyloctan-1-ol (47.3 mmol, 19.6 g) and triethylamine (71.0 mmol, 9.9 mL) in dry dichloromethane (50 mL) at 0 °C. The reaction mixture was stirred at 25 °C for 24 h. After the evaporation of the reaction solution, diethyl ether (150 mL) and distilled water (150 mL) were poured into the flask. The aqueous phase was separated and extracted by diethyl ether (150 mL), and the ether extracts were combined with the organic layer. The combined organic phase was washed with water three times. After the ether was removed by evaporation, the crude product was purified by silica gel column chromatography (the bottom and top layers were covered with sodium sulfate) with hexane/ethyl acetate (10/1, v/v) as an eluent. The solution was evaporated in vacuo to dryness to give colorless liquid of 15FMOMA. Yield: 22.8 g (80%). 

Synthesis of Fluorinated Microgel Star Polymers

The synthesis of star polymers (S1-S5) were carried out by syringe technique under argon in baked round-bottomed flasks equipped with a three-way stopcock.

S1: In a 200 mL round-bottomed flask, Ru(Ind)Cl(PPh3)2 (0.220 mmol, 171 mg) was placed. Into this flask, toluene (58.1 mL), tetrafluoroethylene (4.7 mL), 400 mM toluene solution of n-BuN (2.2 mmol, 5.5 mL), MMA (441 mmol, 47.2 mL), and ECPA (2.2 mmol, 0.38 mL) were added sequentially in this order at 25 °C under argon (total volume: 116 mL). The solution (25 mL) was distributed into four 100 mL round-bottomed flasks to prepare PMMA arms for star polymers (S1, S2, S4, S5). The flask with 25 mL polymerization solution was placed in an oil bath at 80 °C. After 14 h (48% conversion: by 1H NMR), the solution was evaporated in vacuo to 25 °C to give PMMA-Cl (Mn = 12000, Mn/Mw = 1.13, 0.47 mmol) with non-volatile agents (tetrafluoroethylene, n-BuN, and Ru catalyst). Into this flask, toluene (18.7 mL), a 1100 mM toluene solution of 12FODMA (2.5 mmol, 2.25 mL), and a 3290 mM toluene solution of 9FHXMA (5.0 mmol, 1.5 mL) were added consecutively in this order at 25 °C and the flask was placed in an oil bath at 80 °C. After 18 h, the reaction was terminated by cooling the mixture to -78 °C (conversion of 12FODMA/9FHXMA: 90%/79% by 1H NMR). The quenched reaction mixture was evaporated to dryness. The resulting crude was purified by preparative SEC in CHC13 (to remove catalysts and unreacted arm residue and monomers) and dried under vacuum to give S1. Star yield (SEC): 78%. dm/dc (DMF) = 0.029. SEC-MALLS (DMF, 0.01 M LiBr): Mn = 461000 g/mol; arm numbers = 23; Rg = 13 nm, df (500 MHz; CD2Cl2; chloromethane) 7.3 – 7.1 (aromatic), 6.2, 5.7 (olefin), 4.8 – 3.9 (COCH2CH2CF2), 4.7 – 4.6 (COCH2CF2), 4.1 –
at 25 °C solution of 12FODMA (2.5 mmol, 2.25 mL), and a 1490 mM Bu₃Li (21 mmol) round 74.4 (6.2, 5.7 (olefin), 4.8 0.4 (ketone), 6.2, 5.7 (olefin), 4.8 – 3.9 (COCH₂CF₂₇), 4.7 – 4.6 (COCH₂CF₂), 4.1 – 3.9 (COCH₂CH₃), 3.8 – 3.4 (COCH₂CH₃), 3.8 – 3.4 (COCH₂CH₃), 1.12.2 – 1.12.1 (COCH₂CF₂), -121.4 – -121.5 (COCH₂CF₂CF₂), -125.1 – -126.6 (COF₂CF₂CF₂), -126.6 – -128.1 (COF₂CF₂).

