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Are All Polar Molecules Hydrophilic? -Hydration Numbers of Nitro Compounds and Nitriles in Aqueous Solution-

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ABSTRACT: The hydration numbers of typical aprotic polar substances bearing dipole moments larger than 3 D, such as nitro compounds and nitriles, were precisely determined in aqueous solution using high frequency dielectric relaxation techniques up to a frequency of 50 GHz at 25 °C. The hydration number is one of the most quantitative parameters for determining the hydrophilicity or hydrophobicity of a compound. The hydration numbers of various nitriles, such as acetonitrile, propionitrile and *n*-butyronitrile bearing cyano groups, were determined to be ca. 0, irrespective of the species of molecule. Moreover, the hydration numbers of various nitro compounds, such as nitromethane, nitroethane and 1-nitropropane, were also evaluated to be ca. 0. These findings clearly reveal that neither cyano nor nitro functional groups form strong hydrogen bonds to water molecules. Consequently, neither nitro compounds nor nitriles are hydrophilic, despite their high polarities due to their large dipole moments. Rather, these compounds are “hydroneutral,” with hydrophilicities intermediate between those of hydrophilic and hydrophobic molecules. The molecular motions of the examined highly polar molecules in aqueous solution were well described with single Debye-type rotational relaxation modes without strong interactions between the solute and water molecules, but with relatively strong interactions between the polar solute molecules due to the Kirkwood factor being less than unity. This small Kirkwood factor indicated that both nitro and cyano groups have a tendency to align in an anti-parallel intermolecular configuration due to their strong dipole-dipole interactions as a result of their dipole moments greater than 3 D.

INTRODUCTION

Many chemistry textbooks,¹⁻⁴ as well as IUPAC,⁵ classify all polar compounds and polar groups as hydrophilic, while non-polar compounds are classified as hydrophobic. This clear-cut classification is comprehensive and effective for some polar compounds, such as alcohols, ethers, and amides. In the case of alcohols, which possess a hydroxy group ($-\text{OH}$), not only low molar mass alcohols but also large alcoholic compounds, such as polysaccharides and poly(vinyl alcohol)s bearing many $-\text{OH}$ groups in their backbone and side chains, will readily dissolve in water at relatively high concentrations. The water solubility of polar compounds bearing ether groups ($-\text{CH}_2\text{OCH}_2-$) or amide groups ($-\text{C}(=\text{O})\text{NH}_2$) are also rather high. The hydration number per functional group (n_{H}) has been evaluated experimentally for some polar groups. For example, for a hydroxy group, $-\text{OH}$, that is isolated from other $-\text{OH}$ groups without forming intramolecular hydrogen bonds, an n_{H} of ~ 5 has been reported at 25 °C, and the n_{H} value decreases with increasing temperature.⁶ Moreover, it has been reported that the n_{H} value of ether groups is ca. 4 below room temperature and decreases with increasing temperature.⁷ Furthermore, the n_{H} value has been evaluated to be ca. 6 for amide groups of low mass compounds, such as acrylamide, irrespective of temperature.⁸ These finite positive n_{H} values strongly suggest that these three polar groups are truly hydrophilic, at least at temperatures below 25 °C. Finite n_{H} values imply the formation of hydrogen bonds between the polar groups and water molecules.

Low molar mass esters, such as propyl acetate and methyl propionate, are typical polar compounds bearing an ester group ($-\text{C}(=\text{O})\text{O}-$) with a finite electric permanent dipole moment and are highly soluble in water. However, slightly larger esters possess low water solubilities, such as 0.058 M for butyl acetate.⁹ Moreover, polymeric ester compounds, *e.g.*, poly(methyl acrylate) and poly(vinyl acetate), bearing ester groups as side chains, and poly(glycolide) and

poly(lactide), bearing ester groups as backbones, do not dissolve in water at all. Furthermore, although low molar mass ketones, such as acetone, 3-pentanone and cyclohexanone, bearing a carbonyl group ($-\text{C}(=\text{O})-$), are highly soluble in water, the solubilities of slightly larger ketones, such as 3-heptanone, ca. 0.125 M^{10} , are not high. Polymeric carbonyl compounds, such as poly(vinyl methyl ketone), bearing carbonyl groups as side chains and poly(ketone)s as a backbone, have quite low water solubilities. Consequently, the hydrophilicity of ester [$-\text{C}(=\text{O})\text{O}-$] and carbonyl [$-\text{C}(=\text{O})-$] groups appears to be somewhat low. To evaluate the hydrophilicity of the two polar groups quantitatively, we determined the hydration number, n_{H} , in a previous study¹¹. The hydration numbers of the water soluble esters propyl acetate and acetyl propionate and of the ketones 3-pentanone and cyclohexanone were recently determined to be ca. zero at 25 °C using extremely high frequency dielectric relaxation measurements of up to 50 GHz. Therefore, these typical polar compounds should not be classified as hydrophilic compounds but rather as hydroneutral compounds.¹¹ In this context, one may conclude that not all polar compounds are hydrophilic. Moreover, dielectric measurements also revealed that such hydroneutral compounds exhibit rather simple dynamic behaviors, recognized as almost free rotation in aqueous solution due to the weak interactions between the compounds and water molecules resulting from the unique property of a zero hydration number.¹¹ Max *et al.*¹² have reported that interactions or hydrogen bond formation occurs between the oxygen atoms of carbonyl groups and the protons of water molecules; these interactions are weaker than those between oxygen atoms and water protons in mixtures of acetone and water, as determined using infrared spectroscopic techniques. Therefore, the physical meaning of the n_{H} value of 0 obtained for the carbonyl group is that only weak hydrogen bonds form between the oxygen atoms of the

-C(=O)- group and the water protons, and these bonds possess lifetimes or interacting times equal to or less than the rotational relaxation time of free water molecules in the pure liquid state.

