Competitive Attachment of Alkali Cations to Poly(ethylene glycol) and Poly(propylene glycol) Oligomers in Matrix-Assisted Laser Desorption/Ionization Process

Hisashi Togashi
National Institute of Materials and Chemical Research, 1-1 Higashi, Tsukuba, Ibaraki 305-8565

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In the attachment reaction of poly(ethylene glycol) oligomers, consisting of 7-13 monomers, with Li^+ or K^+ in matrix-assisted laser desorption/ionization process, Li^+-attached oligomer distribution shows larger fraction of small oligomer ions than K^+-attached oligomer distribution, while both distributions are similar to each other for poly(propylene glycol) (6-11 monomers), indicating that the chemical structure of chain is essential in the cationization reaction for linear polyglycols.

Since the introduction of matrix-assisted laser desorption/ionization mass spectrometry (MALDI-MS),[1-3] its application to the determination of molecular weight distribution (MWD) of synthetic polymers has been actively investigated.[4] The MWD is calculated from the ion intensities of cationized oligomers which are thought to be formed in temporal plumes induced by laser shots on samples.[5] It has been found that the calculated MWD depends on cation species for some polymers,[6,7] which has been attributed to the different affinities of cations to polymers.

Although poly(ethylene glycol) (PEG) and poly(propylene glycol) (PPG) belong to the class of the most widely investigated polymers[4] because of their simple structures as well as their wide application, the cation dependence effect has not been studied in detail, possibly because of difficulty in observing small difference among ion intensities, due to relatively large shot-to-shot fluctuation in MALDI signal. Nevertheless studying cation attachment reaction of such basic polymers is important to improve the precision of the MWD measurement of polymers.

In order to avoid the effect of ion abundance fluctuation caused by different laser shots or sample conditions, comparison was made between ion peaks in the same mass spectra. To provide Li^+ and K^+ ions together for competitive cationization of oligomers, $LiCl\cdot H_2O$ (99.9%) and KCl (99.9%) (Wako, Japan) were dissolved in the mixture of ethanol and water (0.985:0.015(v/v)) to make 4×10^{-3} $mol\cdot L^{-1}$ concentration for each salt. In the authors laboratory, matrix reagent 4-phenylazophenol[8] (Aldrich, USA) was found very effective to form oligomer-cation complex ions for polyglycols, resulting in spectra of good signal to noise ratio. The matrix reagent was refined by recrystallization to reduce background chemical noise in mass spectra. Poly(ethylene glycol) 400 ($H\text{-}(OCH_2CH_2)_n\text{-}OH$) or poly(propylene glycol) 425 ($H\text{-}(OCH_2CH(CH_3))_n\text{-}OH$) (Aldrich) was dissolved in ethanol (99.5%, Wako) with the matrix reagent, and then was added by the salt solution. Concentrations in the final solution were 2.5×10^{-4} $mol\cdot L^{-1}$ for sample polymer (calculated by the nominal average molecular weight),1.0×10^{-3} $mol\cdot L^{-1}$ for each alkali metal salt, and 5.0×10^{-2} $mol\cdot L^{-1}$ for matrix. The mixed solution of 4 μL was dropped over an area of 4×4 mm^2 on a silver plate while being rapidly dried in the stream of nitrogen gas at room temperature.

The silver plate was inserted into vacuum and shot by nitrogen laser pulses (wavelength 337 nm, pulse width 10 ns, repetition rate 2 Hz) to form cationized ions, which were analyzed by a time-of-flight mass spectrometer (Jordan; AREF Reflectron) and detected by a microchannel plate (MCP), whose signals were stored by a digital sampling oscilloscope (LeCroy; 9450 A). To obtain appropriate spectra, the laser irradiance was adjusted within the range of 10–20 $mJ\cdot cm^{-2}$, according to the samples. The ion signal for each pulse was monitored in order not to exceed the threshold level of the MCP and the limit of the input range of the oscilloscope. The MCP threshold level, above which relative ion intensity becomes incorrect due to MCP saturation,[9] was determined by comparison of the ion intensity ratio of potassium isotope ion peaks, $^{39}K^+$ and $^{41}K^+$, with their natural abundance.

