Anion Binding Properties of Poly(vinylpyrrolidone) in Aqueous Solution Studied by Halide NMR Spectroscopy

Jin Deog Song, Ryong Ryoo, and Mu Shik Jhon*

Department of Chemistry and Center for Molecular Science, Korea Advanced Institute of Science and Technology, P.O. Box 150, Cheongryang, Seoul, Korea

Received August 21, 1990

ABSTRACT: Interaction between halide ions and poly(vinylpyrrolidone) (PVP) in aqueous solution has been shown to cause significant line broadening in ^{35}Cl, ^{81}Br, and ^{127}I NMR. This excess NMR line width has been used to obtain the intrinsic binding constants of Cl^-, Br^-, and I^- with PVP. Other anionic species in the aqueous halide–PVP solution have been found to compete with the halide for binding to the polymer, resulting in a decrease of the excess halide NMR line width. Such competition between the halide and other anion has been used to obtain the intrinsic binding constants of various other anions. The binding constants follow the sequence $SO_4^{2-} < F^- < Cl^- < NO_3^- < Br^- < I^- < SCN^-$, which is nearly identical with the lyotropic series. This binding affinity correlates with the polarizability of anions.

Introduction

Interaction of anions with macromolecules in aqueous solution has been a matter of great interest. This interaction was studied by many methods, and a critical review of this field was presented by von Hippel et al.[1,2] Recently, multinuclear NMR[3-5] has been very useful in the study of halide ion binding onto macromolecules because the quadrupole relaxation rate of halide ions is often very sensitive to the environment of the ion.

In previous work,[6] we studied the origin of ^{127}I NMR line broadening in aqueous solution containing iodide ion and various water-soluble polymers such as poly(vinylpyrrolidone) (PVP), isotactic poly(2-hydroxyethyl methacrylate) (iso-PHEMA), poly(acrylamide) (PAAM), poly-(ethylene oxide) (PEO), poly(vinyl alcohol-*co*-vinyl acetate) (PVAL), and poly(acrylamide-*co*-acrylic acid) (PAA). Severe line broadening in the ^{127}I NMR was observed from PVP, iso-PHEMA, and PAAM solution and was mainly attributed to the specific binding of the iodide ion on these polymers. Small line broadening by PEO and PVAL was rather due to the asymmetric hydration of iodide anions, which is affected by the polymer–water interaction. The intrinsic broadening constant between iodide ion and various water-soluble synthetic polymers was obtained from the excess NMR line width, which was defined as the difference between the ^{127}I NMR line width obtained from an aqueous iodide solution and that from a solution containing polymer at the same iodide concentration. The binding affinity of iodide anions to polymers in aqueous solution was found to follow the order PVP > iso-PHEMA > PAAM > PEO, PVAL > PAA. We also demonstrated that the binding of iodide anion was not affected by the countercation but related to the dipole moment of the polymer segment.

Norne et al.[7] showed that halide NMR line width coming from aqueous halide–protein solution decreased in the presence of other anions that could compete with the halide for the binding on protein. They were able to obtain the intrinsic binding constant of various anions with protein in aqueous solution by using the halide NMR technique. Application of the so-called competition technique using halide NMR would be very interesting if it can also give the intrinsic binding constant of other anions with synthetic polymers in aqueous solution.

The purpose of this work is to study the interaction of PVP with various anions by the halide NMR. We attempt to obtain the intrinsic binding constants of various anions such as F^-, Cl^-, Br^-, I^-, NO_3^-, SO_4^{2-}, and SCN^- on PVP by direct halide NMR or the competition NMR technique. The relative binding affinity of the anions with PVP thus obtained will be discussed in terms of the dipole moment of the anions.

Experimental Section

Materials. PVP (MW 40 000) was dried in a vacuum oven with P_2O_5 for 2 days. Various potassium salts (Aldrich, 99+%) used were also dried in the same way. A small amount of $Na_2S_2O_3$ (10^{-3} M) was added to the polymer solution to prevent the oxidation of iodide anion, which caused a severe ^{127}I NMR line broadening.[6-10] Water was distilled three times.

Measurements of NMR Spectra. The NMR experiments on halides were performed on a Brüker AM 300-MHz spectrometer operating at 60.0 MHz for ^{127}I, 81.0 MHz for ^{81}Br, and 29.4 MHz for ^{35}Cl. All the NMR spectra were obtained with spinning and field locking by placing D_2O, sealed in a 5-mm tube, in the middle of a 10-mm sample tube. The temperature was controlled by flowing heated air around the sample tube located in the NMR probe head. The line widths at half-height were obtained by Lorentzian curve fitting.[6] The errors in measuring the line width were estimated to be ±2% for ^{127}I and ^{81}Br NMR spectra and ±5% for ^{35}Cl.