Other classes of water soluble compounds are available that bear other highly polar groups with dipole moments greater than those of the ester and carbonyl groups (~ 1.8 and ~ 3.0 D, respectively). For example, low molar mass nitro compounds, such as nitro methane (MeNO_2) and nitro ethane (EtNO_2), which bear a nitro group (-NO_2) with a dipole moment of $3.3\text{-}3.6$ D, are highly water soluble, whereas 1-nitropropane (PrNO_2), which is a slightly larger nitro compound than EtNO_2 , possesses a low solubility of 0.17 M^{13} . The low water solubility of PrNO_2 likely suggests that the -NO_2 group has a low hydration number of $n_{\text{H}} \sim 0$, and the high water solubility of MeNO_2 and EtNO_2 are not caused by the hydration effect, similarly to the cases of esters, -C(=O)O- , and carbonyls, -C(=O)- .¹¹ Low molar mass nitriles, such as acetonitrile (AcCN), propionitrile (PrCN) and valeronitrile (*n*-butyronitrile, BuCN), which present highly polar nitro groups (-CN) with a dipole moment of $3.4\text{-}4.0$ D, are also water soluble. However, poly(acrylonitrile) is insoluble in water. The insolubility of poly(acrylonitrile) in water also strongly suggests that the -CN group has a low hydration number of $n_{\text{H}} \sim 0$, and the water solubilities of AcCN , PrCN and BuCN are not assisted by the hydration behavior caused by the formation of strong hydrogen bonding. Thus, one might conclude that n_{H} values are not controlled by the magnitude of the dipole moment of a polar group. Precise determination of the hydration numbers of -NO_2 and -CN groups will clarify the hydrophilicity of these groups and the importance of the magnitude of the dipole moment to the value of n_{H} for polar groups.

Numerous experimental methods for the determination of hydration numbers have been proposed to date, such as nuclear magnetic resonance (NMR) techniques¹⁴, neutron scattering experiments¹⁵, ultrasound interferometry^{17,18}, Raman scattering with multivariate curve

resolution¹⁸, and dielectric spectroscopic measurements^{6-8,19}. However, different methods have provided rather different hydration numbers for the same substance, preserving the order in a molecular series.¹⁷ Discrepancies in hydration number among different methods arise because the physical meaning of hydration number differs depending on the technique.^{19,20} Nonetheless, because the hydration number, n_H , is one of the most reliable numerical parameters to demonstrate quantitatively the hydrophilicity of compounds or functional groups in aqueous solution, it remains an important parameter. Furthermore, it is well known that the temperature dependence of the hydration number usually corresponds well to the temperature dependence of the solubilities of compounds.⁶⁻⁸ The essence of the hydrophobic hydration of alkyl chains in aqueous solution observed at relatively high temperatures has recently been elucidated using Raman scattering techniques.¹⁸

Our group has developed a technique to precisely determine the hydration numbers of solute molecules dissolved in water using dielectric relaxation measurements performed in an extremely high frequency range of up to 20 or 50 GHz.^{6-8,21-24} Because the relaxation strength of free water molecules in aqueous solutions is exactly evaluable in a frequency range higher than 20 GHz, the amount of water molecules hydrated to solute molecules can be exactly determined.

In this study, dielectric measurements over a wide frequency range from 50 MHz to 50 GHz were carried out at 25 °C for aqueous solutions of MeNO₂, EtNO₂, PrNO₂, AcCN, PrCN and BuNC to determine the n_H value of two typical aprotic polar groups, –NO₂ and –CN, which exhibit large dipole moments of ~3.5 and 4.0 D, respectively. We then discuss whether the two typical polar groups are actually hydrophilic based on the obtained n_H values. The molecular dynamics of these polar molecules in aqueous solution and the interaction between these polar

compounds and water molecules are also discussed based on the obtained Kirkwood factors for the compounds in aqueous solutions.

EXPERIMENTAL

Materials: Nitromethane, MeNO₂, (> 98 %) was purchased from Tokyo Chemical Industry Co. Ltd. (Tokyo). Nitroethane, EtNO₂ (> 95 %), acetonitrile, AcCN, (> 99.5 %) and propionitrile (PrCN), (> 98 %) were purchased from Wako Pure Chemical Industries, Ltd. (Osaka). 1-nitropropane, PrNO₂ (> 98 %) and *n*-butyronitrile, BuNC, (> 98 %) were purchased from Kanto Chemical Co. Inc. (Tokyo). All of the purchased chemicals were used without further purification. Highly deionized water with a specific resistance higher than 18 MΩcm obtained by a Direct-Q 3UV system (Millipore-Japan, Tokyo) was used as the solvent for the aqueous sample solution preparation.

The concentrations, *c*, of the aqueous solutions of the nitro compounds ranged from 0.14 to 0.78 M for MeNO₂, 0.11 to 0.61 M for EtNO₂ and 0.09 to 0.15 M for PrNO₂. In the case of aqueous solutions of nitriles, the values of *c* were altered in the range from 0.3 to 1.5 M for AcCN and PrCN and from 0.2 to 0.4 M for BuCN.

Methods: A dielectric probe kit, 8507E, equipped with a network analyzer, N5230C, an ECal module N4693A, and performance probe 05 (Agilent Technologies, Santa Clara) was used for dielectric relaxation measurements over a frequency range from 50 MHz to 50 GHz ($3.14 \times 10^8 \sim 3.14 \times 10^{11} \text{ s}^{-1}$ in angular frequency (ω)). The real and imaginary parts (ϵ' and ϵ'') of the electric permittivity were automatically calculated from the reflection coefficients measured by the network analyzer *via* a program supplied by Agilent Technologies. A three-point calibration procedure using *n*-hexane, 3-pentanone and water as the standard materials was performed prior

to all of the dielectric measurements. The details of the three-point calibration procedure used in this study have been described elsewhere^{25,26}. Dielectric measurements were performed at a temperature of $T = 25$ °C (accuracy of ± 0.1 °C) using a temperature controlling unit made of a Peltier device.

