PHYSICAL REVIEW E **75**, 011801 (2007)

Macroscopically probing the entropic influence of ions: Deswelling neutral microgels with salt

T. López-León[1,*] and A. Fernández-Nieves[2,3]

[1]*Biocolloid and Fluid Physics Group, Department of Applied Physics, University of Granada, Av. Fuentenueva S/N, 18071 Granada, Spain*

[2]*Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

[3]*Interdisciplinary Network of Emerging Science and Technology (INEST) Group, Research Center, Phillip Morris USA, Richmond, Virginia 23298, USA*

(Received 8 June 2006; published 8 January 2007)

Polymeric microgels are very interesting systems to study polymer-solvent interactions since they react to changes in the solvent properties by swelling or deswelling to reach a final equilibrium state of minimal free energy. Accordingly, factors such as pH, temperature, or salt concentration can induce size changes. While the volume phase transition undergone by ionic microgels with addition of salt is reasonably well understood in terms of Donnan effects, the origin of these transitions in neutral microgels is devoid of such understanding. In this paper, the effects of electrolytes on the swelling behavior of neutral thermosensitive microgels are interpreted within the Flory-Rehner theory for the swelling of neutral gels, by considering that ionic concentration affects the entropic contribution to the Flory solvency χ parameter; this manifests macroscopically as particle deswelling. The entropic changes depend on the ability of the electrolyte to disrupt the neighboring water structure and result in increasing values of χ with salt concentration. In this sense, we find a clear correlation between the deswelling ability of the ions and their chaotropic (structure breaking) or kosmotropic (structure making) nature as classified in the Hofmeister series.

DOI: 10.1103/PhysRevE.75.011801 PACS number(s): 61.25.Hq, 83.80.Kn, 61.20.Qg

I. INTRODUCTION

Gels are cross-linked polymers immersed in a liquid. Their mesoscopic versions, microgels, exhibit faster kinetics and the inherent richness of colloidal suspensions. Among these, those based on Poly-(N-isopropylacrylamide) (PNIPAM) have received special attention probably because the volume transition is triggered thermally and temperature is easy to tune. The mechanism responsible for the water solubility of these gels is related to the formation of structured water cages around the isopropyl groups of the polymer [1], which are the hydrophobic sites of PNIPAM. Changes in this water structure, as promoted, for example, by molecular agitation, induce a hydrophobic attraction among isopropyl groups that results in gel collapse. It is this hydrophobic interaction through the entropic contribution to the free energy of the system that is responsible for the deswelling of PNIPAM gels.

Polymeric macrogels and microgels are thus very interesting systems to study polymer-solvent interactions, since the system free energy is minimized by dynamically changing the polymer conformation and the surrounding water structure, that in the end determine the final equilibrium size. They can thus be used to access, in a simple way, the effects of a polymer environment change, as induced by changing the solvent itself or by dissolving substances that can potentially change such an atmosphere.

The presence of electrolytes in aqueous solutions disrupts the molecular structure of the pure liquid water [2]. The structural modifications induced by different electrolytes are not identical at all; in fact, they can be extremely different depending on the nature of the dissolved salt. Ions that interact with water stronger than water itself are known as structure makers or kosmotropes, whereas ions having the opposite effect are known as structure breakers or chaotropes [3]. According to this feature, ions are commonly ranked in the so called lyotropic or Hofmeister series. This ion ranking was first observed in 1888, when Hofmeister studied the effects of different neutral salts on the solubility of proteins [4,5]. Since then, a great number of experiments have revealed the same order when studying systems and properties of a very diverse nature [6].

A representative Hofmeister series for anions and cations is given in Table I. Although there is still no general conceptual framework available to provide a compelling explanation for why these effects occur, water structure and how ions modify such structures are key points in understanding Hofmeister effects; this is inferred from a number of experiments with different techniques. Examples include electrochemistry [7,8], quasielastic neutron scattering [9] and neutron diffraction [10], vibrational spectroscopy [11,12], and nuclear magnetic resonance [13].

While the effect of electrolyte concentration over the swelling of ionic macrogels [14–16] and microgels [17] is reasonably well understood, in the case of neutral gels, despite the existence of experimental evidence showing that salt concentration can greatly affect the particle equilibrium size [18–21], there is little understanding of why this is so. In this paper, we study the equilibrium swelling behavior of PNIPAM microgel particles in the presence of different salts as a function of salt concentration. We find correlation between the deswelling degree exerted by the different ions and the Hofmeister series and interpret the results by considering that the different ions induce a change in the entropic contribution of the polymer-solvent Flory χ parameter; for a given

---

[*] Author to whom correspondence should be addressed. Email address: teresal@ugr.es

TABLE I. Hofmeister series and the encountered experimental classification based on the deswelling capability of the ions.

	Anions	Cations		Anions	Cations
	SO_4^{2-}				
Kosmotropic	PO_4H^{2-}	Mg^{2+}			
	F^-	Ca^{2+}	Decreasing deswelling effect	Cl^-	Ca^{2+}
	CH_3COO^-	H^+			
	Cl^-	Na^+		NO_3^-	Na^+
	Br^-	K^+			
	I^-	Rb^+	↓	SCN^-	NH_4^+
	NO_3^-	Cs^+			
Chaotropic	ClO_4^-	NH_4^+			
	SCN^-				

salt concentration, χ increases with the kosmotropic character of the ion. Overall, our results indicate that disturbances in the water structure caused by electrolytes affect the swelling behavior of PNIPAM colloidal gels and could in fact be the reason for such observations in other neutral microgel systems.

