Static and Dynamic Light Scattering Studies on Dilute Polyrotaxane Solutions

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Abstract. Static and dynamic light scattering measurements were performed for dilute polyrotaxane solutions in different types of solvent systems, i.e. dimethylacetamide (DMAc) or dimethylformamide (DMF) containing 1–6 wt% lithium chloride (LiCl), 1 M aqueous sodium hydroxide (NaOH) and dimethylsulfoxide (DMSO). No aggregation of the polyrotaxane in DMF/LiCl was confirmed in the present study. Radius of gyration of the dissolved polyrotaxane was largest in NaOHaq., followed by values in amide solvents/LiCl and that in DMSO, and was probably dominated not by Coulombic repulsion but by the mutual affinity between solvent and polyrotaxane. Ratio of radius of gyration to hydrodynamic radius suggested the flexible random-coiled conformation in DMSO and relatively more extended, semi-flexible ones in amide solvents/LiCl and NaOHaq. The obtained values of second virial coefficient and weight average molecular weight seemed to be affected by a potential change in differential refractive index increments, caused by selective macrocationization or ionization.

1. Introduction
Polyrotaxane is one of the most vigorously investigated supramolecules in which many cyclic molecules are penetrated with a linear molecule [1–4]. One of the typical polyrotaxane molecules consists of α-cyclodextrins (CDs) as cyclic molecules and poly(ethylene glycol) (PEG) as a linear molecule [5,6]. Recent attentions have been focused on applications of the PEG/CD polyrotaxane to construct a wide variety of functionalized materials, such as a nano-sized tubular molecule [7, 8], molecular machines [9], an advanced drug-delivery system [10] and preparation of topologically crosslinked polyrotaxane gels [11–13]. The polyrotaxane gels called as “slide-ring gels” or “sliding gels” can achieve an extremely high degrees of elongation or swelling due to free sliding movements of the internal crosslinked cyclodextrins [11–14].

Physical and chemical properties of these polyrotaxane-based functional materials, which are prepared via solution state, can be affected by the state of the starting solutions. The physical properties of polyrotaxane solutions are, therefore, of great interest. Previous studies suggested a wide

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variety of intriguing phenomena of polyrotaxane solutions; namely, solvent-dependent changes in aggregation of CDs [15, 16], drastic difference between mechanical properties of slide-ring gels containing different solvents [13, 17], a rigid rod-like structure at a high degree of inclusion and its change into flexible structure by chemical modifications [18, 19], and a surprisingly strong thixotropy of a concentrated polyrotaxane solution in DMSO [20]. In spite of these energetic studies, surprisingly less efforts have been focused on the difference in molecular conformation of a single polyrotaxane chain in a dilute solution with several types of solvents. Such investigations can be now examined thanks to the recent discovery of a variety of good solvents for polyrotaxane [17, 21–23]. Availableness of new solvents stimulated us to investigate solvent-molecule interaction in several dilute polyrotaxane solutions.

Static light scattering (SLS) and dynamic light scattering (DLS) techniques are powerful tools for obtaining information on conformation of polymer chains in a dilute solution [24]. These measurements provide polymer parameters such as radius of gyration \( R_g \), second virial coefficient \( A_2 \), weight average molecular weight \( M_w \), diffusion coefficient \( D \) and hydrodynamic radius \( R_h \). Since there has been unfortunately no SLS and DLS study on the dilute polyrotaxane solutions, we examined an evaluation of the molecular parameters of the PEG/CD polyrotaxane in different solvent systems.

2. Materials and Methods

Reagents other than polyrotaxane were purchased from Wako Pure Chemical Industries, Ltd. All reagents were of experimental grade and used without further purification. Polyrotaxane was prepared according to the previous method [25]. The inclusion ratio, i.e. percentage of the PEG axis covered with CDs, was calculated as 26% from \(^1\)H-NMR measurement. From gel permeation chromatography measurements under the conditions described before [20], weight average molecular weight and polydispersity of the synthesized polyrotaxane was calculated as \( 1.40 \times 10^5 \) and 1.29, respectively.

As solvents for light scattering measurements, the following solvent systems were selected: dimethylsulfoxide (DMSO), 1 M aqueous solution of sodium hydroxide (1 M NaOHaq.), dimethylacetamide (DMAc) containing lithium chloride (LiCl) and dimethylformamide (DMF) containing LiCl. Prior to the light scattering measurements, qualitative solubility of the polyrotaxane in these solvent systems was visually examined after mixing ca. 20 mg of the polyrotaxane with 1 mL of the above solvents, adjusting LiCl content at 0.5–8 wt% in the case of amide solvent/LiCl systems.

