Formation of star-like nanogels via cross-linking reaction of complementarily reactive diblock copolymers was successfully accomplished. The two types of diblock copolymers, consisting of poly(methyl methacrylate) (PMMA) or polystyrene (PS) block and alkoxyamine-based cross-linkable block, were prepared by atom transfer radical polymerization (ATRP) methods. The cross-linking reactions were carried out by merely heating their mixture, and traced by gel permeation chromatography (GPC) and multi-angle light scattering (MALS) measurements. The diblock copolymers were reacted in complementarily reactive systems, showing that all star-like nanogels have necessarily two types of arms as PMMA and PS chains.

1. Introduction

Star polymers have been synthesized by expanded methods using controlled polymerization, and several types of star-like architectures have been reported.[1–5] Designing different kinds of arms in one star polymer is one of the most remarkable challenges, because their physicochemical properties might be different from those of linear polymers. So far, some star polymers have been synthesized by so-called “mixed method” in star polymer synthesis. Hadjichristidis et al. reported 3- or 4-miktoarm (hetero-arm) star polymers by using coupling reactions of chain ends in anionic polymerization and chlorosilane derivatives.[2,3] Higashimura et al. represented hetero-arm amphiphilic star-shaped polymers via cationic polymerization from core-functional star polymers.[4] Furthermore, Hirao et al. synthesized asymmetric star-branched polymers by means of anionic polymerization using 1,1-diphenylethylene derivatives.[5]

The authors have reported the formation of star-like nanogels via cross-linking reaction of diblock copolymers with alkoxyamine units in their side chains.[6] An alkoxyamine is an adduct of styryl radical and nitroxide radical behaving as a typical organic molecule under normal condition, but plural alkoxyamines can dissociate into radicals and exchange their units under heating condition.[7,8] Because of such reactivity, the central C–O bonds in alkoxyamine can be treated as dynamic covalent bonds.[9] In addition, cross-linking reaction occurred by designing and heating linear polymers with alkoxyamine units in their side chains[10], and nanogels with star-like structure were formed in the case of diblock copolymer systems. Interestingly, because an alkoxyamine consists of different types
of radical species, the complementarily reactive systems could be constructed by controlling their
direction. So far, we have reported the formation of macroscopic gels and star-like nanogels using two
types of complementarily reactive linear polymers consisting of poly(methyl methacrylate) (PMMA)
derivatives.[10–12] Such systems essentially possess to combine two different kinds of polymers into
any organized structure. Herein, a novel methodology of formation of star-like architecture with
different arms as PMMA and polystyrene (PSi) is proposed.

2.  Experimental

2.1. Measurement

The relative number average molecular weight ($M_n$) and molecular weight distribution ($M_w/M_n$) of
polymers were estimated by gel permeation chromatographic (GPC) analysis, which was carried out at
40 °C on TOSOH HLC-8220 GPC system equipped with a guard column (TOSOH TSK guard column
Super H-L), three columns (TOSOH TSK gel SuperH 6000, 4000, and 2500), and a UV-vis detector
(TOSOH UV-8020). The absolute molecular weight of nanogels was measured by gel permeation
chromatography – multiangle light scattering (GPC-MALS) in THF at 40 ºC on a Dawn EOS
instrument (Wyatt Technology; Ga-As laser, $\lambda = 690$ nm). The specific refractive index increment
($\partial n/\partial c$) which is necessary for the analysis of GPC-MALS was measured with Otsuka Electric DRM-
1020 (40 °C, $\lambda = 633$ nm). The measured $\partial n/\partial c$ of diblock copolymers and nanogels in THF was
0.0937–0.125 cm$^3$ g$^{-1}$ corresponding to mixing ratio.

2.2. Preparation of diblock copolymers

Diblock copolymer 1 was synthesized by random copolymerization of methyl methacrylate (MMA)
and methacrylic ester with alkoxyamine units from PSi ($M_n = 18800, M_w/M_n = 1.18$) with bromine at
the chain end by the ATRP method, as shown in Scheme 1. The polymerization was carried out by
using CuCl/4,4’-diononyl-2,2’-dipyrydyl (dNbpy) as catalyst in anisole at 50 °C for 24 h. After the
polymerization, the catalyst was removed by an alumina column, and the crude was purified by
reprecipitation in acetonitrile/hexane mixed solvent to obtain polymer as white precipitation ($M_n = 27$
700, $M_w/M_n = 1.37$). Diblock copolymer ($M_n = 26700, M_w/M_n = 1.18$) 2 was synthesized as previously
reported [10] from PMMA-Br ($M_n = 21500, M_w/M_n = 1.18$) preopolymer.