Density measurements for all of the aqueous sample solutions were carried out using a digital density meter, DMA4500 (Anton Paar, Graz), to determine the partial molar volumes of the solute molecules at the same temperature used for the dielectric relaxation measurements.

RESULTS AND DISCUSSION

Dielectric Behavior: Dielectric spectra (angular frequency, ω , dependencies of ϵ' and ϵ'') for an aqueous solution of MeNO₂ at $c = 0.78$ M and $T = 25$ °C are shown in Figure 1 as typical examples of the obtained spectra for aqueous solutions of nitro compounds. The dielectric spectra observed in Figure 1 are perfectly decomposed into two Debye-type relaxation modes, as given by eq 1 below

$$\epsilon' = \epsilon'_1 + \epsilon'_2 + \epsilon_\infty = \sum_{j=1}^2 \frac{\epsilon_j}{1 + \omega^2 \tau_j^2} + \epsilon_\infty, \quad \epsilon'' = \epsilon''_1 + \epsilon''_2 = \sum_{j=1}^2 \frac{\epsilon_j \omega \tau_j}{1 + \omega^2 \tau_j^2} \quad (1)$$

where τ_j and ϵ_j indicate the dielectric relaxation time and strength of mode j ($= 1$ and 2 from the shortest relaxation time). The closed circular and square symbols in this figure represent the values of $\epsilon' - \epsilon'_1 - \epsilon_\infty$ and $\epsilon'' - \epsilon''_1$, respectively. Perfect agreement between $\epsilon' - \epsilon'_1 - \epsilon_\infty$ and ϵ'_2 and between the $\epsilon'' - \epsilon''_1$ and ϵ''_2 curves strongly suggests the presence of the second mode $j = 2$ and the accuracy of eq 1. The decomposition into two types of relaxation modes held well in the dielectric spectra obtained for other aqueous MeNO₂ solutions at different c values and for all of the aqueous solutions of the nitro compounds examined in this study.

Figure 1

Figure 2 (a) and (b)

The dependencies of the ε_j ($j = 1$ and 2) values on the concentration, c , for the aqueous MeNO₂, EtNO₂ and PrNO₂ solutions are shown in Figure 2 (a). The magnitude of relaxation strength of the mode $j = 1$, ε_1 , decreased in proportion to c . However, the magnitude of the relaxation strength of the mode $j = 2$, ε_2 , increased almost in proportion to c in the examined c range, as observed in Figure 2 (a). The relaxation times weakly depended on c , as observed in Figure 2(b). Because the value of the shortest relaxation time, τ_1 , was essentially identical to the dielectric relaxation time, τ_w ($= 8.1$ ps), of water molecules in the pure liquid state at the same temperature of 25 °C, the mode $j = 1$ was assigned to the rotational mode of free water molecules in solution. The depression in the ε_1 value in proportion to c observed in Figure 2 (a) is directly related to the evaluation of the hydration number, n_H , as described later.

The relaxation modes $j = 2$, possessing relaxation times of $\tau_2 \sim 11, 14$ and 16 ps, respectively, for MeNO₂, EtNO₂ and PrNO₂, were assigned to the rotational process of each solute molecule irrespective of the c values because of the large dipole moments of ~ 3.5 D²⁷ for the nitro group. Small differences in the τ_2 values between MeNO₂ and EtNO₂ and between MeNO₂ and PrNO₂ reflect slight differences in the effective molecular sizes of these molecules in water. The partial molar volumes of these nitro compounds were determined to be $V_s = 49.4$ (MeNO₂), 65.5 (EtNO₂) and 82.0 cm³ mol⁻¹ (PrNO₂) at 25 °C, arranged in order of the τ_2 values. If the nitro compounds possess finite (nonzero) hydration numbers, n_H , the mode $j = 2$ can possibly be assigned to an exchange process between hydrated water molecules and free water molecules. However, the n_H values for these nitro compounds are determined to be zero in the next section, indicating that the exchange of hydrated water molecules need not be considered.

The dielectric spectra from an aqueous solution of AcCN at $c = 1.5$ M and $T = 25$ °C are shown in Figure 3 as typical examples of the obtained spectra for aqueous solutions of the examined nitriles. The dielectric spectra observed in Figure 3 were perfectly decomposed into two Debye-type relaxation modes (cf. eq 1), similar to the spectra of the aqueous nitro compounds described above (cf. Figure 1).

Figures 4 (a) and (b) show the concentration dependence of ε_j and τ_j ($j = 1$ and 2) of the aqueous solutions of the examined nitriles. Because essentially the same c dependencies of ε_j and τ_j as observed in aqueous solutions of nitro compounds (cf. Figures 2 (a) and (b)) were obtained, the assignment for each dielectric relaxation mode should be the same as that for the nitro compounds. The partial molar volumes of the nitriles in aqueous solution were determined to be $V_s = 47.6$ (AcCN), 64.8 (PrCN) and 80.7 cm³ mol⁻¹ (BuCN) at 25 °C. The values of V_s , indicating the molecular sizes in aqueous solution, were arranged in order of relaxation time, τ_2 , similar to the behavior observed in the aqueous solutions of the nitro compounds.