The rest of the paper is organized as follows. Section II summarizes the thermodynamic background for understanding the swelling behavior of neutral gels. Section III briefly introduces the experimental system and methods. Section IV presents the results. First we describe the temperature volume phase transition of the PNIPAM particles under consideration and theoretically describe the observations with the Flory-Rehner theory for the swelling of neutral gels. This provides information about some of the intervening system parameters, which we will use to estimate entropic changes induced by salt concentration, for different salts. Finally, in Sec. V, we summarize our work and conclude.

II. SWELLING THERMODYNAMICS

The swelling behavior of PNIPAM microgels is well described by the classic Flory-Rehner theory [22]. At equilibrium, the mixing osmotic pressure (π_m) within the particle is balanced by the elastic osmotic pressure (π_e) of the cross-linked network so that $\pi_{total}=\pi_m+\pi_e=0$, or equivalently, the free energy of the system is minimal. In this case

$$\ln(1-\phi)+\phi+\chi\phi^2+\frac{\phi_0}{N_{gel}}\left[\left(\frac{\phi}{\phi_0}\right)^{1/3}-\frac{\phi}{2\phi_0}\right]=0, \qquad (1)$$

where ϕ is the polymer volume fraction within the particle, N_{gel} the average number of segments between two neighboring cross-linking points in the network, and χ the Flory polymer-solvent interaction parameter. Equation (1) provides a means to determine ϕ from ϕ_0, N_{gel}, and χ. For isotropic swelling, ϕ can be related to the particle diameter d as

$$\frac{\phi}{\phi_0}=\left(\frac{d_0}{d}\right)^3 \qquad (2)$$

with ϕ_0 and d_0 the polymer volume fraction and particle size in a reference state, typically taken as the shrunken state.

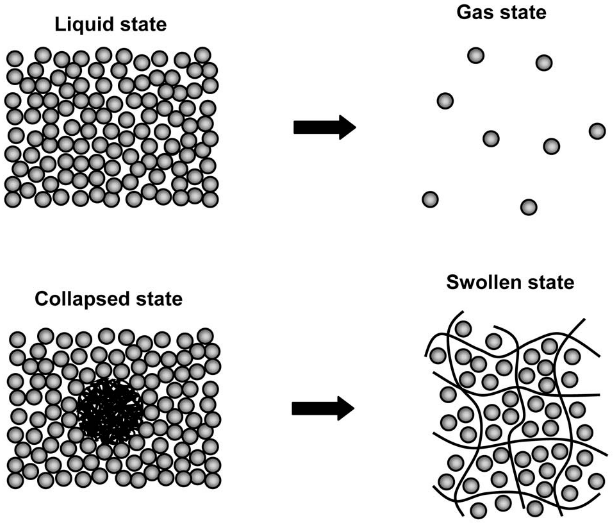

FIG. 1. Analogy between the shrunken-swollen transition in a microgel and the liquid-gas phase transition in a van der Waals fluid.

The Flory χ parameter plays a crucial role in the thermodynamic behavior of the gel. It is defined as the free energy change per solvent molecule (in k_BT units) when a solvent-solvent contact is changed into a solvent-polymer contact

$$\chi=\frac{\Delta G}{k_BT}=\frac{\Delta H-T\Delta S}{k_BT}=\frac{1}{2}-A\left(1-\frac{\Theta}{T}\right), \qquad (3)$$

where k_B and T are the Boltzmann constant and temperature, respectively; A and Θ have been defined as

$$A=\frac{2\Delta S+k_B}{2k_B}, \qquad (4)$$

$$\Theta=\frac{2\Delta H}{2\Delta S+k_B}. \qquad (5)$$

As can be seen, A is directly related to entropy changes, whereas Θ depends on both entropic and enthalpic variations. The latter is the so called Θ temperature and corresponds to the temperature at which the second virial coefficient of the π series expansion in powers of ϕ vanishes; binary interactions among constituents are then negligible and only excluded volume effects are important. For $T=\Theta$, the Flory χ parameter equals $\chi=1/2$. Thereby, the solvent is a *good* solvent for the polymer when $\chi<1/2$ and it is a *poor* solvent when $\chi>1/2$. The Θ temperature is analogous to the Boyle temperature of a van der Waals fluid, where the gas can be taken as ideal. In fact, the volume phase transition of a polymer gel is in some sense analogous to the phase transition of a van der Waals fluid; swollen and deswollen gel states would correspond to the gas and liquid phases, respectively [23] (see Fig. 1).

Equation (1) determines the T-ϕ phase diagram for a polymer gel. The temperature dependence is embodied in the Flory χ parameter, while N_{gel} and ϕ_0 are system properties. Usually, the interactions between polymer and solvent mol-

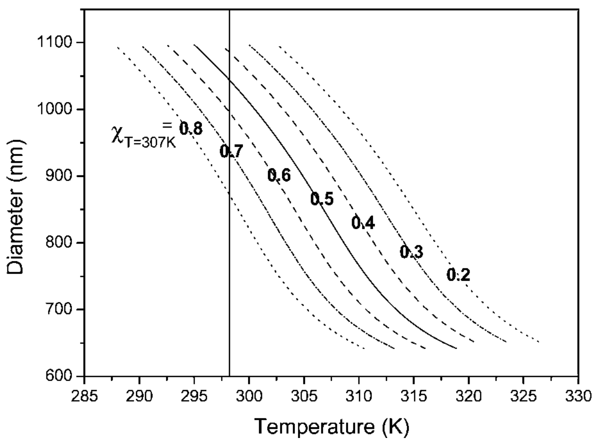

FIG. 2. Size-temperature phase diagram predicted by the Flory-Rehner phenomenological theory for the swelling of neutral microgels. The curves correspond to χ parameters ranging from χ=0.2 to χ=0.8 (at 307 K). Other intervening parameters are taken equal to d_0=600 nm, N_{gel}=42, and ϕ_0=0.8; these values are those obtained for the particular PNIPAM system under consideration. The vertical line corresponds to a constant temperature of 25 °C.