S2: PMMA-CI was prepared as shown in S1. Into the 100 mL round-bottomed flask containing PMMA-CI (Mₚ = 12000, Mₚ/Mₙ = 1.13, 0.47 mmol) and non-volatile agents (tetrahydrofuran, n-Bu₃N, and Ru catalyst), toluene (18.7 mL), a 1110 mM toluene solution of 12FODMA (2.5 mmol, 2.25 mL), and a 2690 mM toluene solution of 12FHPMA (5.0 mmol, 1.86 mL) were added at 25 °C, and the flask was placed in an oil bath at 80 °C. After 18 h, the reaction was terminated by cooling the mixture to -78 °C (total conversion: 85% by ¹H NMR). The quenched reaction mixture was evaporated to dryness. The resulting crude was purified by preparative SEC in CHCl₃ (to remove catalysts and unreacted arm residue and monomers) and dried under vacuum to give S2. Star yield (SEC): 77%. 

SEC-MALLS (DMF, 0.01 M LiBr): Mₚ = 599000 g/mol; arm numbers = 42; Rₛ = 21 nm.  

Monomers) and dried under vacuum to give S3. Star yield (SEC): 73%. 

SEC-MALLS (DMF, 0.01 M LiBr): Mₚ = 59400 g/mol; arm numbers = 42; Rₛ = 21 nm.  

19F T₂ Measurements

Degassed solutions of star polymers (S1-S5: 50 mg) in DMF-d₇ (1 mL) were added into NMR tubes by syringe and the tubes were sealed under nitrogen before ¹⁹F NMR analysis. ¹⁹F T₂ values were determined by the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence using 32 values of τ, with a minimum value of 0.1 ms and the maximum value of 0.2 s. The NMR samples were not spun for the measurement. The number of scans was set at 128. Other parameters were as follows: spectral width = 30 ppm; 90° pulse width = 13.4 μs; relaxation delay = 1 s; data points = 32768.

Encapsulation of Perfluorinated Compounds

Encapsulation of perfluorinated compounds (PFMCH, PFO, PFH, PFO-ester, PFHp-ketone, PFO-OH) with S1-S5 was evaluated by ¹⁹F NMR.

PFMCH, PFO, and PFH: In a 6 mL vial, the guests (0.2 mL) were respectively added into the solution of a star polymer (S1-S5, 70 mg) in DMF-d₇ (1.4 mL). The mixture was vigorously stirred at room temperature for 24 h. After the emulsion mixture was kept calmly for a few days, the solution was separated into two phases. The upper transparent layer containing a guest and a star polymer was analyzed by ¹⁹F NMR.

PFO-ester and PFHp-ketone: In a 6 mL vial, the guests (0.2 mL) were respectively added into a solution of a star polymer (S3 or S5: 50 mg) in DMF-d₇ (0.8 mL). The dispersed mixture was vigorously stirred at room temperature for 24 h. After the solution was kept calmly for a few hours, the solution was separated into two phases. The upper transparent layer containing a guest and a star polymer was analyzed by ¹⁹F NMR.

PFO-OH: In a 6 mL vial, a DMF-d₇ solution of a star polymer (S3 or S5: 50 mg/mL, 1.0 mL) was added to PFO-OH (17.2 mg). The homogeneous mixture was stirred at room temperature for 24 h. The solution was then analyzed by ¹⁹F NMR.
Results and Discussion

Synthesis of Fluorinated Microgel Star Polymers

Five kinds of fluorinated microgel star polymers (S1-S5) were designed with methacrylates carrying different perfluorinated alkyl pendants (RfMA) as core-fluorination groups: 1H,1H,2H,2H-perfluorohexyl methacrylate (9FHxMA), 1H,1H,7H-perfluoroheptyl methacrylate (12FHpMA), 1H,1H,2H,2H-perfluoroocetyl methacrylate (13FOMA), 1H,1H,2H,2H-perfluoro-0-methylethyl methacrylate (15FOMOA), 1H,1H,2H,2H-perfluorodecyl methacrylate (17FDeMA). The fluorous nature of the monomers with CF3 end group would increase with the fluorine numbers in the perfluorinated pendants, while 12FHpMA may have properties distinct from the others because of no CF3 end group.