If one assumes that the nitro compounds and nitriles examined in this study are spherical molecules possessing molar volumes proportional to their V_s values, the Stokes-Einstein-Debye relationship²⁸ provides the dielectric relaxation time of the mode $j = 2$ for each compound as $\tau_2 \propto V_s \eta_w$ at the same temperature, where η_w is the viscosity of the medium, water. This relationship suggests that the τ_2 value is simply proportional to V_s , whereas one should not compare quantitatively the τ_2 values between the examined polar compounds. The physical meaning of η_w is not clear at the molecular level.

Figure 3

Figures 4 (a) and (b)

Hydration Numbers and Dynamics: The depression in the ε_1 value observed in Figures 2 (a) and 4 (a) can be explained by two factors: the volumetric effect of the solute molecules and the hydration effect, as described in detail elsewhere²¹⁻²⁴. The depression of the ε_1 value in the presence of solute molecules in solution is quantitatively described by eq 2²¹⁻²⁴, given below

$$\frac{\varepsilon_1}{\varepsilon_w} = \frac{1 - 10^{-3}V_s c}{1 + 10^{-3}V_s c / 2} - 10^{-3}V_w c n_H \quad (2)$$

where ε_w is the dielectric relaxation strength of pure water at the same temperature as the solution, and V_w is the partial molar volume of the water molecules. The first term of eq. 2 represents the contribution of the volumetric effect of the solute, and the second term reflects the hydration effect.

Figures 5(a), (b) and (c)

Figures 6(a), (b) and (c)

Figures 5(a), (b) and (c) show the concentration dependencies of the depression ratios, $\varepsilon_1 \varepsilon_w^{-1}$, for aqueous solutions of nitro compounds at $T = 25$ °C. If no hydration effect is present, the $\varepsilon_1 \varepsilon_w^{-1}$ data should stay on the line calculated using eq 2, assuming $n_H = 0$. The obtained data agreed well with the $n_H = 0$ line, irrespective of c and the molecular species. If one neglects the contribution of the minor relaxation mode $j = 2$ and is forced to fit the dielectric relaxation spectra with the single relaxation mode $j = 1$, the calculated depression ratios slightly exceed the lines of $n_H = 0$ for the nitro compounds and lead to an impossible negative hydration number, *e.g.*, $n_H \sim -2$ for MeNO₂. Consequently, the hydration number, n_H , is determined to be zero at a temperature of 25 °C for the nitro compounds MeNO₂, EtNO₂ and PrNO₂. The same conclusion was reached for the c dependencies of the depression ratios for the nitriles, as observed in Figures 6(a), (b) and (c). We therefore concluded that $n_H = 0$, irrespective of c and the molecular

identity of the nitrile and nitro compounds. From these considerations, we can conclude that the highly polar species $-\text{NO}_2$ and $-\text{CN}$, with dipole moments greater than 3 D, should not be classified as hydrophilic but rather as “hydroneutral” groups; the same conclusion applies to carbonyl and ester groups, displaying dipole moments of 3.0 and 1.8 D, respectively¹¹. “Hydroneutral” groups have been defined as those functional groups displaying hydrophilicities intermediate between those of hydrophilic and hydrophobic groups; these groups display n_{H} values of 0 and high water solubility for low molar mass compounds. The zero hydration number determined in this study using high frequency dielectric techniques describes two possible scenarios: 1) no hydrogen bonds are formed between the solute and the water molecules, or 2) weak hydrogen bonds form between the solute and the water molecules, but these bonds have lifetimes or interaction times close to or shorter than the rotational relaxation time of free water molecules, τ_{w} , as observed in the carbonyl group.

Bertie *et al.*²⁹ have reported that interactions or hydrogen bond formation occurs between the nitrogen atoms of $-\text{CN}$ groups and the water protons in aqueous AcCN solutions even at low AcCN contents using infrared (IR) integrated absorption spectroscopic techniques. Therefore, the zero hydration number, $n_{\text{H}} = 0$, for nitriles suggests the formation of weak hydrogen bonds between the solute and the water molecules, with lifetimes close to or shorter than the rotational relaxation time of free water molecules, τ_{w} .

The absence of hydrated water molecules, *i.e.*, $n_{\text{H}} = 0$, makes the molecular dynamics of dissolved molecules in aqueous solutions much simpler in general. Because one does not have to take into account the exchange of hydrated water molecules around ketones with free water molecules, the second relaxation mode $j = 2$ can be attributed to the rotational relaxation mode of the solutes in water. If the interactions between the solvent, water, and solute molecules are not

strong, the interaction between the solute molecules is essentially responsible for the value of the Kirkwood factor (g_K). The square of the apparent dipole moment of the solute molecule (μ_{ap}^2) is described by the equation given below, assuming the Kirkwood³⁰ and Fröhlich³¹ relationship.

$$\mu_{\text{ap}}^2 = \frac{9\varepsilon_2(2\varepsilon_2 + 3\varepsilon_\infty)\varepsilon_v k_B T}{(\varepsilon_2 + \varepsilon_\infty)(\varepsilon_\infty + 2)^2 \phi N_A}, \quad \mu_{\text{ap}}^2 = g_K \mu_0^2 \quad (3)$$