ecules lead to positive values of ΔH and ΔS ($A>0$). In this case, the system is characterized by an upper-critical solution temperature above which the polymer becomes soluble. For PNIPAM, the polymer solvency is governed by order-disorder processes induced by hydrophobic interactions between the polymer and the solvent with possible influences from hydrogen bonding. As a result ΔH and ΔS are negative ($A<0$) and the system is characterized by a lower-critical-solution-temperature (LCST). Figure 2 shows some representative T-d isobars (for different χ parameters) for a PNIPAM system. These curves have been obtained from Eq. (1), after considering isotropic swelling [Eq. (2)] and the χ definition [Eq. (3)]. The isobars are plotted using values of N_{gel}, ϕ_0, d_0, and ΔH that characterize our experimental system (see Sec. IV A). Since the χ parameter depends on temperature, we provide χ values at 307 K in order to compare the curves. Figure 2 shows that the particle size decreases with increasing temperature, as one would expect for systems with a LCST. Equivalently, particle deswelling can be induced by increasing χ, i.e., by making the solvent *poorer*, as is also shown in Fig. 2.

III. MATERIALS AND METHODS

A. Experimental system

PNIPAM particles were prepared via batch radical polymerization under emulsifier-free conditions. The monomers employed were N-isopropylacrylamide (NIPAM) from Kodak and methylenebisacrylamide (MBA) from Sigma. Potassium persufate was used as an initiator, leading to sulfate anionic groups at the particles' surface. Polymerization was performed in a 250 ml thermostated reactor, round-bottomed four-necked flask, equipped with a glass anchor-shaped stirrer, condenser, thermocouple, and nitrogen inlet. The reaction took place in boiled and deoxygenated water, under a constant stream of nitrogen. The polymerization temperature was set constant at 70 °C and the stirring rate was 200 rpm throughout the process. The resulting suspension was cleaned through several centrifugation/redispersion cycles (15 000 rpm for 30 min at 25 °C). Further details about particle synthesis and characterization are available in Ref. [24].

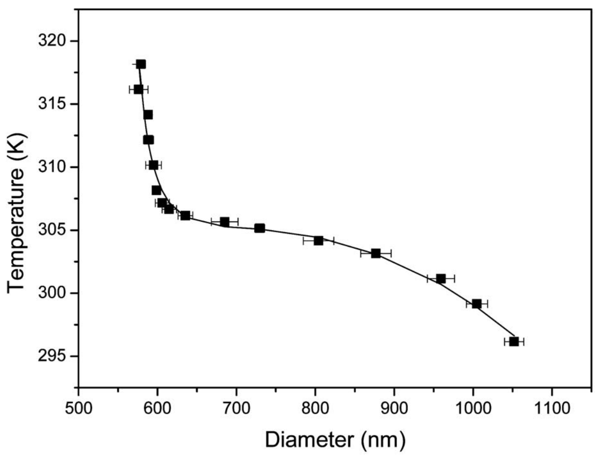

FIG. 3. Experimental mean hydrodynamic diameter versus temperature at 1 mM NaCl. The solid line is the theoretical best least squares fit. Resultant parameter values are d_0=600 nm, A=11.5, T=307 K, N_{gel}=42, χ_2=0.19, and χ_3=0.81.

All salts employed, NaCl, $NaNO_3$, NaSCN, $Ca(NO_3)_2$, and NH_4NO_3, were of analytical grade and were purchased from Merck, Sigma, or Scharlau. Double-deionized water was used throughout.

B. Dynamic light scattering

Particle sizes were measured by dynamic light scattering (DLS) using a Zetasizer 3000HS (Malvern Instruments, UK). In a typical DLS measurement, the intensity autocorrelation function is determined and used to obtain the mean diffusion coefficient D of the particles. The experiments were performed at a scattering angle $\theta=90°$ using a He-Ne laser with vacuum wavelength $\lambda=632.8$ nm. The mean hydrodynamic diameter is calculated from the diffusion coefficient by using the Stokes-Einstein equation: $D=\frac{k_BT}{3\pi\eta d}$, where η is the medium viscosity. Temperature was controlled with a precision of 0.1 K using a peltier chamber that surrounded the sample cell. The $\eta=\eta(T)$ dependence was obtained from the literature [25].

IV. RESULTS AND DISCUSSION

A. Volume phase transition

Figure 3 displays the dependence of the mean hydrodynamic diameter of the PNIPAM particles with temperature

TABLE II. Free parameter values resulting from least squares fit of the d-T experimental data. The bold column corresponds to the best fit.

	$\chi=\chi_1(T)$				$\chi=\chi_1(T)+\chi_2\phi$				$\chi=\chi_1(T)+\chi_2\phi+\chi_3\phi^2$			
ϕ_0	0.6	0.7	0.8	0.9	0.6	0.7	0.8	0.9	0.6	0.7	0.8	0.9
A	−9.4	−13.6	−20.6	−37.3	−1.6	−3.2	−7.0	−21.0	−0.7	−1.8	**−11.5**	−25.0
Θ (K)	300.0	300.9	301.6	302.9	322.5	319.7	316.2	310.0	299.6	303.0	**307.0**	315.3
N_{gel}	247	131	65	25	245	113	51	19	148	400	**42**	14
χ_2	—	—	—	—	0.70	0.83	1.02	1.16	0.19	0.13	**0.19**	2.58
χ_3	—	—	—	—	—	—	—	—	0.66	0.77	**0.81**	−1.19

for a salt concentration of 1 mM (NaCl). The particles are deswollen at high temperatures because thermal agitation is able to break the cagelike water structure surrounding the PNIPAM isopropyl groups. Under these conditions, water is a *poor* solvent for PNIPAM. The volume phase transition temperature T_{VPT}, here considered as the temperature corresponding to the onset of the swelling process, is around 307 K. As in a van der Waals fluid above the critical temperature, the volume transition of our system is continuous, with no first-order discontinuity in the particle size. The swelling process cannot be strictly considered a phase transition then; nevertheless, this term is often used when referring also to a continuous swelling.