Oligomers cationized by Li^+ or K^+, with *n* (number of monomers) = 7–13, were observed in mass spectra of PEG (Figure 1(a)), from which ion intensities were estimated by peak-integration method over linear time scale charts. The

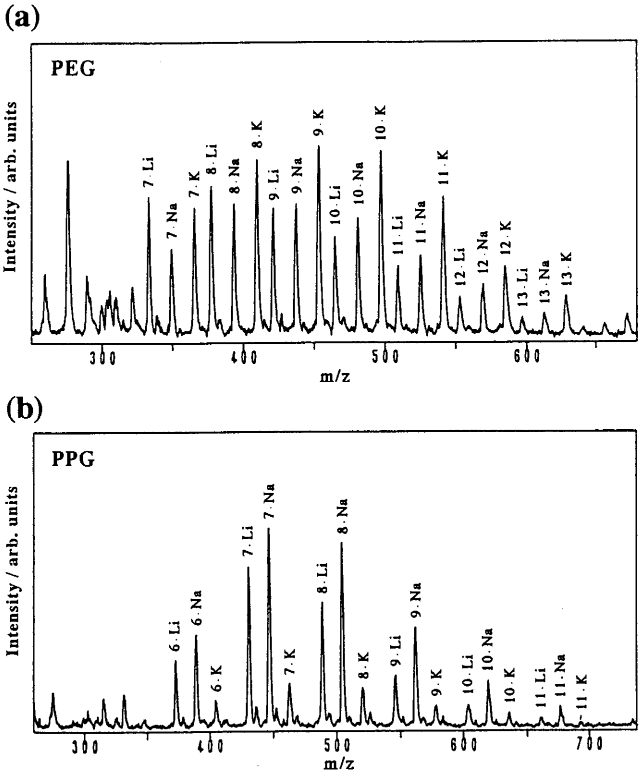

Figure 1. MALDI mass spectra of (a) PEG and (b) PPG which are averaged for 20 laser shots irradiating on the same spot of the sample. The symbol $n \cdot A$ indicates a cationized ($A^+ = Li^+$, K^+) oligomer consisting of *n* monomers.