Results and Discussion

In Table I, half-height line widths in ^{127}I, ^{81}Br, and ^{35}Cl NMR of aqueous halide–PVP solutions are given at various concentrations of halide under constant PVP concentration. The NMR line width is much greater with PVP than without PVP in the solution, and the difference between the two under the same iodide concentration is the excess NMR line width. As described previously,[3-6] such large excess line widths are due to the binding of halide anions on the polymer molecule, which increases the rate of halide nuclear quadrupole relaxation observably. The binding of halide ion on polymer is usually treated as a weak Langmuir adsorption,[3] and the exchange between the free halide ion and the weakly bound halide can be assumed to occur very fast in the halide NMR. Under high excess halide concentrations the free halide concentration can be much more than the bound halide, and we may then use the following linear relation to obtain

* To whom correspondence should be addressed.

Table I
Half-Height Line Width in Halide NMR of Aqueous PVP Solution[a] Measured at Various Anionic Concentrations at 298 K

	line width, Hz							
	0.1 M	0.2 M	0.3 M	0.4 M	0.5 M	0.6 M	0.7 M	0.1 M[c]
^{127}I	5280	4380	3890	3600	3340	3230	3050	1680
^{81}Br[b]	725	680	652	626	612	601	591	419
^{35}Cl[b]	21.5	20.2	19.8	19.1	18.8	18.3	18.1	10.2

[a] PVP monomer unit concentrations were 0.050 M for I[-] and Br^{-} and 0.15 M for Cl^{-}. Approximately 10^{-3} M $Na_2S_2O_3$ was added to prevent oxidation of I[-], which can cause significant line broadening. [b] Total anionic concentration. [c] Without PVP.

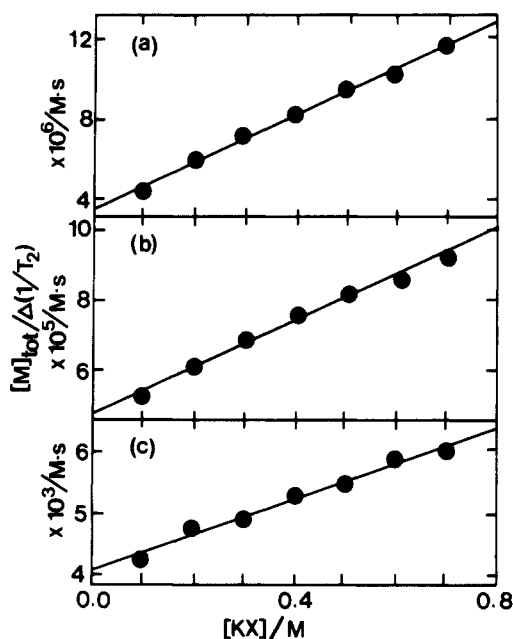**Figure 1.** Plot of $[M]_{total}/\Delta(1/T_2)$ vs (a) $[I^-]_{total}$, (b) $[Br^-]$, and (c) $[Cl^-]$ for a 0.050 M PVP in the presence of 10^{-3} M $Na_2S_2O_3$ at 298 K. $[M]_{total}$ is the total concentration of PVP, $[X^-]$ is the total concentration of halide, and $\Delta(1/T_2)$ is the excess relaxation rate.

the intrinsic binding constant $k_B(X^-)$

$$\frac{[M]_{total}}{\Delta(1/T_2)} = \frac{1}{n_B(T_{2B})^{-1}k_B(X^-)} + \frac{[X^-]_{total}}{n_B(T_{2B})^{-1}} \quad (1)$$

where n_B is the number of binding sites on macromolecules, T_{2B} is the transverse relaxation time of polymer-bound X[-], $\Delta(1/T_2)$ is the excess relaxation rate (i.e., π times the excess line width), and $[X^-]_{total}$ is the total concentration of halide ion in polymer solution. Good linearity between $[M]_{total}/\Delta(1/T_2)$ and $[X^-]_{total}$ in Figure 1a–c indicates that the assumptions used to obtain eq 1 are reasonable. The intrinsic binding constants obtained from the ratio between the slope T_{2B}/n_B and the intercept $T_{2B}/n_Bk_B(X^-)$ are 3.3, 1.4, and 0.7 M^{-1} for I[-], Br^{-}, and Cl^{-} on PVP at 298 K, respectively.