To describe the experimental results with the Flory-Rehner thermodynamic theory presented in Sec. II, it is convenient to rewrite Eq. (1) in terms of the particle diameter [Eq. (2)], also showing explicitly the temperature dependence [Eq. (3)]

$$T_{\pi=0} = \frac{-A\phi_0^2\left(\frac{d_0}{d}\right)^6\Theta}{\ln\left[1-\phi_0\left(\frac{d_0}{d}\right)^3\right]+\phi_0\left(\frac{d_0}{d}\right)^3+\phi_0^2\left(\frac{d_0}{d}\right)^6\left(\frac{1}{2}-A\right)+\frac{\phi_0}{N_{gel}}\left[\frac{d_0}{d}-\frac{1}{2}\left(\frac{d_0}{d}\right)^3\right]}. \tag{6}$$

As can be seen, Eq. (6) relates T and d by means of A, Θ, ϕ_0, d_0, and N_{gel}. We should note that in this equation A must be taken to be negative if the system is characterized by a LCST. Least square fits of the experimental data to this equation lead to physically unrealistic values of the parameters (Table II). The reason for this result seems to be related to the volume fraction dependence of χ. This fact has been experimentally observed through solvent activity measurements with a number of different systems revealing a nonlinear χ parameter dependence on the polymer volume fraction [26]. In addition, the inability of the original Flory-Rehner theory to justify the observed discontinuous phase transitions in neutral gels has been interpreted as a need for including the ϕ dependence on the Flory χ parameter [27]. The microscopic origin of this dependence is one of the current concerns of polymer science. Within the Flory-Rehner phenomenological theory the gel phase transition is understood on the basis of χ, which embodies all the molecular interactions in the system. χ is thus the final cause of such phase transitions and must be determined empirically for every particular case.

The original Flory theory is based on determining the exchange free energy involved in juxtaposing pairs of polymer and solvent segments, and mixed polymer-solvent pairs, in order to obtain the equilibrium polymer configuration. However, in a subsequent work published by Erman and Flory [28], the authors claimed the inadequacy of treating exchange interactions merely in terms of contacts between molecules and asserted that interactions of higher order must be considered; they accounted for this by proposing a power series expansion for χ as a function of ϕ

$$\chi = \chi_1 + \chi_2\phi + \chi_3\phi^2 + \chi_4\phi^3 + \cdots, \tag{7}$$

where χ_1 is the original Flory parameter in Eq. (3), and $\chi_2, \chi_3, \ldots$ are temperature independent coefficients. If the above series expansion is introduced in Eq. (1), one obtains an analogous expression to Eq. (6) with additional terms in χ_2 and χ_3. Better results are then achieved when fitting the diameter-versus-temperature experimental data. Table II summarizes the values of the fitting parameters obtained by considering (i) zero-order $\chi=\chi_1(T)$, (ii) first-order $\chi=\chi_1(T)+\chi_2\phi$, and (iii) second-order $\chi=\chi_1(T)+\chi_2\phi+\chi_3\phi^2$ approximations. Different values of ϕ_0 (0.6, 0.7, 0.8, 0.9) have been tested in the fit. In Fig. 3 the black squares are the experimental points obtained by DLS and the solid line is the theoretical best fit. The latter is selected among all fits with similar statistical χ^2 values (typically around 1.3) based on how realistic the fitting parameters were; these must fulfill three main conditions: (i) the values of A and Θ must be such that $0<\chi_1<1$ within all the temperature range studied, (ii) the Θ temperature should be close to the experimental volume phase transition temperature $T_{\mathrm{VPT}}\approx 307$ K, and (iii) the number of segments per chain N_{gel} must reasonably match the value deduced from the cross-linker concentration employed in the microgel synthesis. For a perfect network, where each cross-linking monomer forms two junction points, the number of total chains N_{chains} will be twice the number of cross-linking molecules. Since the synthesis monomer conversion is close to 100% [29], N_{chains} can be calculated from the mass of MBA to be $N_{chains}=2.21\times 10^{20}$. By dividing the total number of NIPAM molecules by N_{chains} we get $N_{gel}=33$.

As can be seen in Table II, the zero-order and first-order approximations provide low and high values of Θ, respectively, independent of the chosen ϕ_0. Only the second-order approximation for $\phi_0=0.8$ gives a value of Θ in agreement with the experimental phase transition temperature. In this case, reasonable values of A and N_{gel} are also obtained. A further discussion of the resulting parameters is presented below.

(i) The value of the Flory Θ temperature, $\Theta=(307.0\pm 0.3)$ K, is very close to the T_{VPT} indicating that the phase transition is related to a change in the solvent quality. The values of $A=(-11.5\pm 1.9)$ and Θ allow determination of the entropy and enthalphy changes when a solvent-solvent contact is replaced by a PNIPAM-solvent contact. From Eqs. (4) and (5)

$$\Delta S=\left(A-\frac{1}{2}\right)k_B=(-1.7\pm 0.3)\times 10^{-22}\ \mathrm{J/K};$$

$$\Delta H=\Theta A k_B=(-4.9\pm 0.8)\times 10^{-20}\ \mathrm{J}.$$

These quantities agree with the values reported by other authors [30,27,31]. The negative sign of A leads to $\Delta S<0$ and $\Delta H<0$, as expected for a system characterized by a LCST.