SLS and DLS measurements were performed with ALV–5000E (ALV–GmbH, Langen, Germany), using He–Ne laser with wavelength \( \lambda = 632.8 \) nm, at 25 °C and at the measurement angles between 30° and 150°. Rayleigh ratio was calibrated with the value for toluene (\( 1.3522 \times 10^{-5} \) cm \(^{-1} \)). The sample solutions at 0.3–5.0 mg/ml polyrotaxane content were subjected to measurements after optical clarification with a 0.20 µm PTFE filter. Differential refractive indices \( dn/dc \) of the solutions were measured with a differential refractometer (DRM–1021, Otsuka electronics Co. Ltd.). Viscosity of the solvent was measured at 25 °C by an Ubbelohde viscometer.

The data obtained by SLS measurements were analyzed with Zimm plots according to the following eqs 1–3;

\[
\left. \frac{Kc}{R_g} \right|_{\theta=0} = \frac{1}{M_w} \left(1 + \frac{1}{3} R_g^2 q^2 + \cdots \right) \tag{1}
\]

\[
\left. \frac{Kc}{R_g} \right|_{\theta=0} = \frac{1}{M_w} + 2A_2c + \cdots \tag{2}
\]

\[
K = \frac{4\pi^2 n^2}{N_A \lambda^4} \left( \frac{dn}{dc} \right)^2 \tag{3}
\]

where \( K \) is an optical constant, \( c \) polymer concentration, \( n \) a refractive index of the measured solvent, \( q = (4\pi n/\lambda)\sin(\theta/2) \) the magnitude of a scattering vector, \( \lambda \) a wavelength of the incident light under
vacuum, $\theta$ a measurement angle and $dn/dc$ a differential refractive index of the solution. These analyses give the values of $M_w$, $R_g$ and $A_2$.

Calculation of the initial relaxation speed $\Gamma$ obtained with eq 4 gives diffusion coefficient $D$ of the polymer, which was translated into hydrodynamic radius $R_h$ according to eq 5;

$$\Gamma = Dq^2 \quad (4)$$

$$R_h = \frac{kT}{6\pi\eta D} (1+kDc) \quad (5)$$

where $k_D$ represents the effect of the interaction, $k$ is the Boltzmann constant and $\eta$ solvent viscosity.

3. Results and Discussion

3.1. Dissolution Mechanism of Polyrotaxane in Various Solvent Systems

In the present study, we found an excellent dissolution of the PEG/CD polyrotaxane in an unreported type of solvent, i.e. DMF containing LiCl. Qualitative dissolution tests with varied amount of LiCl revealed that the DMF containing LiCl above 1 wt% and DMAc containing LiCl above 0.5 wt% readily dissolve the polyrotaxane, and the dissolution in the former was considerably rapid (typically within 15 minutes at room temperature) compared to that in the latter. The solvents with lower salt content did not give complete dissolution.

Based on the previous investigation [26] on dissolution of cellulose, i.e. a highly hydrogen-bonded crystalline polysaccharide, as well as the examinations by Nakamura et al [27], the dissolution mechanism of the polyrotaxane in DMF/LiCl and DMAc/LiCl can be explained by complexation of $\text{Li}^+$ and solvent molecules (DMAc or DMF), followed by selective binding of the formed macrocation to hydroxyl groups of the polyrotaxane and resulting interruption of intermolecular hydrogen bonding [4, 21, 22]. The polyrotaxane molecules dissolved in these solvent systems are considered to be cationically charged due to this macrocation complexation. Dissolution of the polyrotaxane in 1 M NaOHaq. is also dominated by ionization of the polyrotaxane molecules via dissociation of hydroxyl groups above pH 12, the $pK_a$ of the hydroxyl groups in CD [5, 6]. Considering this mechanism, the polyrotaxane molecules in 1 M NaOHaq. are anionically charged. In contrast to the dissolution in the above solvent systems, the polyrotaxane dissolved in DMSO is considered to be nonionic (unionized). Analogous to the dissolution mechanism of CDs in DMSO, reported by Shikata et al. [28], the polyrotaxane is dissolved by solvation of DMSO molecules hindering hydrogen bond formation.

3.2. Light Scattering Measurements

Figure 1 shows a Zimm plot of the polyrotaxane solution in DMF/LiCl (2 wt%), in which $Kc/R_\theta$ was plotted against $\sin^2(\theta/2) + 0.2c$. According to eq 1, extrapolation of $Kc/R_\theta$ to $c \rightarrow 0$ and $\theta \rightarrow 0$ gives $1/M_w$, while the initial slope at $\theta \rightarrow 0$ reflects $A_2$. The value of $R_g$ is calculated from the slope of $\sin^2(\theta/2)$ at $c \rightarrow 0$.