In this equation, ϕ , N_A , ε_∞ , ε_v , $k_B T$, and μ_0^2 represent the molar concentration of the solute in units of mol cm⁻³, Avogadro's number, the high frequency limiting electric permittivity, the electric permittivity in a vacuum, the product of the Boltzmann constant and the absolute temperature, and the square of the intrinsic dipole moment of the solute, respectively. The $|\mu_0|$ value of the nitro group, -NO₂, was previously reported to be 3.56 D *via* dielectric data from MeNO₂ in a hexane solution²⁷. The concentration dependencies of $|\mu_{\text{ap}}|$ and g_K were calculated from the data in Figure 2 (a) *via* eq. 3 for the examined nitro compounds. Figure 7 clearly demonstrates that the value of $|\mu_{\text{ap}}|$ is 3.4 D at $c = 0$ M and decreases with increasing c . This observation means that $|\mu_0| = 3.4$ D for the nitro group, -NO₂, in aqueous solution, irrespective of the identity of the compound. The value of $|\mu_0|$ in aqueous solution was slightly smaller than that observed in hexane. The g_K values calculated *via* eq 3, assuming the obtained relationship $|\mu_0| = 3.4$ D, gradually decreased from unity with increasing c , as in the case of $|\mu_{\text{ap}}|$, irrespective of the identity of the compound. The observed c dependence of g_K for the nitro group, -NO₂, reveals that the nitro compounds tend to adopt an anti-parallel configuration between the dipole moments due to the relatively strong dipole-dipole interaction caused by the dipole moment of 3.4 D.

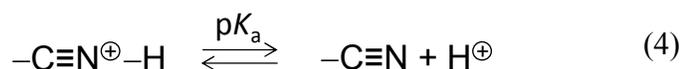
The $|\mu_0|$ value of the cyano group, -CN, was reported to be 3.61 D *via* dielectric data from AcCN in a benzene solution³². The dependencies of the g_K and $|\mu_{\text{ap}}|$ values on c for the

nitriles examined in this study are shown in Figure 8. The value of $|\mu_{\text{ap}}|$ was 3.7 D at $c = 0$ M and decreased with increasing c . This observation reveals that $|\mu_0| = 3.7$ D for the cyano group, $-\text{CN}$, in aqueous solution, irrespective of the identity of the compound. The value of $|\mu_0|$ in aqueous solution was slightly greater than that observed in benzene³². The g_{K} values calculated using eq. 3 and assuming $|\mu_0| = 3.7$ D gradually decreased from unity with increasing c . The observed c dependence of g_{K} for the cyano group, $-\text{CN}$, reveals the tendency of cyano groups to adopt an anti-parallel configuration due to the strong dipole-dipole interactions caused by the dipole moment of 3.7 D, similar to the behavior of the nitro group, $-\text{NO}_2$.

Figure 7

Figure 8

Controlling Factor of Hydration Number: The cyano group, $-\text{CN}$, has neither hydrogen nor oxygen atoms, which allow hydrogen bonding between water molecules. However, the nitrogen atom of the $-\text{CN}$ group has the potential to act as a water hydrogen (proton) acceptor for hydrogen bond formation with water molecules because of the presence of a lone-pair electron orbital. The nitro group, $-\text{NO}_2$, is also an aprotic species and has the ability to be a water proton acceptor for hydrogen bond formation. Because all of the hydroneutral polar groups found in the previous study and this study, *i.e.*, $-\text{C}(=\text{O})-$, $-\text{C}(=\text{O})\text{O}-$, $-\text{CN}$, and $-\text{NO}_2$, are aprotic, the groups must behave as water proton acceptors to be hydrated in aqueous solution. Basically, the protonated form $\text{p}K_{\text{a}}$ values of the groups quantitatively demonstrate how easily the groups are protonated, as illustrated in eq 4 using the cyano group, $-\text{CN}$, as an example.



Nevertheless, it is expected that the $\text{p}K_{\text{a}}$ value is also a rough measure of the ability of a group to be a water proton acceptor. Table 1 summarizes the reported $\text{p}K_{\text{a}}$ values for the hydroneutral

polar groups together with those of the hydrophilic polar groups $-\text{OH}$, $-\text{CH}_2\text{OCH}_2-$, and $-\text{C}(=\text{O})\text{NH}_2$.³³⁻³⁸ The magnitudes of the $\text{p}K_{\text{a}}$ values for the hydroneutral polar groups are considerably larger than those for the hydrophilic polar groups. This fact strongly suggests that the hydrophilic polar groups are more easily protonated than the hydroneutral polar ones. Thus, the hydrophilic polar groups are hydrated and exhibit finite positive n_{H} values more readily compared with the hydroneutral polar groups. There is a specific threshold $\text{p}K_{\text{a}}$ value between -6 and -4 that divides polar groups into hydrophilic or hydroneutral polar groups.

The donor number (DN), proposed by Gutmann,^{39,40} is a quantitative measure of the Lewis basicity of a compound based on the calorimetrically obtained enthalpy showing interaction energies between electron donor (solute) molecules and the reference acidic solute in an inert solvent and conventionally has been used as a measure of the ability of a compound to solvate Lewis acids or cations. In the case of hydration, water molecules are the Lewis acids. Thus, the physicochemical meaning of DN is not so different from that of the protonated form $\text{p}K_{\text{a}}$ value of a compound. The correlation between the hydration number, n_{H} , and DN seems to be more precise than that between n_{H} and $\text{p}K_{\text{a}}$ in the view point of the quantitative values of hydration energy. Here, we summarize the reported DN values for typical polar groups, including nitro and cyano groups, in Table 1, together with the hydration number, n_{H} , and dipole moment, $|\mu_0|$, for comparison. There appears to be a threshold DN value, ca. 18, that divides the polar groups into *hydrophilic* groups bearing finite hydration numbers and hydroneutral groups with no hydrated water molecules, *i.e.*, $n_{\text{H}} = 0$.

