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COMMUNICATION

pH responsive self assemblies from an A_n -core-(B-*b*-C) $_n$ heteroarm star block terpolymer bearing oppositely charged segments†Zacharoula Iatridi^a and Constantinos Tsitsilianis^{*ab}

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We report on the association capability of a novel multisegmented, multiarm star terpolymer to form a diversity of pH-responsive amphoteric micellar nanostructured self-assemblies.

The spontaneous self-organization of amphiphilic molecules, *i.e.* surfactants and segmented macromolecules, towards nanostructured self-assemblies, like for instance liposomes, micelles, nanocapsules and solid lipid particles, has attracted increasing attention thanks to perspectives of applications as nanocarriers for controlled drug delivery and gene therapy. Macromolecular engineering has developed a number of bottom-up strategies, aiming to fabricate well-defined and tunable “smart” nano-objects for this purpose.¹ ABC block terpolymers, *i.e.* comprising three distinct macromolecular chains of different chemical nature, have been explored intensively in the last decade thanks to the novel opportunity on self-assembly that the three different blocks confer.² Moreover, macromolecular architectures (linear or branched modes) with particular topologies offer further possibilities on designed novel nanostructures. Thus, besides linear ABC terpolymers, miktoarm stars (μ -ABC), *i.e.* three different blocks emanated from a common junction point, have received much attention recently, as novel nanostructured micellar self-assemblies have emerged.³

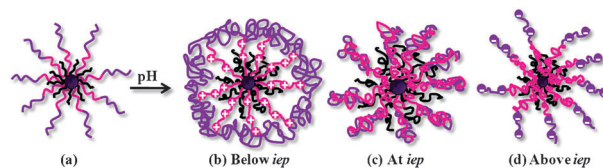
In this communication we report on the ability of a novel multisegmented terpolymer, with a star-shaped macromolecular architecture, to self assemble in dilute aqueous solutions. The star terpolymer under investigation differs in many respects from the three-armed μ -ABC stars explored so far. It is multiarmed, constituted of nine hydrophobic polystyrene (PS) arms and nine poly(2-vinyl-pyridine)-*b*-poly(acrylic acid) (P2VP-*b*-PAA) diblock copolymer arms, all emanated from a tightly crosslinked poly(divinyl benzene) (PDVB) common module. In fact, the A_n (B-*b*-C) $_n$ architecture named heteroarm star block terpolymer is a hybrid between the known A_nB_n heteroarm star copolymer and a (BC) $_n$ star block copolymer. The hydrophilic diblock copolymer arms of the star are

constituted of weak polyelectrolytes of oppositely charged moieties and thus they are highly sensitive to pH. Moreover the different hydrophilic segments (P2VP, PAA) can interact with each other either through electrostatic or H-bonding interactions conferring further association potentials. The aim of this work was to explore, for the first time, the ability of these multifunctional multisegmented star terpolymers, with such complex architecture, to self organize in water, forming nanoobjects triggered by pH changes.

The (PS₃₃)₉-PDVB-[P2VP₁₂₆-*b*-PAA₆₉]₉ star terpolymer (Scheme 1a) displays three main conformations depending on pH of the medium. In acidic conditions, P2VP is protonated behaving as a positively charged polyelectrolyte (Scheme 1b). In basic conditions, PAA is deprotonated behaving as a negatively charged polyelectrolyte (Scheme 1d) and there is a pH window where the two blocks interact electrostatically and are mutually neutralized (Scheme 1c).

ζ -Potentials, measured against pH, revealed three distinct pH regimes (Fig. 1): (a) low pH < 4, where positive charges predominate, (b) high pH > 7, where negative charges predominate and (c) the intermediate pH (4–7) where the polymer precipitates due to electrostatic interactions of the oppositely charged moieties and the hydrophobic transformation of the P2VP segments (pH > 5). This regime is characterized by the isoelectric point (iep) of the polyampholyte arms of the star which can be tuned by the acidic/basic ratio.⁴ The three star conformations of Scheme 1 correspond to the three phases of the plot in Fig. 1.