The star polymers were synthesized by Ru(Ind)Cl(PPh3)2/n-Bu3N-catalyzed linking reaction of a chlorine-capped PMMA [PMMA-Cl: degree of polymerization (DP) = ~100] with 2,2,3,3,4,4,5,5,6,6,7,7-dodecafluoro-1,8-octanediol dimethacrylate (12FODMA) (m = [12FODMA]/[PMMA-Cl]0 = 5) in the presence of RfMA (n = [RfMA]/[PMMA-Cl]0 = 10). MMA was first polymerized with Ru(Ind)Cl(PPh3)2/n-Bu3N (catalyst) and ethyl-2-chloro-2-phenylacetate (ECPA: chloride initiator) in toluene at 80 °C for 14 h (conversion: 48%) to give well-controlled PMMA-Cl with narrow molecular weight distribution (Mw = 12000, Mw/Mn = 1.13). After the removal of the residual MMA from the reaction vessel (by evaporation in vacuo at 25 °C), a toluene solution of 12FODMA and RfMA was then added into the vessel containing the PMMA-Cl and was then added into the vessel containing the PMMA-Cl and

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*a* S1-S5 was prepared by ruthenium-catalyzed linking reaction of PMMA-Cl (S1, S2, S4, S5: Mw = 12000, Mw/Mn = 1.13; S3: Mw = 10500, Mw/Mn = 1.14) with 12FODMA and RfMA: [PMMA-Cl]0/[12FODMA]0/[RfMA]0/[Ru(Ind)Cl(PPh3)2][n-Bu3N]0 = 17/85/170/1.7 mEq in toluene at 80 °C; m = [12FODMA]0/[PMMA-Cl]0 = 5; n = [RfMA]0/[PMMA-Cl]0 = 10.

b Monomer conversion determined by 1H NMR with internal standard (tetralin). S2: total monomer conversion.

c Yield of star polymers in products, calculated from the SEC curve area ratio.

d Weight average molecular weight (Mw) and molecular weight distribution (Mw/Mn) determined by SEC in THF with PMMA calibration (S1-S5: purified by preparative SEC).

e Absolute weight average molecular weight [Mw (MALLS)] and radius of gyration (Rg) determined by SEC-MALLS in DMF (10 mM LiBr).

f Arm numbers per a star polymer: Narm = (weight fraction of arm polymers) × Mn (MALLS)/Marm,arm (SEC).

g Fluorine atom numbers in a polymer: Nf = Narm × (12 × m × (conv./100) + (the number of F in a monomer) × n × (conv./100)).

h Pendant CF3 group numbers in a polymer: NCF3 = Narm × (the number of CF3 in a monomer) × n × (conv./100)).

i Pendant Rf group numbers in a polymer: NRf = Narm × n × (conv./100)).

![Fig. 1. SEC curves of (a) S1, (b) S2, (c) S3, (d) S4, and (e) S5 obtained from Ru(Ind)Cl(PPh3)2/n-Bu3N-catalyzed linking reaction of PMMA-Cl with 12FODMA and RfMA (a: 9FHxMA, b: 12FHpMA, c: 13FOMA, d: 15FOMOA, e: 17FDeMA) in toluene at 80 °C. Monomer feed ratio: [PMMA-Cl]/[12FODMA]/[RfMA]0 = 1/5/10.](image-url)
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Polymer Chemistry

non-volatile ruthenium catalyst under argon. In all cases, the linking reaction of PMMA-Cl efficiently and smoothly proceeded up to over 80% monomer conversion in 18 - 23 h at 80 °C to provide corresponding fluorinated microgel star polymers with high molecular weight (S1-S5) in high yield (> 70%, by SEC in THF) (Figure 1). Importantly, 12FODMA and RfMA were concurrently consumed during arm-linking process (Figure S1), resulting in random, virtually homogeneous, distribution of the perfluorinated alkyl pendants within microgel cores.