Figure 2 shows a plot of diffusion coefficient $D$, measured in the same solvent by DLS and plotted against polyrotaxane concentration $c$. Each $D$ value at every $c$ was calculated according to eq. 4, considering dependence of $\Gamma$ on $q$ (and therefore on $\theta$) by measuring $\Gamma$ at various $q$. According to eq. 5, extrapolation to $c \rightarrow 0$ gives a value of $D$ corresponding to hydrodynamic radius $R_h$ of the dissolved polyrotaxane. These measurements and calculations were also performed for the other solvent systems, i.e. DMF/LiCl (1, 4 and 6wt%), DMAc/LiCl (2wt%), 1 M aqueous NaOH solution and DMSO. The obtained parameters were summarized in Table 1, together with values of refractive index increment $dn/dc$ and solvent viscosity $\eta$.

The values for $R_g$ exhibited a wide variation with the types of solvents. The $R_g$ measured in 1 M NaOHaq. showed the largest value, followed by those in DMF/LiCl and DMAc/LiCl, and the smallest value was observed in the measurement in DMSO. The value in DMSO, 16.9 nm, is comparable to that obtained by the measurement in DMSO after the hydroxypropylation of the same polyrotaxane (19.5 ± 1 nm) [29], and also well correspond to that reported by Fleury et al. (14.5 ± 10 nm) [19] for
the PEG/CD polyrotaxane with similar degree of inclusion (number of CD is 75, correspond to inclusion ratio of 33%).

Figure 1. Typical Zimm plot for the polyrotaxane solution in DMF/LiCl (2wt%), (filled circles) extrapolations to zero concentration, (filled squares) extrapolations to zero angle.

Table.1 Viscosity of the solvent $\eta$, refractive index increment $dn/dc$, radius of gyration $R_g$, hydrodynamic radius $R_h$, $\rho = R_g/R_h$, weight average molecular weight of the polyrotaxane $M_w$ and second virial coefficients $A_2$ determined in various solvent systems.

| Solvent       | $\eta$, mPa·s | $dn/dc$, ml/g | $R_g$, nm | $R_h$, nm | $\kappa$, nm | $\rho$ | $A_2$, mol·cm$^3$/g$^2$ | $M_w$, g/mol |
|---------------|---------------|---------------|-----------|-----------|--------------|--------|------------------------|-------------|
| DMAc/LiCl (2wt%) | 1.73          | $9.59 \times 10^{-2}$ | 19.4      | 10.6      | 0.31         | 1.83   | $5.41 \times 10^{-4}$ | $1.75 \times 10^5$ |
| DMF/LiCl (1wt%) | 1.04          | $1.04 \times 10^{-1}$ | 19.1      | 12.2      | 0.43         | 1.57   | $1.63 \times 10^{-3}$ | $1.07 \times 10^6$ |
| DMF/LiCl (2wt%) | 1.52          | $1.07 \times 10^{-1}$ | 21.1      | 8.3       | 0.31         | 2.54   | $6.90 \times 10^{-4}$ | $1.42 \times 10^6$ |
| DMF/LiCl (4wt%) | 2.01          | $1.10 \times 10^{-1}$ | 20.9      | 9.3       | 0.22         | 2.25   | $1.39 \times 10^{-3}$ | $1.08 \times 10^6$ |
| DMF/LiCl (6wt%) | 2.58          | $1.13 \times 10^{-1}$ | 25.6      | 10.7      | 0.18         | 2.39   | $2.09 \times 10^{-3}$ | $9.0 \times 10^6$ |
| 1 M NaOHaq.    | 1.00          | $1.43 \times 10^{-1}$ | 29.8      | 13.9      | 0.22         | 2.14   | $4.67 \times 10^{-3}$ | $1.86 \times 10^6$ |
| DMSO          | 2.00          | $5.84 \times 10^{-2}$ | 16.9      | 10.4      | -            | 1.62   | $5.28 \times 10^{-3}$ | $1.12 \times 10^6$ |

As stated in the above section, polyrotaxane molecules dissolved in NaOHaq., DMF/LiCl and DMAc/LiCl are ionized. Such ionization mechanisms are readily expected to affect net $R_g$ values of the dissolved polyrotaxanes through short- and long-range interactions. To our surprise, the recent results by Mayumi et al. [30] evidently contradict the above forecast; namely, SANS measurement of the nonionic water-soluble polyrotaxane (hydroxypropylated polyrotaxane) in D$_2$O and 1 M NaOD gave almost identical scattering profiles, in spite of the ionization of the polyrotaxane in the latter solvent [30]. Their results clearly indicate the identical $R_g$ in both solvents, and subsequently no effect of the electrical ionization on both short- and long-range interactions. Considering the results by Mayumi et al. together with ours, the present variations in $R_g$ with change in the type of solvents seems to be affected mainly by the mutual affinity between solvent and polyrotaxane, which should be evaluated by the parameter $A_2$.

