ION/POLYMER INTERACTIONS IN POLYELECTROLYTE GELS

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Abstract

We report results from experimental studies performed on polyelectrolyte gels to understand the volume transition induced by multivalent cations. Macroscopic osmotic and mechanical measurements are made to determine the effect of ion binding on the elastic and mixing contributions of the network free energy. Small-angle neutron scattering is used to reveal the role of multivalent ions in the organization of the polymer segments. We demonstrate that combination of scattering and osmotic measurements allows us to determine the characteristic size of the structural elements that contribute to the osmotically driven concentration fluctuations, and yields important information on the effect of ions on the structure and thermodynamic properties at both molecular and supermolecular levels.

Introduction

Polymers, biomaterials, and soft-matter science are of ever increasing importance, both from the fundamental and applied viewpoints. An emerging area of considerable importance relates to biomimetic polymer networks and gels. There is a rapidly increasing demand for materials with controlled properties such as "smart hydrogels", medical implants, scaffolds for tissue engineering, and *in-vivo* drug-delivery systems. In polymer gels different kind of interactions (electrostatic, van der Waals, hydrophobic interactions, hydrogen bonding, etc.) play role in driving the formation of complex hierarchical structures. What is unique about these materials is that, rather than the local molecular configuration, the long-range polymer structures are most likely to be the key to their physical behavior. Consequently, material properties such as osmotic and mechanical properties, hydration, transport properties (permeability) must be characterized to dimensions below a few hundred nanometers. Small-angle neutron scattering (SANS) and small-angle X-ray scattering (SAXS) are ideally suited methods for such studies since enhanced spatial resolution is crucial.

In this work we study the volume transition induced by the addition of calcium ions in charged synthetic and biopolymer gels. Macroscopic osmotic and mechanical measurements are made to determine the effect of changes in the ionic environment on the elastic and mixing contributions of the network free energy. SANS is used to reveal the organization of the polymer segments and obtain information on the thermal concentration fluctuations that control the thermodynamic properties. A comparison is made between the scattering and osmotic measurements to reveal the correspondence between the microstructure and the macroscopic thermodynamic response.

Theory

The free energy of a swollen polymer network can be expressed as a sum of three terms (1), corresponding to the mixing, the elastic and the ionic contributions, respectively

$$\Delta F = \Delta F_{mix} + \Delta F_{el} + \Delta F_{ion} \qquad (1)$$

The contribution of the elastic term in lightly cross-linked networks can be described by the Gaussian theory of rubber elasticity (2,3). In fully neutralized polyelectrolytes, in the presence of added salt, the ionic term is not expected to play an explicit role. Ionic interactions, however, may modify the mixing free energy contribution. In neutral polymer solutions the Flory-Huggins theory (1), based on the lattice model of solutions, expresses the mixing pressure as

$$\Pi_{mix} = \frac{\partial F_{mix}}{\partial n_1} = -\frac{RT}{v_1}\left[\ln(1-\varphi) + \varphi + \chi_0\varphi^2 + \chi_1\varphi^3\right] \qquad (2)$$

where φ is the volume fraction of the polymer, v_1 is the molar volume of the solvent, n_1 is the number of the moles of the solvent, R is the gas constant, T is the absolute temperature, and χ_0 and χ_1 are constants that depend on the strength of the interactions.

The neutron scattering intensity from a neutralized polyelectrolyte gel can be given by a sum of thermodynamic and static components (4-6)

$$I(q) = I_{osm}(q) + I_{stat}(q)$$

$$= \Delta\rho^2\left[\frac{kT\varphi^2}{M_{os}}\frac{1}{(1+qL)}\frac{1}{\left(1+q^2\xi^2\right)} + A\varphi^n\right] \qquad (3)$$

where $\Delta\rho^2$ is a constrast factor, k is the Boltzmann constant, ξ and L are correlation lengths, q is the scattering vector, A and n are constants. The first term in eq. 3 describes the thermodynamic concentration fluctuations the amplitude of which is governed by the longitudinal osmotic modulus M_{os} of the gel, while the

second term arises from concentration fluctuations frozen-in by the cross-links.