In Table II, the excess line widths in ^{127}I, ^{81}Br, and ^{35}Cl NMR of aqueous halide–PVP solution are compared with those obtained in the presence of other anions. For example, 0.050 M PVP–0.20 M KI solution gave an excess ^{127}I NMR line width of 2990 Hz, whereas the excess line width decreased to 1810 Hz when 0.20 M KSCN was added into the solution. This decrease in the ^{127}I NMR line width is due to the competition between SCN[-] and I[-] for the same binding site of PVP, which generally results in decreasing the concentration of PVP-bound I[-]. The excess ^{127}I NMR line width from 0.050 M PVP–0.20 M KI–0.20 M KSCN solution is even smaller than that (1920 Hz) from 0.050 M PVP–0.4 M KI, which indicates that SCN[-] binds more strongly to PVP than does I[-]. On the other hand, the excess ^{127}I NMR line width of 2340 Hz was
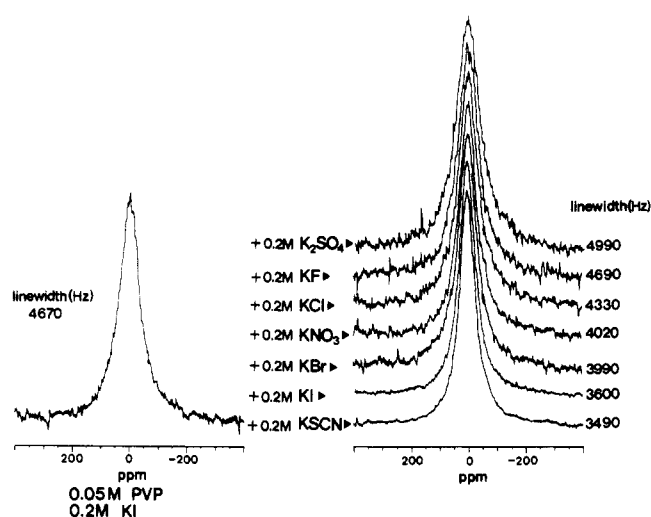

Figure 2. NMR spectra obtained from aqueous solution containing 0.20 M KI and 0.20 M other salt and 0.050 M PVP at 298 K, in the presence of 10^{-3} M $Na_2S_2O_3$.

Table II
Excess Line Width in ^{127}I, ^{81}Br, and ^{35}Cl NMR of Aqueous PVP Solution[a] with Different Anions at 298 K

	line width, Hz		
	^{127}I[b]	^{81}Br[c]	^{35}Cl[d]
SCN[-]	1810	153	10.7
I[-]	1920[e]	187	11.2
NO$_3$[-]	2340	214	13.5
Br^{-}	2310	226[f]	13.2
Cl^{-}	2650	256	15.2[g]
F[-]	2960	304	16.4
SO$_4$[2-]	3310	341	16.8
I[-]	2990	268	16.3

[a] In the presence of 10^{-3} M $Na_2S_2O_3$. [b] 0.050 M PVP, 0.20 M KI, and 0.20 M other potassium salt except for e. [c] 0.050 M PVP, 0.20 M KBr, and 0.20 M other potassium salt except for f. [d] 0.21 M PVP, 0.20 M KCl, and 0.10 M other potassium salt except for g. [e] 0.050 M PVP and 0.40 M KI. [f] 0.050 M PVP and 0.40 M KBr. [g] 0.21 M PVP and 0.30 M KCl.

Table III
Activation Energy[a] of Transverse Relaxation in ^{127}I in Aqueous PVP Solution[b] Containing Other Anions, in the Temperature Range of 25–55 °C

KI[c]	KI[d]	KBr[e]	KCl[e]	KF[e]	KNO$_3$[e]	KSCN[e]	K$_2$SO$_4$[e]
22.8	20.9	22.2	23.0	23.7	22.1	20.4	24.8

[a] From $(1/T_2) = Ae^{E/RT}$ in kJ mol^{-1}.[3] [b] In the presence of 10^{-3} M Na_2S_2O. [c] 0.050 M PVP and 0.20 M KI. [d] 0.050 M PVP and 0.40 M KI. [e] 0.050 M PVP, 0.20 M KI, and 0.20 M other salt.