(ii) The polymer volume fraction $\phi_0=0.8\pm 0.1$ implies that around 20% of the particle volume in the reference state is occupied by solvent molecules. This also agrees with previous results in similar systems [32–34] and implies that the deswollen particle size contains water and is not equivalent to the collapsed size that by definition has no solvent molecules.

(iii) The average number of segments between two neighboring cross-linking points, $N_{gel}=42\pm 6$, agrees well with the value gauged from the microgel synthesis.

(iv) A second-order approximation in $\chi(\phi)$ is required to describe the microgel swelling. The need of introducing $\chi_2\neq 0$ and $\chi_3\neq 0$ becomes evident by analyzing the $\chi=\chi(T)$ relation. The χ parameter can be experimentally determined from the d-T data by using Eqs. (1) and (2), provided N_{gel}, ϕ_0, and d_0 are known

$$\chi=\frac{-1}{\phi_0}\left\{\frac{1}{N_{gel}}\left[\left(\frac{d}{d_0}\right)^5-\frac{1}{2}\left(\frac{d}{d_0}\right)^3\right]+\left(\frac{d}{d_0}\right)^3+\frac{1}{\phi_0}\left(\frac{d}{d_0}\right)^6\ln\left[1-\phi_0\left(\frac{d_0}{d}\right)^3\right]\right\}. \qquad (8)$$

The χ parameter calculated in this way is plotted as a function of T^{-1} in Fig. 4. When $\phi\to 0$, the ϕ-dependent terms in Eq. (7) can be neglected and $\chi=\chi_1$, which according to Eq. (3) should be proportional to T^{-1}. This linear dependence between χ and T^{-1} is indeed experimentally observed at high T^{-1} (low temperatures), where the particles are swollen and ϕ is low. Furthermore, as shown in Fig. 4, for high $T^{-1}(\phi\to 0)$ the experimental points are well described with the theoretical solid line corresponding to the $\chi_1(T)$ obtained using the A and Θ values that resulted from the d-T fit. Note also that $\chi<1/2$ in this region, as expected for a polymer in a *good* solvent.

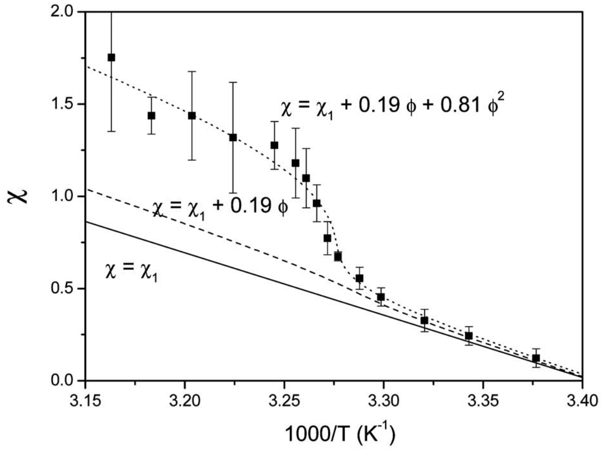

FIG. 4. Flory χ parameter as a function of the inverse temperature. The points are the experimental χ values obtained from the swelling data. The solid lines correspond to three theoretical approximations within the Flory theory: $\chi=\chi_1$; $\chi=\chi_1+\chi_2\phi$, with $\chi_2=0.6$; $\chi=\chi_1+\chi_2\phi+\chi_3\phi^2$, with $\chi_2=0.19$ and $\chi_3=0.81$.

The linear $\chi-T^{-1}$ dependence disappears when T^{-1} decreases below $\sim 1/T_{\mathrm{VPT}}$. The system is rather deswollen in this temperature range and χ exhibits a more pronounced temperature dependence. This behavior can only be justified if a dependence on ϕ is introduced in χ. Hirotsu interpreted the d-T curve of a neutral PNIPAM gel undergoing a discontinuous phase transition by introducing a linear ϕ correction in the χ parameter [30]. This author found that $\chi_2\approx 0.6$; a value that is higher than that theoretically predicted by Erman and Flory for a discontinuous transition in a gel of infinitely long chains, $\chi_2=1/3$. This suggests that a more important dependence on ϕ is required when dealing with real gels. The dashed line in Fig. 4 corresponds to Hirotsu's results, which clearly cannot account for our experimental data. In our particular case there is no value of χ_2 able to reproduce, within a linear χ-ϕ dependence, the experimental results, and a second-order ϕ dependence needs to be included. The dotted line is the theoretical prediction corresponding to $\chi_2=0.19$ and $\chi_3=0.81$, the values obtained in the d-T fit (Table II). With these last values, the experimentally obtained Flory parameters are rather well reproduced.

A microscopic understanding of this second-order dependence is not evident. The χ-ϕ relation given in Eq. (7) must be taken as an empirical series expansion that aims to account for various many-body molecular interactions but that lacks a clear physical meaning. According to Erman and Flory [28], the χ_i coefficients are related in some way to the equation of state of the individual components (polymer and solvent) and their mixture. However, these coefficients are not directly related to any specific interaction. First- and second-order χ-ϕ dependences have been deduced from experiments with systems based on PNIPAM [27,30,35]. Typically, the second-order dependences on ϕ are associated to discontinuous phase transitions, which are not observed in our case. However, not every set of (χ_1,χ_2,χ_3) values implies coexistence of swollen/deswollen phases [28] and thus there are values of this triad giving rise to continuous changes in the gel size. In addition, the continuous or discontinuous character of the phase transition depends not only on the interaction coefficients, but also on the structural parameters contained in the Flory-Rehner theory, and on more subtle variables not contemplated in this theory. In fact, Hirotsu observed differences in the character of the phase transition of two PNIPAM gels synthesized under the same conditions and with identical nominal compositions [27]. The only difference was the initiator employed: While sodium bisulfite (BS) led to continuous transitions, N, N, N′, N′-tetramethylethylenediamine (TEMED) led to discontinuous ones. This qualitatively different behavior was attributed to some imperfections of the network, which were believed to play a decisive role in the phase behavior. Nonetheless, the concrete effect of these imperfections is not well known yet. In our case, potassium persulfate is employed as initiator, which is certainly more similar to the BS molecule than to the TEMED molecule. The particular χ-ϕ dependence thus seems to delicately depend on the particularities of the experimental system. The synthesis method and the initiator employed are variables not accounted for in any theory but which seem to affect the system phase behavior; it is the complexity of the many-body interactions that has prevented a microscopic understanding of these effects.