Experimental

Gel Preparation

Sodium polyacrylate (SPA) gels were made by free-radical polymerization at 30 % (w/w) acrylic acid monomer concentration in the presence of 0.3 % N,N'-methylenebis(acrylamide) cross-linker as described previously (7). After gelation the remaining acrylic acid units were neutralized by NaOH.

DNA gels were made from deoxyribonucleic acid sodium salt (Sigma). The molecular weight determined by ultracentrifugation was 1.3×10^6 Da. DNA gels were prepared (8) from a 3 % (w/w) solution by cross-linking with ethyleneglycol diglycidyl ether at pH = 9.0 using TEMED to adjust the pH.

Both SPA and DNA gels were swollen in 40 mM NaCl solution, and then the concentration of the $CaCl_2$ in the surrounding NaCl solution was gradually increased up to 2.0 mM.

Swelling Pressure and Elastic Modulus Measurements

Swelling pressure measurements were made by equilibrating the gels with aqueous solutions of poly(vinyl pyrrolidone) (M_n = 29 kDa) of known osmotic pressure (9,10). The penetration of the polymer into the swollen network was prevented by a semipermeable membrane.

Elastic (shear) modulus measurements were carried out on cylindrical gel samples using a TA.XT2I HR Texture Analyser (Stable Micro Systems, UK). Swollen networks were uniaxially compressed (at constant volume) between two parallel flat plates. The stress-strain isotherms were determined in the range of deformation ratio $0.7 < \Lambda < 1$.

The data were analyzed using the relation (1,2)

$$\sigma = G(\Lambda - \Lambda^{-2}) \qquad (4)$$

where σ is the nominal stress (related to the undeformed cross-section of the gel cylinder). The absence of volume change and barrel distortion was checked by measuring the dimensions of the deformed and undeformed gel cylinders.

Small-angle Neutron Scattering

SANS measurements were made on the NG3 instrument (11) at the National Institute of Standards and Technology (NIST, Gaithersburg MD). The q range explored was $0.003\ \text{Å}^{-1} \le q \le 0.25\ \text{Å}^{-1}$, and counting times of between twenty minutes and two hours were used. D_2O was used as solvent. After radial averaging, corrections for incoherent background, detector response and cell window scattering were applied. The neutron scattering intensities were calibrated using absolute intensity standards (11). All experiments were carried out at 25 ± 0.1°C.

Results and Discussion

Figure 1 shows the dependence of the swelling degree ($1/\varphi$) on the $CaCl_2$ concentration for SPA and DNA gels swollen in 40 mM NaCl solution. With increasing $CaCl_2$ concentration both systems display a sudden volume change. The sharp variation of the swelling degree indicates that the transition is a cooperative process.

It follows from eq. 1 that the swelling pressure of the gel Π_{sw} is the sum of elastic Π_{el}, mixing Π_{mix} and ionic Π_{ion} contributions (1)

$$\Pi_{sw} = \Pi_{el} + \Pi_{mix} + \Pi_{ion} \qquad (5)$$

In what follows we investigate the effect of calcium ions on the terms of eq. 5.

The elastic contribution can be expressed by the shear modulus G of the gel (1,2)

$$\Pi_{el} = -G = -\mathrm{ART}\nu\varphi^{1/3} \qquad (6)$$

where ν is the concentration of the elastic chains in the network, and A is a constant that depends on the functionality of the cross-links.

In Figures 2 and 3 the effect of Ca^{2+} ions on the shear moduli of SPA and DNA gels is compared. In SPA gels G is practically independent of the $CaCl_2$ concentration. This result implies that Ca^{2+} ions make no significant contribution to the cross-link density. In contrast, the elastic properties of DNA gels are substantially modified by Ca^{2+} ions. It is likely that Ca^{2+} ions replace condensed sodium ions, and reduce the repulsion between DNA strands. Molecular association creates DNA-rich domains separated by regions of diminished DNA concentration. The elastic modulus of a gel containing concentrated zones embedded into a soft elastic matrix is governed by the properties of the matrix. This picture is consistent with the observed decrease of G at high swelling degrees in the presence of Ca^{2+} ions. At higher DNA concentration, however, the elastic modulus of the Ca-containing gel exceeds that of the corresponding Ca-free gel (8)

Figure 4 illustrates the dependence of the osmotic mixing pressure Π_{mix} on the polymer volume fraction φ for gels shown in Figure 1. Each curve was measured at constant $CaCl_2$ concentration. The data indicate that the osmotic pressure gradually decreases as Ca^{2+} ions replace Na^+ ions. At a threshold $CaCl_2$ concentration the osmotic pressure vanishes and a volume transition occurs.