Several years ago, Gojło *et al.*⁴¹ discussed the hydration behavior of aprotic compounds, including AcCN and acetone, bearing a carbonyl group, $-\text{C}(=\text{O})-$, using FTIR spectroscopic methods. They concluded that the compounds with DN values less than 18, such as AcCN and

acetone, rotate freely in cavities formed by water molecules around the solute molecules and classified the hydration states of these compounds as hydrophobic type hydration, as observed in the behavior of alkyl chains^{18,41}. They also found that the intermolecular oxygen atom distance between interacting water and solute molecules possessing DN values less than 18 was substantially longer than that of solutes possessing DN values greater than 20.⁴¹ Consequently, it has been confirmed that the hydration states of compounds bearing aprotic polar groups and possessing DN values less than 18 (or $pK_a < -4$), such as $-\text{NO}_2$ and $-\text{CN}$, are crucially different from those of compounds bearing polar groups with DN values higher than 19.

Finally, we should point out that the hydration free energies of the nitro compounds and nitriles remain to be slight negative values irrespective of their zero hydration number, since other spectroscopic methods like IR techniques^{12,29} have clearly demonstrated the presence of the interaction between the compounds and water molecules.

CONCLUSIONS

A technique to determine the hydration numbers of solute molecules dissolved in water using dielectric relaxation measurements in an extremely high frequency range of up to 50 GHz was used in this study. Since the relaxation strength of free water molecules in aqueous solutions is exactly evaluable in a frequency range higher than 20 GHz at 25 °C, the amount of water molecules hydrated to solute molecules was precisely determined.

The hydration numbers of water soluble nitro compounds and nitriles bearing nitro or cyano groups, respectively, were determined to be ca. zero at 25 °C using extremely high frequency dielectric relaxation measurements at up to 50 GHz. Therefore, these typical highly polar compounds should not be classified as hydrophilic compounds but rather as hydroneutral

compounds, along with ketones and esters. Consequently, not all the polar molecules and groups are hydrophilic, despite their large dipole moments.

Hydroneutral nitro compounds and nitriles exhibit a distinctively separated rotational relaxation process that is slightly slower than the rotational process of water molecules and have a tendency to adopt an anti-parallel orientation between their dipoles because of the remarkably strong dipole-dipole interactions resulting from their large dipole moments of over 3 D. Whether aprotic polar compounds or groups have finite nonzero hydration numbers is not controlled by the magnitude of the dipole moment but rather by the ability of the molecule to act as a water proton acceptor, as is roughly quantifiable by the values of the protonated pK_a and/or the donor number of the functional group.

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REFERENCES AND NOTES

- 1) For example, Gilbert, T. R.; Kirss, R. V.; Foster, N.; Davies, G. *Chemistry*, 2nd ed.; W. Norton & Comp.: New York, 2009; Chapter 10.
- 2) Vollhardt, K. P. C.; Schore, N. E. *Organic Chemistry structure and function*, 5th ed.; W. H. Freeman & comp.: New York, 2007; Chapter 8.
- 3) McMurry, J.; Castellion, M. E.; Ballantine, D. S.; Hoeger, C. A.; Peterson, V. E. *Fundamentals of General, Organic, and Biological Chemistry*, 6th ed.; Pearson Education: Upper Saddle River, 2009; Chapter 18.
- 4) Holum, J. R. *Fundamental of General, Organic, and Biological Chemistry*; John Wiley and Sons: New York, 1998; Chapter 21.
- 5) IUPAC. Compendium of Chemical Terminology, 2nd ed. (the "Gold Book"). Compiled by A. D. McNaught and A. Wilkinson. Blackwell Scientific Publications, Oxford (1997). XML on-line corrected version: <http://goldbook.iupac.org> (2006-) created by M. Nic, J. Jirat, B. Kosata; updates compiled by A. Jenkins. ISBN 0-9678550-9-8. doi:10.1351/goldbook.
- 6) Shikata, T.; Okuzono, M. Hydration/Dehydration Behavior of Polyalcoholic Compounds Governed by Development of Intramolecular Hydrogen Bonds, *J. Phys. Chem. B* **2013**, *117*, 2782-2788.
- 7) Shikata, T.; Okuzono, M.; Sugimoto, N. Temperature-Dependent Hydration/Dehydration Behavior of Poly(ethylene oxide)s in Aqueous Solution, *Macromolecules* **2013**, *46*, 1956-1961.

- 8) Ono, Y.; Shikata, T., Contrary Hydration Behavior of *N*-Isopropylacrylamide to its Polymer, P(NIPAm), with a Lower Critical Solution Temperature, *J. Phys. Chem. B* **2007**, *111*, 1511-1513.
- 9) Riddick, J. A.; Bunger, W. B.; Sakano, T. K. *Organic Solvent, Physical Properties and Methods of Purification*, 4th ed.; John Wiley & Sons: New York, 1986: P. 404.
- 10) Riddick, J. A.; Bunger, W. B.; Sakano, T. K. *Organic Solvent, Physical Properties and Methods of Purification*, 4th Ed.; John Wiley & Sons: New York, 1986: P. 350.
- 11) Shikata, T.; Okuzono, M. Are All Polar Molecules Hydrophilic? Hydration Numbers of Ketones and Esters in Aqueous Solution. *J. Phys. Chem. B* **2013**, *117*, 7718-7723.
- 12) Max, J-J.; Chapados, C. Infrared spectroscopy of acetone–water liquid mixtures. I. Factor analysis. *J. Chem. Phys.* **2003**, *119*, 5632-5643.
- 13) Riddick, J. A.; Bunger, W. B.; Sakano, T. K. *Organic Solvent, Physical Properties and Methods of Purification*, 4th ed.; John Wiley & Sons: New York, 1986; P. 578.
- 14) Ishihara, Y.; Okouchi, S.; Uedarira, H. Dynamics of Hydration of Alcohols and Diols in Aqueous Solutions. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 3337-3342.
- 15) Mason, P. E.; Neilson, G. W.; Enderby, J. E.; Cuello, G.; Brady, J. W. Neutron Diffraction and Simulation Studies of the Exocyclic Hydroxymethyl Conformation of Glucose, *J. Chem. Phys.* **2006**, *125*, No. 224505.
- 16) Magazù, S. NMR, Static and Dynamic Light and Neutron Scattering Investigations on Polymeric Aqueous Solutions. *J. Mol. Str.* **2000**, *523*, 47-59.