Nevertheless, we conclude that the Flory-Rehner theory captures the essential physics of the phase transition of neutral PNIPAM microgels, since it reasonably describes the observed swelling curves using logical values of the parameters involved. We will use the values of these intervening parameters to interpret the effects of salt on the system swelling behavior at a fixed temperature.

B. Salt induced deswelling

We study the effects of six electrolytes on the swelling behavior of neutral PNIPAM microgels. We chose the following salts: (i) NaCl, $NaNO_3$, and NaSCN, all with the same cation, and (ii) $Ca(NO_3)_2$, $NaNO_3$, and NH_4NO_3, that share the anion. This selection allows the effects of different anions and cations to be analyzed independently.

Figures 5(a) and 5(b) show the PNIPAM particles' diameter against salt concentration n, for anions and cations, respectively. The measurements are made at $T=25\ ^\circ C < T_{VPT}$ and thus the particles are swollen. The following conclusions can be extracted from these curves:

(i) At low salt concentrations, the particles are swollen. No great differences among the ions can be detected. It is only when $n \approx 300$ mM that particle diameters decrease and important differences among ions are evidenced. This characteristic is typical of Hofmeister effects—which usually appear at moderate to high ionic concentrations [3].

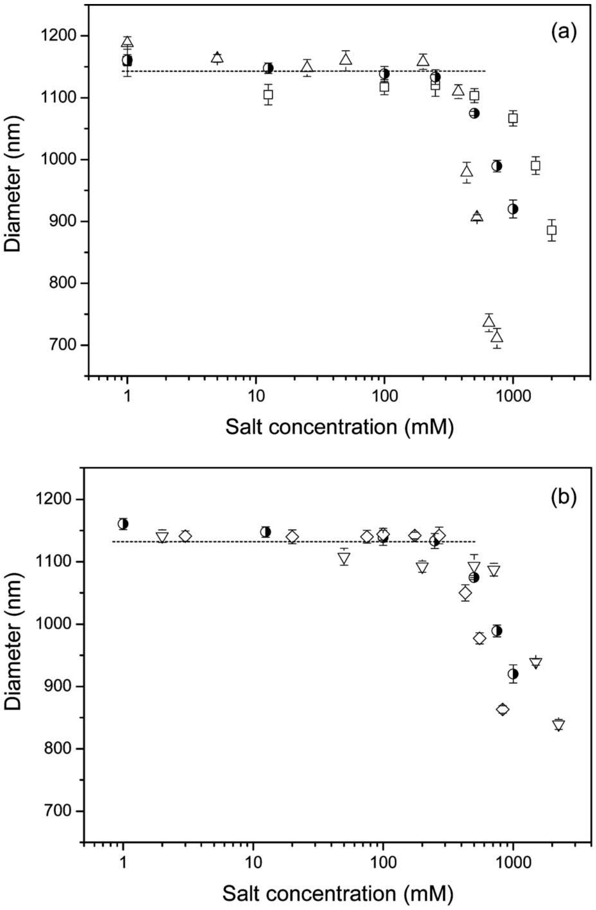

FIG. 5. Hydrodynamic particle size as a function of salt concentration at $T=25\ ^\circ C$. (a) Effect of anions: (△) NaCl, (◑) $NaNO_3$, (□) NaSCN. (b) Effect of cations: (◑) $NaNO_3$, (◇) $Ca(NO_3)_2$, (▽) NH_4NO_3. For a comparative analysis, the curve corresponding to the asymmetric electrolyte, $Ca(NO_3)_2$, is plotted versus the ionic strength of the medium.

(ii) Although all the ions cause deswelling at roughly the same concentration; the salt concentration required to reach a given swelling ratio ϕ_0/ϕ depends strongly on the particular ion. For example, the salt concentration needed to attain a swelling ratio of 1.5 is about 500 mM in the case of NaCl, 1000 mM for $NaNO_3$, and 2000 mM for NaSCN.

(iii) Differences among anions [Fig. 5(a)] are more pronounced than among cations [Fig. 5(b)]. This is also a general feature of all Hofmeister phenomena—which are frequently dominated by anion effects [3].

The results can be summarized by classifying the ions in terms of their deswelling capacity, which we can quantify through their swelling ability for $n > 300$ mM (Table I). The obtained series exactly agrees with the Hofmeister series: the more kosmotropic or structure-maker anions have the stronger deswelling effect.