In Figure 5 is shown the variation of χ_0 and χ_1 with the $CaCl_2$ concentration for SPA and DNA gels. In both systems the second order interaction parameter χ_0 varies weakly with the polymer concentration, while the third order interaction parameter χ_1 exhibits a sharp, jump-like increase at low $CaCl_2$ concentration.

In general, changes in the thermodynamic properties are reflected by changes in the scattering response since the scattering intensity is governed by the osmotic compressibility of the system (4-6). To reveal structural changes induced by the ion exchange process we made SANS measurements. In the SANS experiment, small mobile counterions are not directly visible; their effect is expected to be perceived only through the changes they induce in the local structure. Figure 6 shows the SANS spectra of SPA and DNA gels below the volume transition. For small values of q both gels exhibit a power law behavior with a slope close to –4. This dependence can be attributed to surface scattering caused by aggregated polymer molecules (12). The observed behavior is quite common in polyelectrolyte solutions and gels, however as yet poorly understood (13). At intermediate values of q the scattering intensity decreases linearly with q. This scattering response is characteristic of rod-like structural elements (14). At high values of q the scattering intensity is governed by the local (short-range) geometry of the polymer chains.

The continuous curve through the data points is the fit of eq. 3 to the SANS data. The values of ξ and L obtained from the fits are displayed in Figure 6. The results indicate that in the length scale range relevant to the osmotic properties the scattering intensity is dominated by scattering from rod-like elements. Furthermore, the similarities between the behavior of SPA and DNA gels suggest that the interactions that govern the large-scale organization of the molecules are not significantly affected by the chemical structure of the polymer.

According to eq. 3 the intensity scattered by thermal fluctuations is proportional to φ^2/M_{os}. This quantity can be calculated independently from macroscopic measurements using eq. 7

$$M_{os} = \varphi \frac{\partial \Pi_{sw}}{\partial \varphi} + \frac{4}{3} G$$

$$= \varphi^2 \frac{RT}{v_1} \left(\frac{1}{1-\varphi} - 2\chi_0 - 3\chi_1 \varphi \right) + G \qquad (7)$$

Figure 7 compares the dependence upon the calcium concentration of φ^2/M_{os}, calculated from macroscopic measurement (open circles) with the intensity of osmotic scattering component measured by SANS (filled circles). The agreement between these results indicates that the effective molecular interactions that govern the volume transition are independent of the length scale of the observations, i.e., the large structures detected in the SANS experiment do not affect significantly the thermodynamic properties of the gel.

Conclusions

Osmotic and scattering measurements reveal close similarities between the structure and macroscopic osmotic properties of weakly cross-linked SPA and DNA gels swollen in nearly physiological salt solutions. Addition of $CaCl_2$ induces a reversible volume transition in both systems. Ca ions produce a sudden increase in the third order Flory-Huggins interaction parameter, while the second order interaction parameter only weakly increases. Shear modulus measurements reveal differences between the elastic properties of SPA and DNA gels. The shear modulus of SPA gels is practically independent of the $CaCl_2$ concentration of the surrounding salt solution. The shear modulus of Ca-containing DNA gels is smaller at low DNA concentration, and greater at high DNA concentration than that of the corresponding Ca-free DNA gel. SANS measurements indicate that the main features of the scattering spectra of SPA and DNA gels are identical. The thermodynamic properties of both gel systems are governed by rod-like structural elements.

Acknowledgements

This research was supported by the Intramural Research Program of the NICHD, NIH. The authors acknowledge the support of the National Institute of Standards and Technology, U.S. Department of Commerce for providing access to the NG3 small angle neutron scattering instrument used in this experiment. This work utilized facilities supported in part by the National Science Foundation under Agreement No. DMR-0454672.