† Change in $R_g$ value with the difference in the length of PEG axis should be considered. $R_g$ is proportional to (degree of polymerization)\(^{\frac{3}{5}}\) and therefore to (chain length)\(^{\frac{3}{5}}\) in a good solvent. The contour length of polyrotaxane is equal to that of PEG axis. Values of number average molecular weight $M_n$ of PEG used by Fleury et al. and us are 20000 [19] and 28600 [25], respectively. $R_g$ value of 14.5 nm for the polyrotaxane with PEG20000 axis corresponds to that of 18.0 nm for the polyrotaxane with PEG28600 axis, which well agrees with our experimental results (16.9 nm).
Our measurements on polyrotaxane solution in DMF/LiCl series also showed almost no change in $R_g$ values with the amount of added LiCl. This behavior is reasonably explained by evaluating Debye length $\kappa^{-1}$, i.e. a distance which Coulombic repulsive force is shielded, by the following eqs [31];

$$\kappa^2 = \frac{8\pi d_B C_S}{\varepsilon}$$

(7)

$$d_B = \frac{e^2}{4\pi \varepsilon_0 \varepsilon_0 kT}$$

(8)

where $d_B$ is Bjerrum length (ca. 0.7 nm in the case of aqueous systems), $C_S$ a salt concentration, $e$ the elementary charge, $T$ the absolute temperature, $\varepsilon$ the relative dielectric constant of solution, and $\varepsilon_0$ the vacuum permittivity. The values of $\kappa^{-1}$ in the used solvent systems except for DMSO are also summarized in Table 1. All of the obtained values are less than 1 nm, indicating almost shielded Coulombic interactions in these solvents. This may be the reason for the above-mentioned independence of $R_g$ values on ionization [30], especially for no change in short-range interactions.

Hydrodynamic radii $R_h$ of polyrotaxane obtained in DMAc/LiCl and DMF/LiCl seemed to be relatively lower than those in NaOHaq. and DMSO, but slightly increased with the increase in LiCl content, probably due to enhanced hydrodynamic interactions by larger degree of macrocationization. Another study on DLS measurements of cellulose dissolved in aqueous alkali metal complex solvents also suggests the quite complicated effect of selective ion/polymer binding on hydrodynamic interactions [32].

Ratio of $R_g$ to $R_h$, $\rho = R_g/R_h$, is a parameter which provides a significant information on the conformation of a polymer molecule in dilute solution. While suspension of spherulitic particles theoretically gives $\rho = 0.775$ [33], a random-coiled polymer in a theta solvent and a good solvent shows the $\rho$ values of 1.506 and 1.862, respectively [34], and the higher values are observed for semiflexible polymer solutions. The $\rho$ values calculated for all solvent system used are listed in Table 1. The $\rho$ values calculated for NaOHaq. and DMF/LiCl with LiCl content over 2wt% are all beyond 2, and indicate the semi-flexible and relatively extended chain conformation of polyrotaxane molecules in these solvent systems. The $\rho$ values for DMSO, DMAc/2wt% LiCl and DMF/1wt% LiCl (between 1.5 and 1.9), which are comparable to that of the random-coils in a good solvent (1.862), suggest that the polyrotaxane behaves as a flexible chain in these solvents.

In contrast to the estimation of $R_g$ and $R_h$ that were independent on $dn/dc$, Some considerations should be taken for the interpretation of $M_w$ and $A_2$, since these values can be affected by several difficulties such as a fluctuation of $dn/dc$ values with types of solvents [35] or selective and localized macrocation complexation [32], especially in the case of electrolyte solvents. Therefore, only a qualitative evaluation for the tendency of $M_w$ and $A_2$ are discussed in the following text.

The values of $M_w$ calculated from SLS results exhibited a wide variation with the types of solvents used, despite the use of the same polyrotaxane sample for all measurements. One of the reasons is related to the above-mentioned selective complexation or ionization of polyrotaxane, resulting in difference between refractive indices of the solution close to and apart from polymer. It can be concluded that the SLS measurements in DMSO give the most reliable $M_w$ value, considering no effect of selective cation binding and a $\rho$ value indicating flexible conformation. The $M_w$ of the polyrotaxane calculated from SLS measurement of a DMSO solution ($1.12 \times 10^5$) actually shows a value very similar to that calculated from GPC measurements ($1.40 \times 10^5$, show the experimental section), as well as that of the similar previous sample obtained by $^1$H NMR and GPC ($1.18 \times 10^5$) [25].
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