As mentioned before, deswelling processes promoted by electrolytes have commonly been discussed in terms of a

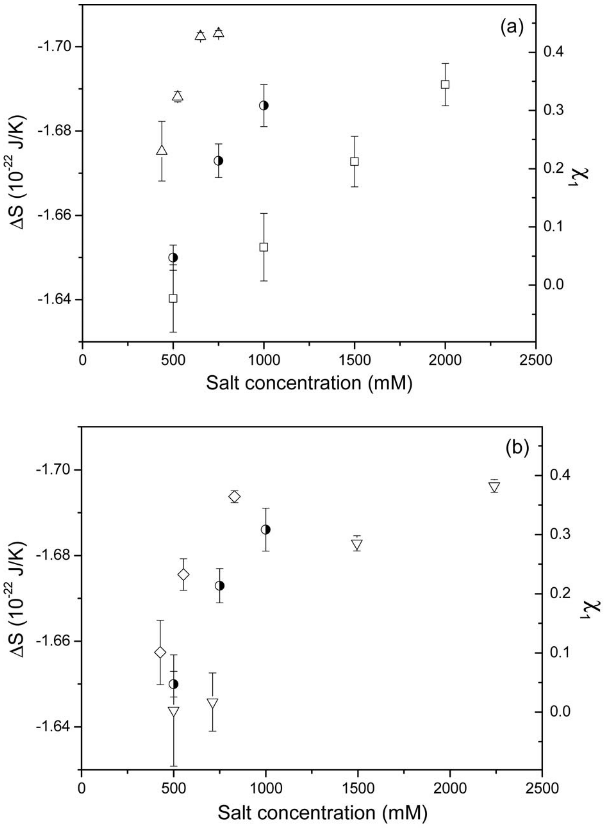

FIG. 6. Experimental changes in the entropy and Flory χ_1 parameter with electrolyte concentration. (a) Effect of anions: (△) NaCl, (◑) $NaNO_3$, (□) NaSCN. (b) Effect of cations: (◑) $NaNO_3$, (◇) $Ca(NO_3)_2$, (▽) NH_4NO_3. For a comparative analysis, the curve corresponding to the asymmetric electrolyte, $Ca(NO_3)_2$, is plotted versus the ionic strength of the medium.

Donnan equilibrium for ions inside and outside the gel. This explanation, plausible for ionic microgels, cannot justify our results because there is no reason to think that a Donnan potential is established in a nonionic microgel. On the other hand, although the molecular origin of the Hofmeister series is not completely understood, it is well known that they emerge from a combination of effects in which water structure is the cornerstone of the problem. Therefore, it is reasonable to think that the presence of ions above certain concentrations modifies the entropic contribution to the Flory solubility χ parameter. Figure 5 will thus be analyzed by means of the Flory-Rehner theory under the assumption that ions modify the entropic component ΔS of the χ parameter.

We then calculate ΔS from the experimental (d,n) pairs in Fig. 5, using Eqs. (1) and (3). In this case, χ has been replaced by the experimentally found series expansion in ϕ, with χ_1 written in terms of ΔH and ΔS. We also assume that only ΔS changes are responsible for the observed deswelling. For the rest of the parameters, values resulting from the *d*-*T* fit are employed. Results are presented in Figs. 6(a) for anions and 6(b) for cations. In the same figures we also plot χ_1. Inasmuch as differences among ions are important beyond 300 m*M*, only results corresponding to this concentration range are displayed.

To understand the entropic change ΔS, recall that $\Delta S = S_{sp} - S_{ss}$, with S_{sp} and S_{ss} representing the entropies due to solvent-polymer and solvent-solvent contacts, respectively. The fact that $\Delta S < 0$ implies, from an entropic point of view, that the latter are favored over the polymer-solvent contacts, resulting in the macroscopic deswelling of the particles. This is why increasing *T* results in a size reduction. According to Fig. 6, there are two factors that promote the increase in $|\Delta S|$: (i) salt concentration and (ii) the kosmotropic character of the ion. The results can thus be interpreted based on the competition between the polymer and the electrolyte for the water molecules. The highly kosmotropic ions tend to strongly interact with water molecules. As a result, they are able to seriously disturb the water cage responsible for the PNIPAM hydration, thus reducing the polymer-solvent contacts and leading to the polymer collapse. This effect becomes more pronounced as the number of ions in the solution increases. Conversely, chaotropic ions, which interact only slightly with water, have a far more attenuated effect. Figure 6 shows that in these cases high salt concentrations are necessary to get a considerable increase in $|\Delta S|$. Although anions and cations exhibit the same trend, the entropic changes induced by the former are in general slightly more significant than those provoked by the latter, in agreement with what is typically encountered for Hofmeister effects [3]. Finally, the values for ΔS at low salt concentrations are consistent with the value provided by the *d*-*T* fit, as expected.

Perhaps it is more intuitive to describe the ion effects in terms of χ_1 rather than through entropy changes. As can be seen in Fig. 6, $\chi_1 < 1/2$ as expected for swollen phases. It also increases with salt concentration. Furthermore, for a given *n*, the value of the Flory parameter increases with the kosmotropic character of the ion. This feature can be qualitatively understood from Fig. 2. This diagram displays the microgel phase transition curves for different values of the Flory parameter. The vertical solid line corresponds to a temperature of 25 °C, at which all *d*-*n* curves were measured. According to this figure, the increase in the Flory parameter implies a reduction in the particle diameter; this is consistent with the experiment and equivalent to increasing temperature. The equivalent effects of temperature and salt concentration can be further emphasized. For example, the change in the Flory parameter caused by adding 750 m*M* of the most kosmotropic anion Cl^- is analogous to the change provoked by increasing the temperature by $\Delta T = 7.0$ K. Accordingly, 750 m*M* of $NO_3{}^-$, a moderately kosmotropic anion, is equivalent to a temperature change $\Delta T = 1.4$ K, while the same concentration of the less structure-maker anion SCN^- would not have any appreciable effect. Regarding cations, a $\Delta T = 4.3$ K is obtained with $Ca_2{}^+$ at 750 m*M* ionic strength, whereas salt concentrations above 750 m*M* are necessary to observe any effect arising from $NH_4{}^+$, that is far less kosmotropic than $Ca_2{}^+$. This *equivalent increment of temperature* can be used, then, as an estimation of the chaotropic/kosmotropic character of the ion.