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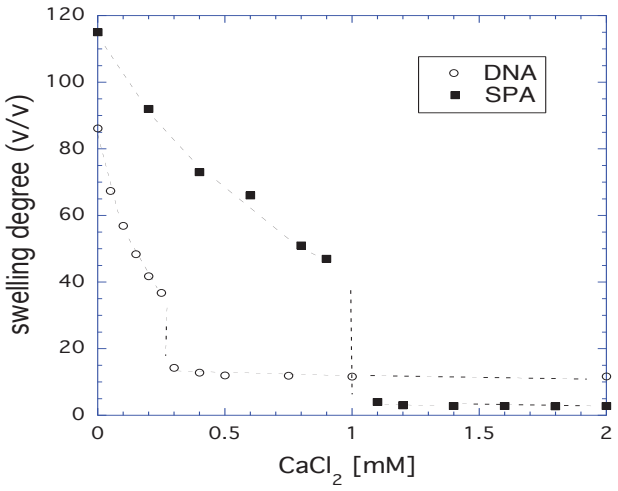

Figure 1. Dependence of the swelling degree of DNA and SPA gels on the $CaCl_2$ concentration of the surrounding 40 mM NaCl solution.

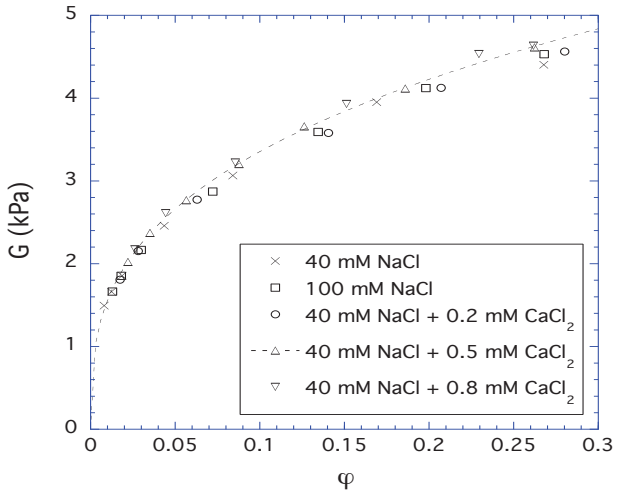

Figure 2. Variation of the shear modulus of SPA gels with the polymer volume fraction in 40 mM NaCl solution containing different amounts of $CaCl_2$.

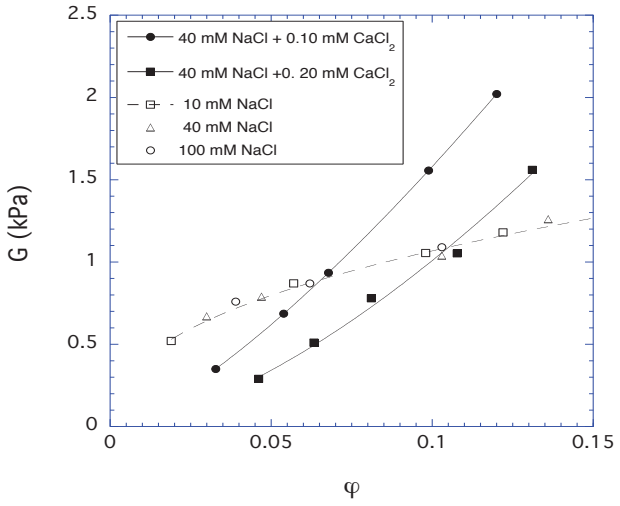

Figure 3. Variation of the shear modulus of DNA gels with the polymer volume fraction in 40 mM NaCl solution containing different amounts of $CaCl_2$.

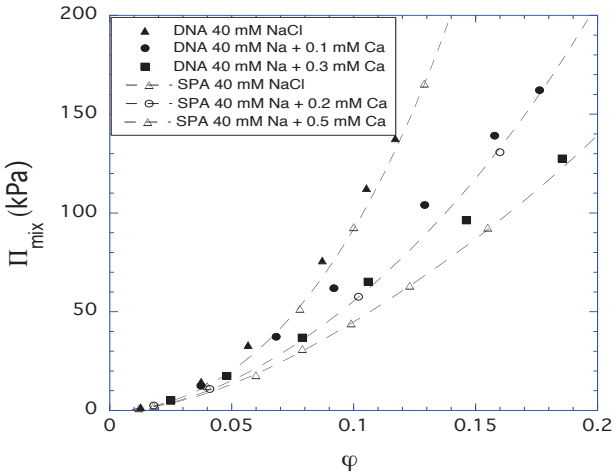

Figure 4. Osmotic mixing pressure of DNA and SPA gels as a function of the polymer volume fraction measured in 40 mM NaCl solutions containing different amounts of $CaCl_2$. Dashed curves show the fits of eq. 2 to the SPA data.