- 17) Impey, R. W.; Madden, P. A.; McDonald, I. R. Hydration and Mobility of Ions in Solution. *J. Phys. Chem.* **1983**, *87*, 5071-5083.
- 18) Davis, J. G.; Gierszal, K. P.; Wang, P.; Ben-Amotz, D. Water Structural Transformation at Molecular Hydrophobic Interfaces. *Nature* **2012**, *491*, 582-585.
- 19) Buchner, R.; Capewell, S. G.; Hefter, G.; May, P. M. Ion-Pair and Solvent Relaxation Processes in Aqueous Na₂SO₄ Solutions. *J. Phys. Chem. B* **1999**, *103*, 1185-1192.
- 20) Bockris, J. O.; Reddy, A. K. N. *Modern Electrochemistry 1: Ionics*; Plenum: New York, 1998, Vol. 1.
- 21) Ono, Y.; Shikata, T. Hydration and Dynamic Behavior of Poly(*N*-isopropylacrylamide)s in Aqueous Solution: A Sharp Phase Transition at the Lower Critical Solution Temperature. *J. Am. Chem. Soc.* **2006**, *128*, 10030-10031.
- 22) Shikata, T.; Takahashi, R.; Sakamoto, A. Hydration of Poly(ethylene oxide)s in Aqueous Solution As Studied by Dielectric Relaxation Measurements. *J. Phys. Chem. B* **2006**, *110*, 8941-8945.
- 23) Satokawa, Y.; Shikata, T. Hydration Structure and Dynamic Behavior of Poly(vinyl alcohol)s in Aqueous Solution. *Macromolecules* **2008**, *41*, 2908-2913.
- 24) Shikata, T.; Takahashi, R.; Satokawa, Y. Hydration and Dynamic Behavior of Cyclodextrins in Aqueous Solutions. *J. Phys. Chem. B* **2007**, *111*, 12239-12247.
- 25) Shikata, T.; Sugimoto, N. Reconsideration of the Anomalous Dielectric Behavior of Dimethyl Sulfoxide in the Pure Liquid State. *Phys. Chem. Chem. Phys.* **2011**, *13*, 16542-16547.

- 26) Shikata, T.; Sugimoto, N.; Sakai, Y.; Watanabe, J. Dielectric Behavior of Typical Benzene Monosubstitutes, Bromobenzene and Benzonitrile. *J. Phys. Chem. B* **2012**, *116*, 12605-12613.
- 27) Coetzee, J. F.; Chang, T.-H. Recommended Methods for the Purification of Solvents and Tests for Impurities Nitromethane. *Pure & Appl. Chem.* **1986**, *58*, 1541-1545.
- 28) Daniel, V. V. *Dielectric Relaxation*; Academic Press: London, 1967; Chapters 7 and 8.
- 29) Bertie J. E.; Lan, Z. Liquid Water–Acetonitrile Mixtures at 25 °C: The Hydrogen-Bonded Structure Studied through Infrared Absolute Integrated Absorption Intensities. *J. Phys. Chem. B*, **1997**, *101*, 4111–4119
- 30) Kirkwood, J. G. The Dielectric Polarization of Polar Liquids. *J. Chem. Phys.* **1939**, *7*, 911–919.
- 31) Fröhlich, H. General Theory of the Static Dielectric Constant. *Trans. Faraday Soc.* **1948**, *44*, 238–243.
- 32) Thakur, N.; Sharma, D. R. Dielectric Relaxation of Acetonitrile in Benzene Solution from Microwave Adsorption Studies. *Indian J. Pure & Appl. Phys.* **2003**, *41*, 806-809.
- 33) Anslyn, E. V.; Dougherty, D. A. *Modern Physical Organic Chemistry*; University Science Books: Sausalito, 2004; Chapter 1.
- 34) Thibault-Starzyk, F.; Travert, A.; Saussey, J.; Lavalley, J.-C. Correlation between Activity and Acidity on Zeolites: a high temperature infrared study of adsorbed acetonitrile. *Topics in Catalysis* **1998**, *6*, 111–118.

- 35) Chin, J.; Jubian, V. A highly Efficient Copper (II) Complex Catalyzed Hydrolysis of Methyl Acetate at pH 7.0 and 25 °C. *J. Chem. Soc., Chem. Comm.* **1989**, 839-841.
- 36) Arnett, E. M. *Progress in Physical Organic Chemistry*, Vol. 1, Cohen, S. G. Streitwieser, A.; Taft, R. W. Jr. edited.; Interscience: New York, 1963; P. 223.
- 37) Chauhan, B. S. *Principles of Biochemistry and Biophysics*; Univ. Sci. Press: New Delhi, 2008; Chapter 1.
- 38) Grant, H. M.; Mctigue, P. ; Ward, D. G. The Basicities of Aliphatic Amides. *Australian J. Chem.* **1983**, *36*, 2211 – 2218.
- 39) Gutmann, V. Empirical Parameters for Donor and Acceptor Properties of Solvents. *Electrochimica Acta* **1976**, *21*, 661-670.
- 40) Gutmann, V. *The Donor-Acceptor Approach to Molecular Interactions*; Plenum Press: New York; 1978.
- 41) Gojłó, E.; Gampe, T.; Krakowiak, J.; Stangret, J. Hydration of Aprotic Donor Solvents Studied by Means of FTIR Spectroscopy. *J. Phys. Chem. A* **2007**, *111*, 1827-1834.