The self-organization of the star terpolymers was explored by transmission electron microscopy (TEM). Fig. 2 displays TEM images obtained from the low pH regime (between 1.4 to 2.0). At pH 1.4 the P2VP segments are highly protonated adopting a stretched conformation and the driving force for



Scheme 1 Schematic representation of star terpolymer (a) and its conformations at different pH regimes: P2VP protonated (b), PAA/P2VP complexation (c), PAA deprotonated (d). Colors denote: PS (black), P2VP (pink), PAA (purple).

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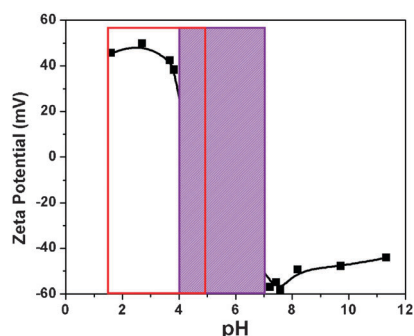


Fig. 1 pH dependence of the ζ -potential of $(\text{PS}_{33})_9\text{-PDVB-[P2VP}_{126}\text{-}b\text{-PAA}_{69}]_9$ star terpolymer solutions in H_2O at a concentration of 0.3 wt%. The region marked with purple color denotes the precipitation regime (iep). The region marked with red color denotes the corona segments interaction area.

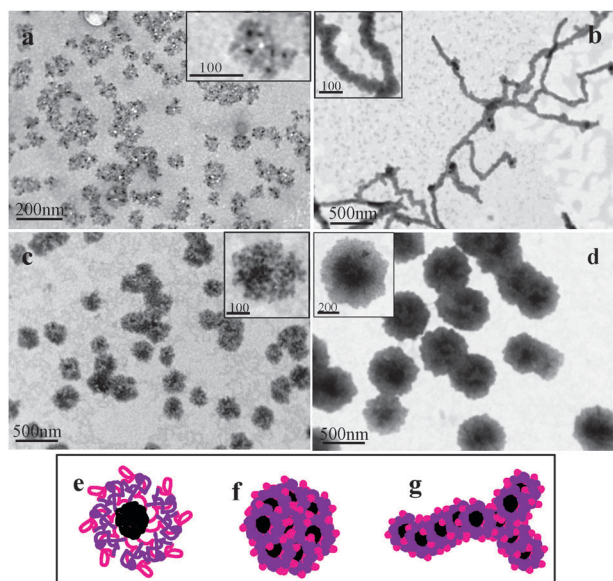


Fig. 2 TEM images of a 0.007 wt% star terpolymer aqueous solution at (a) pH 1.4, (b) pH 1.6, (c, d) pH 2.0. Schematic drawing of a unimolecular micelle (e), multicore micelle (f), worm-like micelle (g).

the self-assembly may arise mainly from the PS hydrophobic attractions. In Fig. 2a, core-shell micelles of *ca.* 25 nm in diameter can be observed. It seems that the observed nanostructures are unimolecular micelles constituted of PS cores (dark dots) surrounded by positively charged P2VP segments mixed with PAA segments in the corona, as dictated by the topology of the blocks. The high positive values of the ζ -potential implied that a significant number of P2VP positively charged moieties are located in the outer part of the corona. In previous investigations on $\text{PS}_n\text{P2VP}_n$ heteroarm stars (precursor of the star terpolymer) we have provided evidence that unimolecular micelles were formed through PS collapsing on the PDVB nodule, due to the star architecture of the heteroarm copolymer which can mimic the core-shell micellar structure.⁵ Thus, it is reasonable to accept that this structure is adopted in the present case (Fig. 2e).