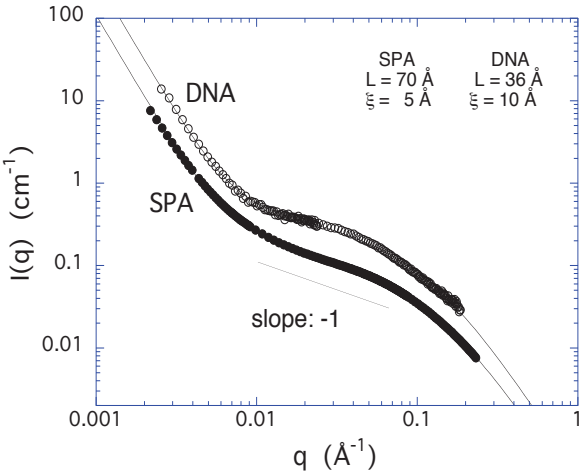

Figure 6. SANS intensity from DNA and SPAA gels in 40 mM NaCl solution containing $CaCl_2$. (DNA gel: 0.25 mM $CaCl_2$, SPA gel: 0.8 mM $CaCl_2$). Lines: fit of eq. 3 to the SANS data.

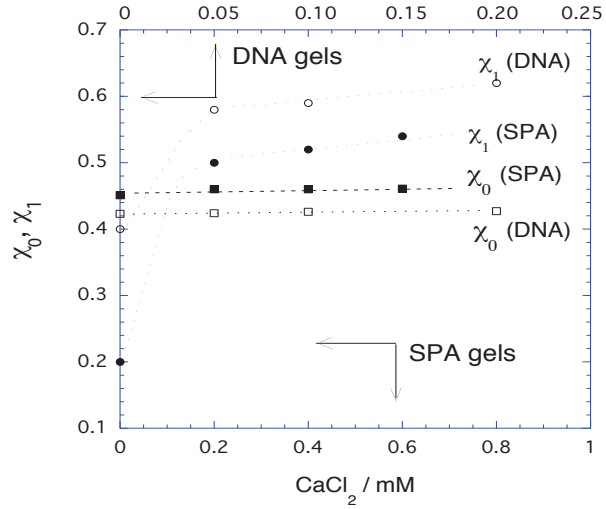

Figure 5. Variation of χ_1 and χ_2 as a function of the $CaCl_2$ concentration in DNA and SPA gels swollen in 40 mM NaCl solution.

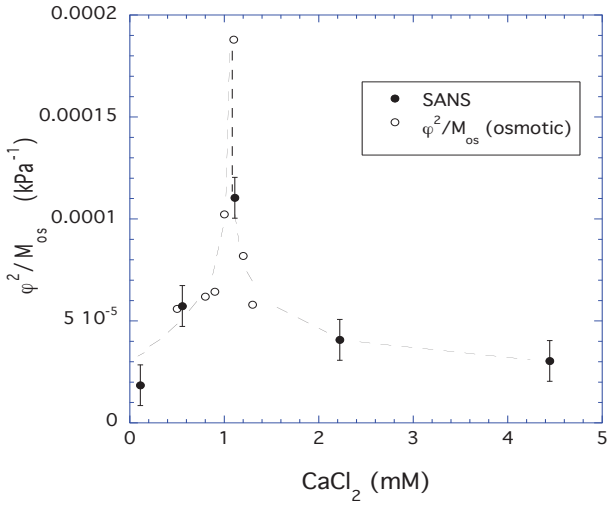

Figure 7. Comparison between φ^2/M_{os} determined from macroscopic measurements (open circles) and the amplitude of the osmotic contribution of the SANS spectrum (filled circles). The latter data were multiplied by the factor $3.8\ 10^{-3}$.

Key Words: polymer gel, swelling, osmotic pressure, elastic modulus, small-angle neutron scattering