After purified by preparative SEC (removing the residues of unreacted arms, a ruthenium catalyst, and monomers), S1-S5 were characterized by multi-angle laser light scattering coupled with SEC (SEC-MALLS) in DMF to determine absolute weight-average molecular weight ($M_w$), arm numbers ($N_{arm}$), and radius of gyration ($R_g$): $M_w = 393000 - 954000$ g/mol; $N_{arm} = 19 - 42$; $R_g = 13 - 21$ nm. Uniquely, S1-S4 have almost constant arm numbers ($N_{arm} = \sim 20$), whereas S5 has $N_{arm} (\sim 40)$ about twice larger than S1-S4. The former corresponds to the fact that $N_{arm}$, i.e., the efficiency of intermolecular crosslinking, is generally determined by the molar ratio of a linking agent to an arm polymer chain ($m = [12FODMA]_0/[PMMA-Cl]_0$ = 5). The latter means that, beyond such a general feature, S5 underwent the intermolecular linking of arm polymers more efficiently than the other star polymers. This is because the strong fluororous properties of the perfluorinated segment of 17FDeMA promote the intermolecular association of intermediates, i.e., block copolymers with dangling olefin and perfluorinated pendants and star polymers with small arm numbers therefrom, during microgel formation process.

The numbers of in-core fluorine atoms ($N_F$), in-core CF$_3$ end groups ($N_{CF_3}$), and in-core polyfluorinated groups ($N_{RF}$) were calculated form $N_{arm}$ the feed ratio of a linking reagent and RfMA ($m$ and $n$), and their conversion: $N_F = N_{arm} \times [12 \times m \times (conv./100) + (the\ number\ of\ F\ in\ a\ monomer) \times n \times (conv./100)]$, $N_{CF_3} = N_{arm} \times (the\ number\ of\ CF_3\ in\ a\ monomer) \times n \times (conv./100)$, $N_{RF} = N_{arm} \times n \times (conv./100)$. As shown in Table 1, these were estimated as 2810 - 8070 ($N_F$), 0 - 388 ($N_{CF_3}$), 150 - 343 ($N_{RF}$). Thus, lots of fluorine atoms and

Fig. 2 $^1$H NMR (500 MHz) spectra of (a) S1, (b) S2, (c) S3, (d) S4, and (e) S5 ([star] = 50 mg/mL) in CD$_2$Cl$_2$ at 30 °C.
perfluorinated alkyl units were successfully accumulated within microgel cores by this simple arm-linking reaction.

**S1-S5** were analyzed by $^1$H NMR in CD$_2$Cl$_2$ at 30 °C (Figure 2). **S1-S5** showed broad methylene proton signals of in-core 12FODMA (g, $^g$: 4.6 ppm) and corresponding R$_p$MA ($^h$: 4.6 – 4.2 ppm, $^j$: 2.6 – 2.4 ppm) and small olefin protons ($^k$: 6.2, 5.7 ppm) in addition to the proton signals for PMMA arms ($^e$: 1.3 – 0.7 ppm, $^d$: 2.1 – 1.4 ppm, $^f$: 3.7 – 3.4 ppm) and the end initiator fragment ($^a$: 4.1 – 4.0 ppm, $^b$: 3.4 ppm, $^c$: 7.4 – 7.2 ppm). The broad signals for the in-core R$_p$MA importantly support that R$_p$MA is placed within microgels crosslinked with 12FODMA. Calculated from the area ratio of olefin signal ($^m$), support that R$_p$MA was consumed by intra-chain: i.e., in all star polymers, over 94% of the pendant olefin 12FODMA was estimated as about 0.3 unit per a single arm chain: i.e., in all star polymers, over 94% of the pendant olefin was consumed by intra- and intermolecular crosslinking reaction. Additionally, S2 quantitatively exhibited a tip proton signal ($^p$) of in-core 12FHpMA ($^q$: 6.2 – 5.8 ppm), the area ratio is in good agreement with the content per a single arm chain ($^p$ = 10).