obtained from 0.050 M PVP–0.20 M KI–0.20 M KNO$_3$ solution, indicating that NO$_3$[-] binds more weakly to PVP than I[-]. Such successive comparisons of ^{127}I NMR line width in Table II give us the order of binding affinity, SCN[-] > I[-] > Br^{-} > NO$_3$[-] > Cl^{-} > F[-] > SO$_4$[2-]. The competing effect of other anions with iodide on the ^{127}I NMR spectra can be seen in Figure 2. As can also be inferred from the ^{81}Br and ^{35}Cl NMR data listed in Table II, similar

Table IV
Excess [127]I NMR Line Width[a] from Aqueous PVP–KI Solutions[b] Containing Competing Anions

	line width							
	0.10 M	0.15 M	0.20 M	0.25 M	0.30 M	0.35 M	0.40 M	0.45 M
KI[c]	3.60	3.02	2.70	2.44	2.21	2.06	1.92	1.84
KSCN	2.56	2.04	1.81	1.62	1.43	1.32	1.22	1.15
KNO_3	3.10	2.71	2.34	2.12	1.95	1.80	1.69	1.60
KBr	3.00	2.62	2.31	2.07	1.97	1.74	1.64	1.54
KCl	3.45	3.00	2.65	2.37	2.20	2.02	1.91	1.82
KF	3.62	3.23	2.96	2.74	2.60	2.40	2.28	2.21
K_2SO_4	4.00	3.57	3.31	3.19	2.94	2.85	2.79	2.66

[a] In kilohertz. [b] Same concentrations of I^- and competing anions except for c in the presence of approximately 10^{-3} M $Na_2S_2O_3$ at 298 K. [c] KI aqueous solution without PVP.
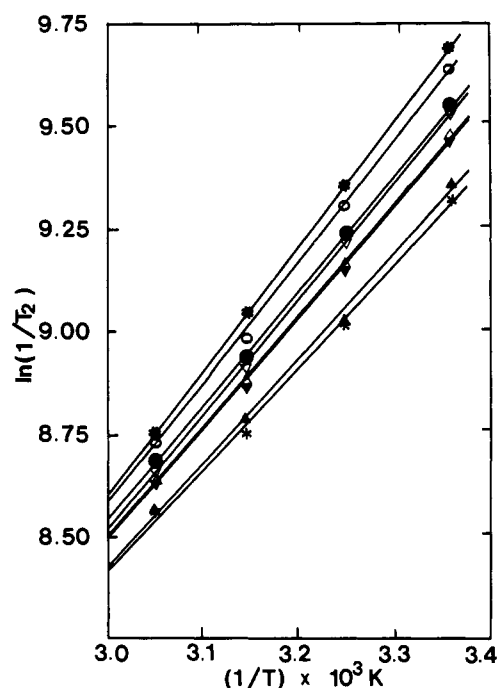

Figure 3. Temperature dependence of [127]I NMR relaxation rate obtained from aqueous 0.050 M PVP solution containing 0.20 M KI and 0.20 M other salt in the presence of 10^{-3} M $Na_2S_2O_3$. Other salt: K_2SO_4 (✳), KF (○), KCl (▽), KNO_3 (△), KBr (▼), KI (0.4 M) (▲), KSCN (*), KI (0.20 M) (●).

Figure 4. $k_B(X^-)/k_B(I^-)$, under the same concentrations of I^- and competing anions (X^-) in 0.050 M aqueous PVP solution given as a function of concentration in the presence of 10^{-3} M $Na_2S_2O_3$ at 298 K. $k_B(X^-)$ is the intrinsic binding constant for PVP. Competing anions: SO_4^{2-} (✳), F^- (○), Cl^- (▽), NO_3^- (△), Br^- (▼), SCN^- (*).

Table V
Intrinsic Binding Constants of Various Anions Obtained from Direct Halide NMR or from [127]I NMR Competition Experiments at 298 K

	from eq 4[a]	from eq 1[b]
SCN^-	5.3	
I^-	3.3	3.3
Br^-	2.4	1.4
NO_3^-	1.9	
Cl^-	0.5	0.7
F^-	−0.1	
SO_4^{2-}	−1.2	

[a] By competition NMR experiment at 0.1 M anions concentration. [b] By halide NMR experiment.

competition experiments using ^{81}Br or ^{35}Cl NMR have independently provided the same binding order obtained by the competition experiments using [127]I NMR. The order of intrinsic binding constants of anions is nearly identical with the well-known lyotropic series, which is determined by dispersion forces. Consequently, the polarizability of anions parallels their affinity for PVP.