V. CONCLUSIONS

In this work, we provide a plausible explanation for understanding volume changes induced by salt in neutral microgels. The increase in ionic concentration above $\approx$300 mM induces deswelling of the particles; the amount is highly dependent on the electrolyte nature, with a clear correlation between deswelling ability and ion position in the Hofmeister series. These findings emphasize the entropic influence of the ions over the polymer-solvent interactions that control the microgel size. We thus interpret the phase transitions induced by salt as changes in the entropic contribution to the Flory χ parameter within the phenomenological Flory-Rehner theory for the swelling of neutral gels. As salt concentration increases, the entropy gain due to solvent-solvent contacts rises, implying χ also grows, and the particles deswell; similar trends are found when the kosmotropic character of the ions in solution is increased. To obtain the entropy changes, knowledge of some important system parameters is necessary. A detailed analysis of the particle size temperature dependence provided this information.

ACKNOWLEDGMENTS

T.L.-L. acknowledges financial support from the Comisión Interministerial de Ciencia y Tecnología (CICYT, Spain) under project MAT2003-01257. A.F.-N. is grateful to Ministerio de Ciencia y Tecnologia (MAT2004-03581), to the University of Almeria (leave of absence), and to Dr. Manuel Márquez from INEST Group (financial support). The authors would also like to thank J. L. Ortega-Vinuesa and D. Bastos-González for their critical reading of the manuscript and their interesting suggestions.

[1] H. G. Schild, Prog. Polym. Sci. **17**, 163 (1992).
[2] M. G. Cacace, E. M. Landau, and J. J. Ramsden, Q. Rev. Biophys. **30**, 241 (1997).
[3] K. D. Collins and M. W. Washabaugh, Q. Rev. Biophys. **18**, 323 (1985).
[4] S. Lewith, Arch. Exp. Pathol. Pharmakol. **24**, 1 (1888).
[5] F. Hofmeister, Arch. Exp. Pathol. Pharmakol. **24**, 247 (1888).
[6] W. Kunz, P. Lo Nostro, and B. W. Ninham, Curr. Opin. Colloid Interface Sci. **9**, 1 (2004).
[7] R. W. Gurney, *Ionic Processes in Solution* (McGraw-Hill, New York, 1953).
[8] J. P. Chatterjee and I. N. Basumallick, J. Chem. Soc., Faraday Trans. **86**, 3107 (1990).
[9] R. Jimenez, G. R. Fleming, P. V. Kumar, and M. Maroncelli, Nature (London) **369**, 471 (1994).
[10] R. Leberman and A. K. Soper, Nature (London) **378**, 364 (1995).
[11] S. E. Jackson and M. C. R. Symons, Chem. Phys. Lett. **37**, 551 (1976).
[12] N. G. M. Pay and M. C. R. Symons, J. Chem. Soc., Faraday Trans. **89**, 2417 (1993).
[13] J. Davies, S. Ormondroyd, and M. C. R. Symons, Trans. Faraday Soc. **67**, 3465 (1971).
[14] I. Ohmine and T. Tanaka, J. Chem. Phys. **77**, 5725 (1982).
[15] J. Ricka and T. Tanaka, Macromolecules **17**, 2916 (1984).
[16] R. A. Siegel and B. A. Firestone, Macromolecules **21**, 3254 (1988).
[17] A. Fernández-Nieves, A. Fernández-Barbero, and F. J. de las Nieves, J. Chem. Phys. **115**, 7644 (2001).
[18] T. G. Park and A. S. Hoffman, Macromolecules **26**, 5045 (1993).
[19] K. Suwa, K. Yamamoto, M. Akashi, K. Takano, N. Tanaka, and S. Kunugi, Colloid Polym. Sci. **276**, 529 (1998).
[20] E. Daly and B. R. Saunders, Langmuir **16**, 5546 (2000).
[21] T. López-León, A. Elaïssari, J. L. Ortega-Vinuesa, and D. Bastos-González, ChemPhysChem (to be published).
[22] P. J. Flory, *Principles of Polymer Chemistry* (Cornell University Press, Ithaca, NY, 1953), Chaps. 12 and 13.
[23] M. Shibayama and T. Tanaka, *Volume Phase Transition and Related Phenomena in Polymer Gels*, edited by K. Dusek, Responsive Gels I (Springer, Berlin, 1993).
[24] T. López-León, J. L. Ortega-Vinuesa, D. Bastos-González, and A. Elaïssari, J. Phys. Chem. B **110**, 4629 (2006).
[25] *Handbook of Chemistry and Physics*, 68th ed. (CRC Press, Boca Raton, FL, 1987–1988).
[26] V. A. Baulin and A. Halperin, Macromolecules **35**, 6432 (2002).
[27] H. Hirotsu, Phase Transitions **47**, 183 (1994).
[28] B. Erman and P. J. Flory, Macromolecules **19**, 2342 (1986).
[29] A. Elaissari, *Handbook of Surface and Colloid Chemistry*, 2nd ed. (CRC Press, Boca Raton, FL, 2003), Chap. 12.
[30] A. Fernández-Barbero, A. Fernández-Nieves, I. Grillo, and E. López-Cabarcos, Phys. Rev. E **66**, 051803 (2002).
[31] S. Hirotsu, Y. Hirokawa, and T. Tanaka, J. Chem. Phys. **87**, 1392 (1987).
[32] W. McPhee, K. C. Tam, and R. Pelton, J. Colloid Interface Sci. **24**, 156 (1993).
[33] X. Wu, R. H. Pelton, A. E. Hamielec, D. R. Woods, and W. McPhee, Colloid Polym. Sci. **272**, 467 (1994).
[34] L. C. Dong and A. S. Hoffman, Sci. Am. **86**, 26 (1993).
[35] R. Moerkerke, R. Koningsveld, H. Berghmans, K. Dusek, and K. Solc, Macromolecules **28**, 1103 (1995).