The addition of the PAA segments sequentially to P2VP arms in the star terpolymer, as compared to $\text{PS}_n\text{P2VP}_n$ stars, induces new properties on these stars, *i.e.* the unimolecular micelles

exhibit interactive coronas. At pH 2, the star terpolymers interact intermolecularly through likely H-bonding, leading to larger associates with a radius larger than the contour length of the arms (48 nm) (Fig. 2c and d). Two main populations of large compound micelles (LCM) were thus observed which however differ in size and internal structure from those reported by Zhang and Eisenberg.⁶ As demonstrated in Fig. 2c, patchy multicore micelles of *ca.* 100–150 nm in radius were formed. We should distinguish the multicore micelles from the multi-compartment ones, formed from terpolymers bearing two highly incompatible hydrophobic segments.³ In the latter case, a compartmentalized hydrophobic core was formed through solvophobic repulsive interactions between the different hydrophobic segments, surrounded by a nonionic hydrophilic corona. The multicore micelles, observed herein, seem to arise from a novel path of association, *i.e.* through corona solvophilic interactions (H-bonding) between unimolecular micelles (segregated stars). Fig. 2c reveals that large spherical micelles can be stabilized from this inter-star association bearing PS cores distributed on the entire micellar volume. The micellar surface is occupied by positively charged P2VP segments as the ζ -potential dictates. The second population that coexist with the multicore micelles are larger LCM of *ca.* 310–370 nm in radius, which seem to result from a tighter packing of the various segments, exhibiting a dense core (dark area) surrounded by a less dense corona (Fig. 2d).

Dynamic light scattering (Fig. S3, ESI†) at 25 °C showed broad micellar size distribution in good agreement with TEM results. Upon heating to 45 °C, the size distribution was significantly shrunk and the mean R_H of the micelles was found to be similar to that of the unimolecular micelles. This reversible effect should be ascribed to the H-bonding suppression, corroborating the hypothesis of the proposed aggregation mechanism in this pH window.

Surprisingly at pH 1.6 worm-like micelles were also revealed by TEM (Fig. 2b). The average width of the micelles is comparable to the diameter of spherical unimolecular micelles of Fig. 2a. One could also observe loops, Y-junctions and free end-cups. Due to short PS arms, PS core hydrophobic stacking may not be the mechanism for the formation of wormlike supermicelles as have been observed for the $\text{PtBS-}b\text{-PB-}b\text{-PtBMA}$ linear block terpolymers in a selective solvent for PtBMA.⁷ It seems that, the driving force for the formation of a wormlike nanostructure is again the inter-star H-bonding of the corona segments (Fig. 2g).

As pH increases, the acrylic acid units are deprotonated and the electrostatic interactions between the oppositely charged moieties increase, driving the polymer to precipitate (two phase regime). Strong ionization of the PAA segments at pH higher than 7 allows redissolution of the star terpolymers, as clear homogeneous solutions were obtained.

Due to the entire deprotonation of P2VP in this regime (above pH 5) the star terpolymer has been transformed from bis-hydrophilic (P2VP, PAA hydrophilic segments) to bis-hydrophobic (PS, P2VP hydrophobic segments), altering significantly the hydrophobic/hydrophilic balance of the terpolymer. The incompatibility factor of the hydrophobic segments, as expressed by the $\chi_{\text{PS,P2VP}} N_{\text{PS+P2VP}}$, was calculated to be 17, implying segregation in the dry solid state.⁸

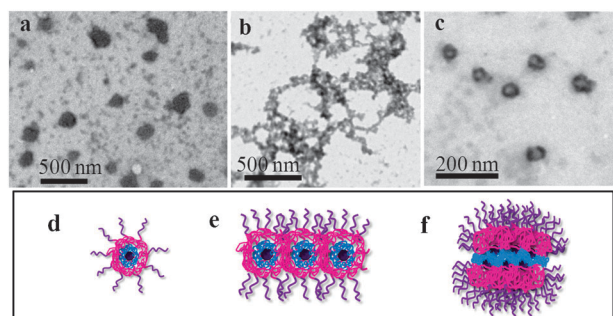


Fig. 3 TEM images of a 0.007 wt% star terpolymer aqueous solution at (a) pH 7.5, (b) pH 8.5, (c) pH 11.8. Schematic drawing of a unimolecular micelle (d), unimolecular micelle association towards network-like assemblies (e), multicompartment multimolecular micelle (f).