To evaluate the properties of the in-core perfluorinated alkyl pendants, S1-S5 were further analyzed by $^{19}$F NMR in CDCl$_3$ at 30 °C (Figure 3). All of the star polymers exhibited the $^{19}$F signals of the in-core R$_p$MA pendants ($^a$-$^f$), whereas the $^{19}$F signals of the 12FODMA perfluorinated spacer ($^A$, $^B$) were hardly detected. This indicates that R$_p$MA pendants are more thermally mobile than 12FODMA spacer unit. In particular, the tip CF$_3$ and CHF$_2$ groups of the perfluorinated pendants were the most clearly observed. They were thus used as a probe in analyzing the thermal mobility of in-core perfluorinated pendants below.

### Table 2. $T_d$ and $E_w$ of In-Core Perfluorinated Pendants in Star Polymers

<table>
<thead>
<tr>
<th>Entry</th>
<th>Polymer</th>
<th>$T_d$ [ms] (30 °C)</th>
<th>$E_w$ [kJ/mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>16</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>S2</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>S3</td>
<td>7.0</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td>S4</td>
<td>5.4</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>S5</td>
<td>2.6</td>
<td>44</td>
</tr>
</tbody>
</table>

$^{a}$ $^{19}$F $T_d$ values of the in-core CF$_3$ groups for S1-S5 in DMF-$d_7$ at 30 °C.

$^{b}$ Apparent activation energy for molecular motion ($E_w$) determined from the slope of Arrhenius plots of the $^{19}$F $T_d$ values for the in-core CF$_3$ groups for S1-S5 in DMF-$d_7$.

### Core-Mobility Analysis by $T_d$ Measurements

Thermal mobility of the in-core perfluorinated pendants was evaluated with $^{19}$F NMR spin-spin relaxation time ($T_2$) measurements of S1-S5 in DMF-$d_7$. It has already found that the perfluorinated pendants in star polymers effectively aggregate within microgel cores via fluorous interaction in DMF. The mobility of the perfluorinated pendants would thus tend to decrease with increasing fluorous nature.

At 30 °C, $^{19}$F $T_2$ values of the in-core CF$_3$ or CHF$_2$ groups in S1-S5 were determined as 16 (S1), 20 (S2), 7.0 (S3), 5.4 (S4), and 2.6 (S5) ms (Table 2). The $T_2$ values decreased with increasing the fluorine atom numbers of in-core R$_p$MA unit (S1 < S3 < S4 < S5). This indicates that perfluorinated pendants gradually aggregate each other within microgels to be less

**Fig. 3** $^{19}$F NMR (470 MHz) spectra of (a) S1, (b) S2, (c) S3, (d) S4, and (e) S5 ([*star*] = 50 mg/mL) in CDCl$_3$ at 30 °C (TFA: trifluoroacetic acid, $\delta$ = 76.5 ppm).

**Fig. 4** Arrhenius plots of $^{19}$F $T_2$ values of the terminal CF$_3$ or CHF$_2$ groups for S1 (open circle), S2 (open rhombus), S3 (open triangle), S4 (open square), and S5 (filled circle) determined in DMF-$d_7$ at 30, 50, 70, 90, and 110 °C.
mobile as the fluorine numbers increase. S5 comprising 12FODMA and 17FDeMA afforded the most stable fluorous compartment. Importantly, T2 for S2 was much larger than that for S3 in spite of the almost identical fluorine atom numbers of R3MA (12 - 13), meaning that CHF2-capped pendants are not so fluorous to freely mobile within S2 without aggregation.

Temperature-dependent 19F T2 measurements of S1-S5 were conducted in DMF-d7 at the various temperatures of 30, 50, 70, 90, and 110 °C (Figure 4). Here, the effects of the in-core R3MA species on the pendant mobility is quantitatively evaluated with the apparent activation energy (Eap) for the molecular motion that is obtained from Arrhenius plots of T2 (temperature-dependence of T2). T2 is proportional to reciprocal of correlation time of dynamics (τc) according to the following equation: 

\[ T_2 \propto \tau_c^{-1} = A \exp \left(-\frac{E_{ap}}{RT}\right) \] 

(1) where R and T means gas constant and temperature.