![Scheme 1. Preparation of diblock copolymer 1 by random copolymerization of MMA and methacrylic ester with alkoxyamine via the ATRP method.](image)

2.3. Cross-linking Reaction

A 10 wt% anisole solution of mixture of diblock copolymers 1 and 2 was charged into a glass tube,
degassed by seven freeze-pump-thaw cycles, and sealed off under vacuum. The solution was heated at
100 °C for 24 h to afford a colorless gel. The gel product was washed with chloroform and dried in
vacuo to afford a white solid of cross-linked polymer 3 in quantitative yield.
3. Results and discussion

Two types of diblock copolymers 1 and 2 with alkoxyamine units connected at different positions were synthesized by ATRP methods. The reactions were carried out by copolymerization of MMA and methacrylic ester with alkoxyamine units from PST and PMMA prepolymers, respectively, and the connecting diblock copolymers with relatively low molecular weight distributions were obtained. In the case of diblock copolymer 1, a halogen exchange method was used,[13] and unreacted PST homopolymer was removed by reprecipitation using acetonitrile/hexane mixed solvent. The molecular weight distribution of diblock copolymer 1 ($M_w/M_n = 1.37$), however, was larger than that of 2 ($M_w/M_n = 1.18$), because the polymerization rate might be larger than initiation reaction rate for the preparation of 1. Cross-linking reactions were carried out by heating mixtures of diblock copolymers 1 and 2 in anisole at 100 °C for 24 h to exchange alkoxyamine units in the radical process, as shown in Scheme 2. After heating, no gelation of the system was observed in spite of higher concentration condition such as 10 wt %, because the PST and PMMA chains without alkoxyamine units depressed the macroscopic gelation. Furthermore, the coloration corresponding to a generation of nitroxide radicals was not also observed.

**Scheme 2.** Formation of hetero-arm star-like nanogels via radical crossover reaction of diblock copolymers 1 and 2 with alkoxyamine units in their side chains.

**Figure 1.** GPC curves of reaction products after heating a mixture of diblock copolymers 1 and 2 ([1]:[2] = 3:7), and each diblock copolymer ([1]:[2] = 10:0, 0:10) in anisole (10 wt %) for 24 h at 100 °C.

**Figure 2.** Mixing ratio dependence of $M_w$ of reaction product after heating mixtures of diblock copolymers 1 and 2, and each diblock copolymer in anisole (10 wt %) for 24 h at 100 °C.
observed, which showed that the exchange reaction of alkoxyamine units proceeded without detectable side reaction.

Figure 1 shows GPC curves after heating the mixture ([1]:[2] = 3:7) and each diblock copolymer (1 and 2) in anisole at 100 °C for 24 h. In the case of heating each diblock copolymer, the GPC curves hardly changed. On the other hand, the higher molecular weight peaks, corresponding to cross-linked polymer, could be obtained without exceeding exclusion limit in the case of mixing conditions. These results indicated that cross-linking reaction occurred by exchange reaction of alkoxyamine units, and the excessive gelation was depressed by existence of PMMA and PST chains.

In order to investigate the complementarily reactive system, the cross-linking reactions were carried out in several mixing ratio condition. Figure 2 represents $M_w$ data of reaction products after heating diblock copolymers 1 and 2 in several mixing ratio condition. The Job’s plots show convex upward, which indicated that two types of diblock copolymers were reacted in complementarily reactive systems, because of controlling the directions of alkoxyamine units. The peak top seems to be reached between ([1]/[1]+[2]) = 0.3 and 0.4, because the number of two types of alkoxyamine units become equalized at this mixing ratio. Consequently, the present system ensures to form star-like nanogels necessarily with two types of molecular chains as PST and PMMA.

4. Conclusion
The authors have demonstrated the formation of hetero-arm star-like nanogels via cross-linking reaction of diblock copolymers with alkoxyamine units connected at different positions. The diblock copolymers with alkoxyamine units were prepared by ATRP methods, and GPC curves and $M_w$ data showed two types of diblock copolymers were reacted in complementarily reactive system. The prepared star-like nanogels should have two types of chains as PST and PMMA, and to the best of our knowledge, this is the first report on the synthesis of star polymers with different arms by using block copolymers. The present reaction system can be easily applied to core-functional star polymers, amphiphilic star-polymers, and so on.

Acknowledgements
The authors gratefully acknowledge the financial supports by a Grant-in-Aid for Scientific Research (20350057) and a Grant-in-Aid for the Global COE Program, “Science for Future Molecular Systems” from the Ministry of Education, Culture, Science, Sports and Technology of Japan. Y. A. acknowledges the financial support of a Grant-in-Aid for JSPS Fellows.

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