In Fig. 3, TEM images showing self-assemblies deposited on carbon substrates from basic environments are demonstrated. At pH 7.5, irregular multicompartment multistar aggregates were observed surrounded by non-visible negatively charged PAA segments, as implied by electrophoresis (Fig. 3a).

At pH 8.5 where the degree of ionization of PAA reaches about 100%, another morphology was observed (Fig. 3b). A network-like structure was developed, built by small particles of about 30 nm in diameter which are unimolecular star micelles interacting strongly by hydrophobic interactions. Thus, spherical nanoparticles with a negatively charged PAA corona and PS/P2VP concentric compartmentalized hydrophobic core were formed (Fig. 3d). The star cores of neighboring interacting stars can approach each other by retraction of the stretched arms (Fig. 3e), as molecular dynamic simulations and experimental findings have shown.⁹ This mechanism seems to work in our case driving the nanoparticles to self assemble leading to network-like super structures stabilized by interparticle hydrophobic attractions.

Finally at pH 11.8, multimolecular micelles with compartmentalized cores were observed as can be seen in Fig. 3c. Under these conditions, elevated ionic strength provokes partial screening of the charged PAA moieties of the corona, driving the unimolecular micelles observed at pH 8.5 to self assemble in a different morphology. The arm segregated unimolecular micelles are associated forming nonuniform structures with inner PS and outer P2VP compartments (darker areas) surrounded by the PAA non-visible protected corona (Fig. 3c and f).

In conclusion, a novel multisegmented, multiarm star-shaped terpolymer bearing PS hydrophobic arms and P2VP-*b*-PAA diblock copolymer amphoteric arms was explored in aqueous media. Thanks to the nature and the topology of the three kinds of segments, this star terpolymer exhibits pH responsive self-organization in dilute aqueous solutions. A variety of amphoteric self-assemblies was observed by TEM, depending on the pH of the medium. Below the iep of the diblock polyampholyte arms in which the terpolymer possesses a bis-hydrophilic nature with interactive arms, we found conditions leading to core-shell unimolecular micelles, worm-like micelles and multicore large compound micelles. A novel association pathway is suggested to account for the formation of the large self-assemblies in this pH window.

The LCM arise from coronal interactions without the need of the presence of complexing agents as reported recently.¹⁰

Above the iep, the star terpolymer was transformed to bis-hydrophobic, bearing incompatible segments. In this regime multistar aggregates, network-like large assemblies and finally patchy compartmentalized micelles were formed.

Intensive work is in progress towards potential applications of these multifunctional stars as materials for fabricating “smart” Langmuir–Blodgett monolayers, emulsifying agents for dispersion of nanotubes and/or graphene sheets, nano-carriers in water environments for controlled multimodal delivery of small and large molecules and responsive hydrogels. Provided that P2VP can be coordinated with a variety of inorganic nanoparticles *e.g.* Fe₃O₄, gold, quantum dots, novel organic/inorganic smart hybrids can be developed.