Figure 4 shows plots of logarithmic T2 for S1-S5 against inverse temperature (1/T) in DMF-d7. All of ln T2 values were inversely proportional to 1/T, demonstrating that the mobility of their CF3 or CHF2 groups obeys Arrhenius equation (eq. 1). Eap was estimated from the slope of the plots as follows: 

E_{ap} = 33 (S1), 26 (S2), 39 (S3), 44 (S4), and 44 (S5) kJ/mol (Table 2). This revealed that activation energy (Eap) also increased with the physical association of perfluorinated pendants by fluorous interaction within the cores; S5 had the largest Eap to form most stable fluorous compartment.

**Guest Encapsulation and Stimuli-Responsive Release**

Encapsulation of perfluorinated guest molecules was investigated with fluorinated microgel star polymers (S1-S5) in DMF-d7. Discussion was especially focused on encapsulation efficiency, fluorous interaction, and host/guest mobility, dependent on the in-core perfluorinated units. The guest encapsulation would be enhanced with increasing the fluorous interaction between the in-core perfluorinated pendants and a guest molecule.

**PFMCH Encapsulation.** Perfluoromethylcyclohexane (PFMCH) was first employed as a guest molecule that is fluorous, immiscible with common organic solvents (e.g., DMF) and water.39 PFMCH was mixed and solubilized with S1-S5 in DMF-d7 at 25 °C for 24 h, resulting in emulsion mixtures. After the phase separation, the transparent supernatant was analyzed by 19F NMR at 30 °C (Figure 5). The CF3 multiplet signal of PFMCH alone (\(a'\) - 70.25 ppm) turned broad and shifted to upfield in the presence of S1 (\(a'\) - 70.35 ppm), S3 (\(a'\) - 70.6 ppm), S4 (\(a'\) - 70.7 ppm), and S5 (\(a'\) - 70.95 ppm). This demonstrated that S1, S3-S5 efficiently interacted with PFMCH to enclose the guest within their fluorous microgels. Particularly, S5 with long perfluorinated alkyl units (1H,1H,2H,2H-perfluorodecyl) led to the broadest fluorine signal of PFMCH (Figure 5f). In the presence of S2, the CF3 signal of PFMCH was in turn still multiplet despite of the upfield shift (\(a'\) - 70.45 ppm). This indicates that S2 actually solubilized PFMCH but does not so efficiently enclose it within the core owing to the less fluorous properties of the in-core 12FHpMA bearing a -CHF2 end group.

**Table 3. Encapsulation of PFMCH into fluorinated microgel star polymers**

| Polymer | T2 (PFMCH) | T2 (Core) | N_{ext} | Efficiency
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>S1</td>
<td>177</td>
<td>15</td>
<td>40</td>
<td>0.24</td>
</tr>
<tr>
<td>S2</td>
<td>472</td>
<td>24</td>
<td>80</td>
<td>0.54</td>
</tr>
<tr>
<td>S3</td>
<td>136</td>
<td>8.2</td>
<td>106</td>
<td>0.64</td>
</tr>
<tr>
<td>S4</td>
<td>69</td>
<td>5.6</td>
<td>250</td>
<td>1.29</td>
</tr>
<tr>
<td>S5</td>
<td>69</td>
<td>7.4</td>
<td>260</td>
<td>0.77</td>
</tr>
</tbody>
</table>

a 19F T2 of the CF3 groups for PFMCH with S1-S5 in DMF-d7 at 30 °C. PFMCH alone in CDCl3 at 30 °C: T2 = 3150 ms.

b 19F T2 of the in-core CF3 groups for S1-S5 with PFMCH in DMF-d7 at 30 °C.

c The number of PFMCH encapsulated within a star polymer in DMF-d7.

d Encapsulation efficiency of PFMCH per an in-core RMA unit: \(\eta_{ext}/N_{ext}\) (\(N_{ext}\): see Table 1).