It is unusual tht the excess line width from 0.050 M PVP–0.20 M KI–0.20 M KF or K_2SO_4 is greater than the excess line width, i.e., 2990 Hz, from 0.050 M PVP–0.20 M KI. This exceptional result can be explained as arising from enhanced hydrophobic attraction between polymer chains due to the water-structure-making ions. According to von Hippel et al.,[1] F^- and SO_4^{2-} are typical water-structure-making ions, the water-structure-enhancing effect of which stabilizes conformations[11] of various proteins. Such a stabilization effect, if it also exists in PVP solution, will make the polymer chain more hydrophobic[12,13] because water is expelled from the vicinity of the nonpolar groups of PVP into the bulk phase. It may be expected that this enhanced hydrophobic nature of PVP chain will increase the excess [127]I line width due to asymmetric hydration.[14-16] The concept of asymmetric hydration means that the arrangement of water molecules around an ion is distorted by the presence of other species in the solution. The more
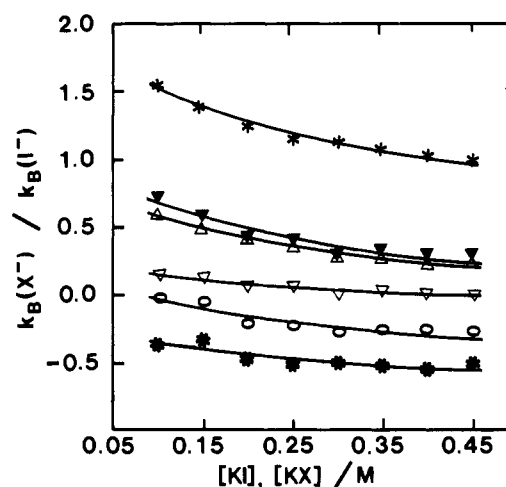
asymmetric the hydration of a quadrupole nucleus, the higher its relaxation rate.

Figure 3 shows an Arrhenius plot of the [127]I NMR line width at half-height and the temperature for aqueous KI–PVP solutions in the presence of other competing anions. Good linearity with a positive slope confirms our previous assumption that I^- exchanges very rapidly between the free state and the PVP-bound state. Table III shows that the activation energy obtained from Figure 3 agrees with the binding affinity sequence of anions on PVP, which was determined by the above competition experiments. Therefore, it appears that the bound I^- has a much higher activation energy of transverse relaxation than the free I^- does, and thus the average value of the activation energy becomes smaller with competing ions of higher binding affinities.[6]

If the binding of halide ion X^- and competing ion Y^- occurred without interference such as the change in the

hydrophobic nature of the PVP chain, their binding can be treated as independent Langmuir adsorptions.[3] Then

$$\Delta\left(\frac{1}{T_2}\right) = [M]_{total}\left(\frac{n_B(T_{2B})^{-1}k_B(X^-)}{1 + k_B(X^-)[X^-]_{total} + k_B(Y^-)[Y^-]_{total}}\right) \qquad (2)$$

where $k_B(Y^-)$ and $[Y]_{total}$ are the intrinsic binding constant and the concentration of Y^-, respectively. When $[Y^-]_{total}$ = 0, eq 2 becomes

$$\Delta(1/T_2)_0 = [M]_{total}\left(\frac{n_B(T_{2B})^{-1}k_B(X^-)}{1 + k_B(X^-)[X^-]_{total}}\right) \qquad (3)$$

where $\Delta(1/T_2)_0$ denotes $\Delta(1/T_2)$ at $[Y^-]_{total}$ = 0. From eqs 2 and 3, the ratio of two intrinsic binding constants can be obtained as

$$\frac{k_B(Y^-)}{k_B(X^-)} = \frac{n_B(T_{2B})^{-1}}{[Y^-]_{total}}\left[\frac{[M]_{total}}{\Delta(1/T_2)} - \left(\frac{[M]_{total}}{\Delta(1/T_2)_0}\right)\right] \qquad (4)$$

where $n_B(T_{2B})^{-1}$ is obtained from the slope and intercept in Figure 1 and $\Delta(1/T_2) = \pi\Delta\nu_{1/2}$.