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Notes and references

- (a) M. Motornov, Y. Roiter, I. Tokarev and S. Minko, *Prog. Polym. Sci.*, 2010, **35**, 174; (b) M. A. Cohen Stuart, W. T. S. Huck, J. Genzer, M. Muller, C. Ober, M. Stamm, G. B. Sukhorukov, I. Szleifer, V. V. Tsukruk, M. Urban, F. Winnik, S. Zauscher, I. Luzinov and S. Minko, *Nat. Mater.*, 2010, **9**, 101.
- F. S. Bates and G. H. Fredrickson, *Phys. Today*, 1999, **52**, 32.
- (a) Z. Li, E. Kesselman, Y. Talmon, M. Hillmyer and T. Lodge, *Science*, 2004, **306**, 98; (b) N. Saito, C. Liu, T. P. Lodge and M. A. Hillmyer, *ACS Nano*, 2010, **4**, 1907; (c) A. Walther, J. Yuan, V. Abetz and A. H. E. Muller, *Nano Lett.*, 2009, **9**, 2026; (d) N. Saito, C. Liu, T. P. Lodge and M. A. Hillmyer, *Macromolecules*, 2008, **41**, 8815; (e) Z. Zhou, Z. Li, Y. Ren, M. A. Hillmyer and T. P. Lodge, *J. Am. Chem. Soc.*, 2003, **125**, 10182; (f) K. Van Butsele, C. A. Fustin, J. F. Gohy, R. Jerome and C. Jerome, *Langmuir*, 2009, **25**, 107; (g) W. Kong, B. Li, Q. Jin, D. Ding and A.-C. Shi, *J. Am. Chem. Soc.*, 2009, **131**, 8503; (h) A. Walther and A. H. E. Muller, *Chem. Commun.*, 2009, (9), 1127; (i) C. Li, Z. Ge, H. Liu and S. Liu, *J. Polym. Sci., Part A: Polym. Chem.*, 2009, **47**, 4001; (j) Y. Zhang, H. Liu, H. Dong, C. Li and S. Liu, *J. Polym. Sci., Part A: Polym. Chem.*, 2009, **47**, 1636; (k) H. Liu, C. Li, H. Liu and S. Liu, *Langmuir*, 2009, **25**, 4724.
- (a) V. Sfika, C. Tsitsilianis, A. Kiriy, G. Gorodyska and M. Stamm, *Macromolecules*, 2004, **37**, 9551; (b) C. Tsitsilianis, Y. Roiter, I. Katsampas and S. Minko, *Macromolecules*, 2008, **41**, 925.
- (a) A. Kiriy, G. Gorodyska, S. Minko, M. Stamm and C. Tsitsilianis, *Macromolecules*, 2003, **36**, 8704; (b) M. Stepanek, P. Matejcek, J. Humpolickova, J. Havrankova, K. Podhajecka, M. Spirkova, Z. Tuzar, C. Tsitsilianis and K. Prochazka, *Polymer*, 2005, **46**, 10493; (c) A. Gorodyska, A. Kiriy, S. Minko, C. Tsitsilianis and M. Stamm, *Nano Lett.*, 2003, **3**, 365; (d) A. Kiriy, G. Gorodyska, S. Minko, M. Stamm and C. Tsitsilianis, *Macromolecules*, 2003, **36**, 8704; (e) A. Kiriy, G. Gorodyska, S. Minko, C. Tsitsilianis, W. Jaeger and M. Stamm, *J. Am. Chem. Soc.*, 2003, **125**, 11202.
- L. Zhang and A. Eisenberg, *J. Am. Chem. Soc.*, 1996, **118**, 3168.
- (a) B. Fang, A. Walther, A. Wolf, Y. Xu, J. Yuan and A. H. E. Muller, *Angew. Chem., Int. Ed.*, 2009, **48**, 2877; (b) A. Walther, C. Barner-Kowollik and A. H. E. Muller, *Langmuir*, 2010, **26**, 12237.
- V. Grayer, E. E. Dormidontova, G. Hadzioannou and C. Tsitsilianis, *Macromolecules*, 2000, **33**, 6330.
- (a) A. Jusufi, C. N. Likos and H. Löwen, *J. Chem. Phys.*, 2002, **116**, 11011; (b) A. Jusufi, C. N. Likos and H. Löwen, *Phys. Rev. Lett.*, 2002, **88**, 018301; (c) A. Jusufi, C. N. Likos and M. Ballauff, *Colloid Polym. Sci.*, 2004, **282**, 910; (d) A. Wittermann, M. Drechsler, Y. Talmon and M. Ballauff, *J. Am. Chem. Soc.*, 2005, **127**, 9688.
- R. C. Hayward and D. J. Pochan, *Macromolecules*, 2010, **43**, 3577.