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Fig. 5 19F NMR (470 MHz) spectra of (a) PFMCH alone and (b-f) PFMCH with S1-S5 (b: S1, c: S2, d: S3, e: S4, f: S5); [S1-S5] = 50 mg/mL in DMF-d7 at 30 °C.
The mobility of PFMCH enclosed within S1-S5 was evaluated with $^1$H T$_2$ measurements of the guest CF$_3$ group. The T$_2$ values were dependent on the star polymer species: T$_2$ = 177 (S1), 472 (S2), 136 (S3), and 69 (S4 and S5) ms. All of the values were much shorter than T$_2$ for PFMCH alone (3150 ms, in CDCl$_3$). In particular, S4 and S5 effectively shortened T$_2$ for PFMCH, i.e., reduced the guest mobility, indicating that S4 and S5 with long perfluorinated pendants tightly capture PFMCH within the cores. Among S1-S5, S2 in turn gave relatively long T$_2$ for PFMCH. This clearly demonstrates that PFMCH is not so tightly bound with the 12FHpMA-based microgel owing to the less fluorous properties. The mobility for PFMCH (T$_2$: S5 ~ S4 < S3 < S1 < S2) decreased with increasing E$_{ap}$ for the in-core perfluorinated pendants (E$_{ap}$: S5 ~ S4 > S3 > S1 > S2, Table 2). In contrast, the mobility of the in-core perfluorinated pendants in star polymers (T$_2$ values for the CF$_3$ or CHF$_2$ groups) was almost independent of a PFMCH guest molecule (Table 2 and 3).

The encapsulation efficiency of PFMCH was quantitatively evaluated with the number of PFMCH solubilized in a single star polymer ($N_{guest}$). $N_{guest}$ was calculated from the area ratio of the guest CF$_3$ signal (Figure 5) to the CF$_3$ or CF$_2$H signals of the in-core perfluorinated pendants by $^1$F NMR, assuming that all of their $^1$F signals were quantitatively observed: $N_{guest}$ = 40 (S1), 80 (S2), 106 (S3), 250 (S4), and 260 (S5). The number of PFMCH bound by one R$_f$MA unit ($N_{guest}/N_{RF}$) was thus determined to be 0.24 (S1), 0.54 (S2), 0.64 (S3), 1.29 (S4), and 0.77 (S5) (Figure 6). This result reveals that the encapsulation efficiency is not only enhanced with the total fluorine atom numbers (S1 < S2 < S3 < S5) but also with the tip CF$_3$ numbers (S3 < S4). Actually, S4 (1.29) was twice more effective per one R$_f$MA unit than S3 (0.64), while the efficiency of S4 per one CF$_3$ group was almost identical with that of S3. Thus, the

**Fig. 6** Encapsulation efficiency ($N_{guest}/N_{RF}$) of PFMCH into S1-S5 per an in-core R$_f$MA unit in DMF-d$_7$ at 30 °C.

**Fig. 7** $^1$F NMR (470 MHz) spectra of polyfluorinated guests (a: PFO, b: PFH, c: PFO-ester, d: PFHp-ketone, e: PFO-OH) with S3 or S5: [S3 or S5] = 50 mg/mL in DMF-d$_7$ at 30 °C.
accumulation of CF₃ group in microgels is also quite important for the encapsulation of large number of perfluorinated guests.

**Various Guest Molecules.** Next, S₃ and S₅ were applied to the encapsulation of perfluorinated compounds including perfluorooctane (PFO), perfluorohexane (PFH), methyl perfluorooctanoate (PFO-ester), methyl perfluorohexyl ketone (PFHₚ-ketone), and 1H,1H-perfluoro-1-octanol (PFO-OH). These guests were mixed with S₃ or S₅ in DMF-d₄ for 24 h. PFO, PFH, PFO-ester, and PFO-ketone gave heterogeneous mixture (PFO and PFH: emulsion, PFO-ester, and PFO-ketone: dispersion), whereas PFO-OH did homogenous counterpart. The phase-separated, transparent supernatants or the homogenous solution were analyzed by ¹⁹F NMR (Figure 7).