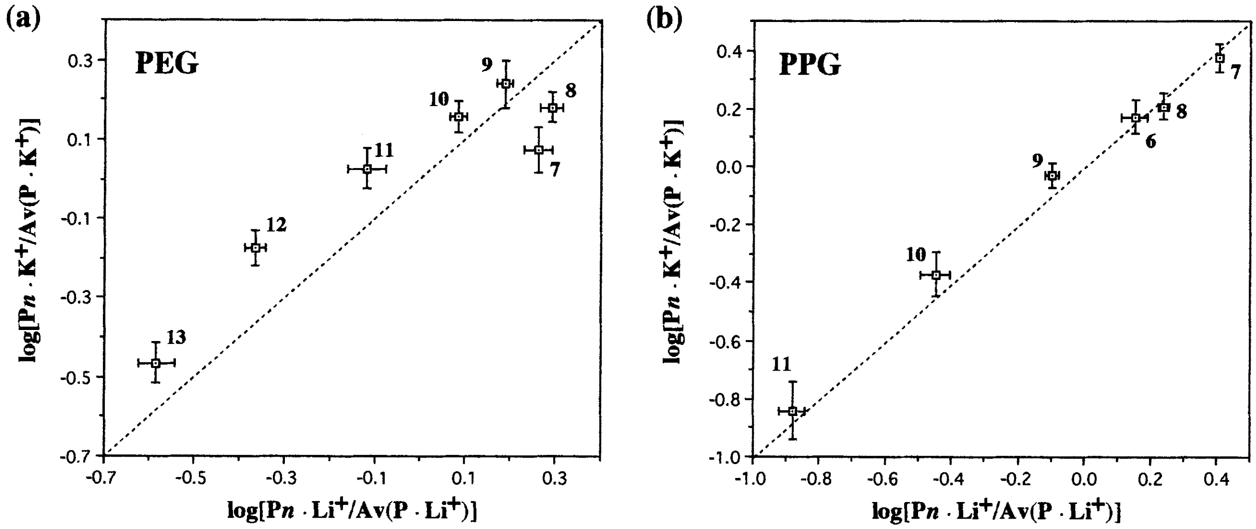

Figure 2. Comparison of relative ion abundance of cationized oligomers of (a) P=PEG and (b) PPG. The symbol P*n* · A$^+$ denotes ion intensity of a cationized (A$^+$ = Li$^+$ or K$^+$) oligomer consisting of *n* monomers and Av(P · A$^+$) is their average over *n*. Numbers in graphs indicate *n*. Bars indicate standard deviation.

Na$^+$-attached oligomers are due to sodium impurities in the polymer or matrix reagents. Area intensities for Li$^+$- and K$^+$-cationized oligomers (P*n*·A$^+$, (A = Li or K)) were normalized by their respective averages over *n* (Av(P·A$^+$)) and the normalized intensities for each oligomer are compared in Figure 2(a). The comparison of relative ion intensity, P*n*·A$^+$/Av(P·A$^+$) (≡ *Rn*A), reveals that this value is larger for Li$^+$ than K$^+$ for small oligomers and this gap decreases as *n* increases. This finding presents two possibilities: one that the small oligomers prefer Li$^+$ than K$^+$ in comparison to large oligomers in the attachment process; the other that Li$^+$ (K$^+$) is abundant with small (large) oligomers in the laser plume due to biased distributions of metal salts and polymers in the solid samples.

To examine the latter possibility, which would show certain correlation between Li$^+$ or K$^+$ ion intensities and number average molecular weights derived from corresponding cationized oligomer ions, several series of single pulse data over consecutive ten shots were measured. For both Li$^+$ and K$^+$, calculated correlation coefficients for each pulse series were distributed randomly within the range of ± 0.6, which confirms that the biased distribution is not responsible for this phenomenon. Thus the relative ion intensity represents the degree of preference of oligomers for metal ions in the attachment process, i.e. *Rn*A is proportional to cation attachment efficiency in each metal-oligomer group.

PPG showed cationized oligomer ions of 6–11 monomers (Figure 1(b)) and their relative intensities are compared in Figure 2(b). In contrast to PEG, no difference is observed between small and large oligomers in terms of cation attachment efficiency.

The similarity of *Rn*K/*Rn*Li for large PEG oligomers (Figure 2(a)) suggests that only part of the polymer chain is involved in complexation with the metal ions. This indication is consistent with the calculated structure of PEG that the number of monomers coordinating to alkali metal ions is seven or eight.[10] The flat dependence of *Rn*K/*Rn*Li on *n* for PPG may indicate that the number of coordinating monomers in the PPG chain is less than PEG because of less flexibility due to methyl groups bonded to the main chain.

With the fact that (*Rn*K/*Rn*Li)/(*R*7K/*R*7Li) ≈ 2 (*n* = 11–13) (Figure 2(a)), and with an assumption that equilibrium is established in the laser plumes with temperature of the order of 10^3 K, which is typical of plumes induced by low intensity lasers (less than 1 J·cm^{-2}) on inorganic crystals,[11] the corresponding gap in the differences in stabilization energy *E*, [*E*(P*n*·K$^+$)-*E*(P*n*·Li$^+$)]-[*E*(P7·K$^+$)-*E*(P7·Li$^+$)], would be of the order of 1 kcal·mol^{-1} when simple exponential statistical distribution is presumed. It may be worth noting that this value is much less than the difference (47.6 kcal·mol^{-1}) of aqueous solvation enthalpies of Li$^+$ (536.3 kJ·mol^{-1}) and K$^+$ (337.1 kJ·mol^{-1}).[12] It seems that relation between laser plume conditions, and the structures and energies of the cationized oligomers should be elucidated to understand ion formation process and then to improve the quantitativeness of MALDI-MS for polymers.

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