The ^{127}I NMR line widths ($\Delta\nu_{1/2}$) are given in Table IV for 0.050 M aqueous PVP solutions containing various concentrations of I^- and other competing ions. When the values in Table IV are put into eq 4, $k_B(Y^-)/k_B(I^-)$ was obtained at various concentrations of KI as shown in Figure 4. The relative binding constant between iodide and other anions for PVP decreased as the concentration of ions increased. At high concentrations, the iodide and the competing ions will be difficult to bind to PVP independently because the binding sites on PVP become occupied by anions. The PVP chain in this state will be more or less stretched. Therefore, the ratio of intrinsic binding constants can be obtained only at sufficiently low concentrations of ions. At extremely low concentrations, however, the precision of the NMR line-width measurement is limited by the low intensity of the halide NMR signal. In this work, $k_B(X^-)/k_B(I^-)$ obtained at 0.1 M concentration was chosen to give $k_B(X^-)$ values by multiplying with $k_B(I^-) = 3.3$ M^{-1} (listed in Table V). Comparison of $k_B(Br^-) = 2.4$ obtained from eq 4 and 1.4 obtained from eq 1 indicates that the uncertainty of k_B can be at least ± 0.5 M^{-1}.

Conclusions

In this work, ^{127}I, ^{81}Br, and ^{35}Cl NMR experiments at 298 K gave the intrinsic binding constants of 3.3, 1.4, and 0.7 M^{-1}, respectively, for the binding of I^-, Br^-, and Cl^- to PVP dissolved in aqueous solution. Using competitive binding between I^- and other anions, similar ^{127}I NMR experiments gave the intrinsic binding constants of 0.5, 1.9, 2.4, 3.3, and 5.3 M^{-1} for Cl^-, NO_3^-, Br^-, I^-, and SCN^-, respectively. It has been shown that anions with higher polarizability can bind to PVP more strongly, which suggests that dispersion forces are responsible for the binding between anion and PVP. F^- and SO_4^{2-} did not seem to bind to PVP significantly but increased the hydrophobic property of the PVP chain in aqueous solution. In this way, our work using direct or competitive halide NMR was very useful in elucidating the nature of anion binding on polymer in aqueous solution.

References and Notes

(1) von Hippel, P. H.; Schleich, T. In *Structure and Stability of Biological Macromolecules*; Timasheff, S. N., Fasman, G. D., Eds.; Marcel Dekker: New York, 1969; p 409.
(2) von Hippel, P. H.; Peticolas, V.; Schack, L.; Karlson, L. *Biochemistry* **1973**, *12*, 1256.
(3) Lindman, B.; Forsén, S. In *Chlorine, Bromine and Iodine NMR*; Diehl, P., Fluck, E., Kosfeld, R., Eds.; Springer Verlag: Berlin, 1976.
(4) Lindman, B.; Forsén, S. In *NMR and the Periodic Table*; Harris, R., Mann, B., Eds.; Academic Press: New York, 1978; Chapter 13.
(5) Drakenberg, T.; Forsén, S. In *The Multinuclear Approach to NMR Spectroscopy*; Lambert, J. B., Riddell, F. G., Eds.; D. Reidel Publishing Company: Dordrecht, The Netherlands, 1983.
(6) Oh, S. H.; Ryoo, R.; Jhon, M. S. *Macromolecules* **1990**, *23*, 1671.
(7) Norne, J. E.; Hjalmarsson, S. G.; Lindman, B.; Zeppezauer, M. *Biochemistry* **1975**, *14*, 3401.
(8) Cournoyer, R. F.; Siggia, S. *J. Polym. Sci., Polym. Chem. Ed.* **1974**, *12*, 603.
(9) Sakurada, J.; Hosoya, T.; Shimizu, T.; Hatano, M. *Chem. Lett.* **1985**, 211.
(10) Parsegian, V. A. *Annu. Rev. Biophys. Bioeng.* **1973**, *2*, 221.
(11) Schrier, E. E.; Schrier, E. G. *J. Phys. Chem.* **1967**, *71*, 1851.
(12) Frank, H. S.; Evans, M. W. *J. Chem. Phys.* **1945**, *13*, 507.
(13) Kauzman, W. *Adv. Protein Chem.* **1959**, *14*, 1.
(14) Hertz, H. G.; Holz, M. *J. Phys. Chem.* **1974**, *78*, 1002.
(15) Florin, E. *Macromolecules* **1985**, *18*, 360.
(16) Yudasaka, M.; Sugawara, T.; Iwamura, H.; Fujiyama, T. *Bull. Chem. Soc. Jpn.* **1982**, *55*, 311.