In the presence of S₃, the CF₃ peaks for PFO, PFH, and PFO-ester shifted to upfield and broadened, while those for PFHₚ-ketone and PFO-OH were still observed as triplet signals. This indicates that perfluorinated alkanes and the ester derivative are bound within S₃ core via fluorous interaction, whereas PFO and PFH in DMF may be due to the originally high affinity of PFO and PFH. Perfluorinated star polymers efficiently encapsulated perfluorinated alkane derivatives with ester functionality by enhancing the fluorous interaction.

**Thermoresponsive Reversible Encapsulation and Release.** We have already found that perfluorinated compounds can be released from perfluorinated microgel star polymers by the addition of good solvents for the guest compounds. Here, we examined temperature-responsive, reversible encapsulation and release of PFMCH with S₃ in DMF-d₄ (Figure 8). PFMCH is known to have thermoresponsive solubility against organic solvents: i.e., the compound is miscible with them upon heating owing to reduced fluorous properties. As already confirmed by ¹⁹F NMR (up-field shift and broadening of CF₃: a' -70.6 ppm, Figure 8b), S₃ efficiently interacted with PFMCH in DMF-d₄ at 30 °C. Importantly, the correlation peak between PFMCH CF₃ group (a) and the CF₃ of the in-core perfluorinated unit (b) was clearly observed in ¹⁹F nuclear Overhauser effect (NOE) difference spectrum (Figure 8c). This strongly supports that PFMCH is enclosed within S₃ core at 30 °C. Upon heating the solution to 60 °C, the CF₃ signal of PFMCH shifted to the original position (a' -70.3 ppm) and turned multiplet (Figure 8d); the NOE signal between PFMCH and in-core perfluorinated pendants also disappeared (Figure 8e). Thus, PFMCH was released from the core at 60 °C. This is due to the reduced fluorophilicity of PFMCH upon heating. By cooling the solution to 30 °C, the released PFMCH was again encapsulated into S₃ core, as confirmed by ¹⁹F NMR (Figure 8f). Similarly to S₃, S₅ also showed such a thermoresponsive release of PFMCH upon heating. Thus, independently of the in-core fluoroilicity, fluorinated microgel star polymers, S₃ and S₅, successfully realized the temperature-dependent, reversible encapsulation and release of PFMCH in DMF.

**Conclusions**

We successfully created fluorinated microgel star polymers as fluorous nanocapsules for the encapsulation and release of polyfluorinated guest compounds. Five kinds of star polymers with different fluorous cores were efficiently prepared in high yield via the ruthenium-catalyzed linking reaction of PMMA-Cl with a perfluorinated linking agent (12FODMA) in the presence of perfluorinated alkyl monomers (RₐMA); RₐMA consists of different perfluorinated pendants (the number of the carbon and fluorine atoms and CF₃ group, the tip structure of the pendant: CF₃ vs. CHF₂), ¹⁹F T₂ measurements of star polymers revealed that the mobility of the in-core perfluorinated units decreased with increasing the fluorous properties: i.e., the number of fluorine substitution and CF₃ group in RₐMA units. Core-fluorinated star polymers efficiently encapsulated perfluorinated alkanes and the derivatives with ester or ketone functionality in DMF. The efficiency increased with increasing the number of fluorine substitution and CF₃ group in the in-core RₐMA units. Additionally, a fluorinated star polymer successfully afforded the reversible encapsulation and release of a perfluorinated guest by changing temperature. Thus, star polymers developed herein would be useful as temperature-responsive fluorous nanocapsules for the encapsulation, separation, and delivery of various perfluorinated compounds.
Acknowledgements

This research was supported by the Ministry of Education, Science, Sports and Culture through Grants-in-Aid for Scientific Research (A: 24245026, C: 26410134) and Young Scientist (B: 24750104), for which T.T. is grateful. Y.K. is grateful to the Japan Society for the Promotion of Sciences (JSPS) for a Grant-in-Aid for JSPS Research Fellows (DC1: 24–6140).

Notes and references

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Electronic Supplementary Information (ESI) available: [time-conversion curves of 12FDOMA and RMA for S1–S5]. See DOI: 10.1039/b000000x/