Table 1. Values of $|\mu_0|$, n_H , pK_a and DN for typical polar groups at 25 °C

Polar groups	nitro	cyano	carbonyl	ester	ether	hydroxy	amide
Structure	$-\text{NO}_2$	$-\text{CN}$	$-\text{C}(=\text{O})-$	$-\text{C}(=\text{O})\text{O}-$	$-\text{CH}_2\text{OCH}_2-$	$-\text{OH}$	$-\text{C}(=\text{O})\text{NH}_2$
$ \mu_0 / \text{D}$	3.4	3.7	3.0	1.8	1.3	1.6	3.5~3.7
n_H	0 [*]	0 [*]	0 ¹¹	0 ¹¹	4 ^{7,22}	5 ⁶	6 ⁸
pK_a	-12 ³³	-11.8 ³⁴	-7.5 ³³	-6.0 ³⁵	-3.6 ³⁶	-2.4 ³⁷	-0.6 ³⁸
DN ^{36,37}	3~4	12~14	17	17	19~20	19~20	~24

^{*}this study

FIGURES

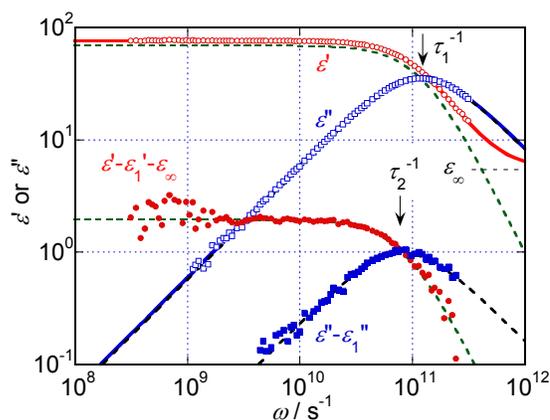


Figure 1. Frequency, ω , dependence of the real and imaginary parts of the electric permittivity, ϵ' (open circles) and ϵ'' (open squares), for an aqueous solution of MeNO₂ at a concentration of $c = 0.78$ M and at 25 °C. The dashed lines represent constituent Debye-type relaxation functions to describe the experimental ϵ' and ϵ'' , shown as solid lines, via eq 1. The closed circles and squares represent data for $\epsilon' - \epsilon_1' - \epsilon_\infty$ and $\epsilon'' - \epsilon_1''$, respectively.

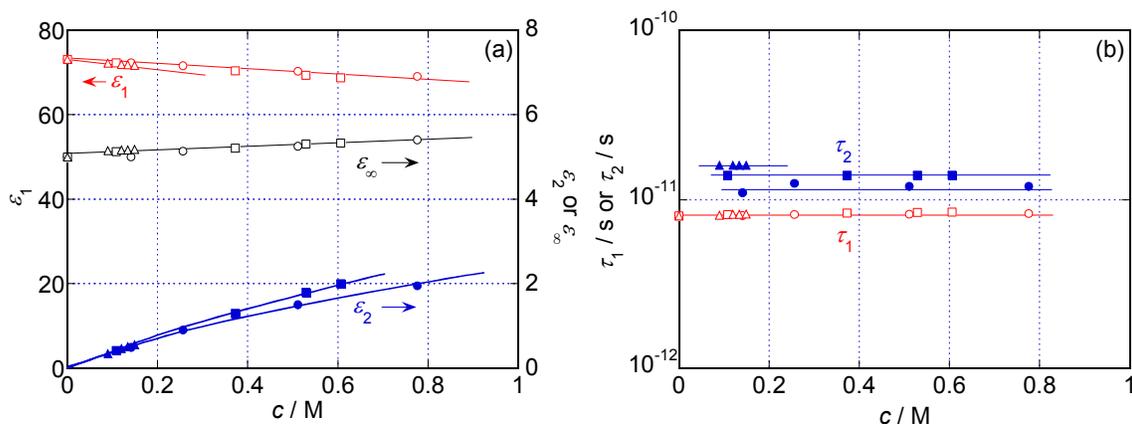


Figure 2. The concentration, c , dependencies of the relaxation strength, ϵ_j ($j = 1, 2$, and ∞) (a), and times, τ_j ($j = 1$ and 2) (b), of the constituent Debye-type relaxation modes for aqueous solutions of MeNO₂ (circles), EtNO₂ (squares) and PrNO₂ (triangles) at 25 °C. The lines are a guide for the eyes.

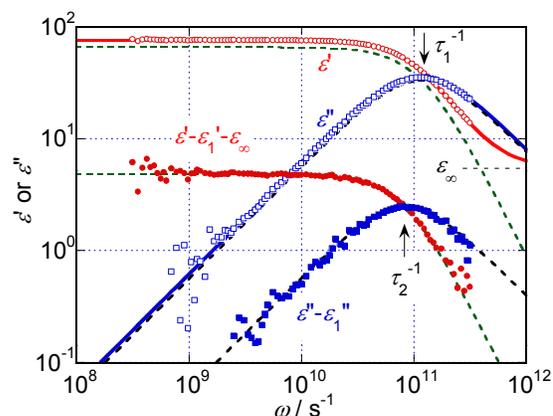


Figure 3. The ω dependence of ϵ' (open circles) and ϵ'' (open squares) for an aqueous solution of AcCN at a concentration of $c = 1.5$ M and at 25 °C. The dashed lines represent constituent Debye-type relaxation functions to describe the experimental ϵ' and ϵ'' , shown as solid lines, via eq 1. The closed circles and squares represent the data for $\epsilon' - \epsilon_1' - \epsilon_\infty$ and $\epsilon'' - \epsilon_1''$, respectively.

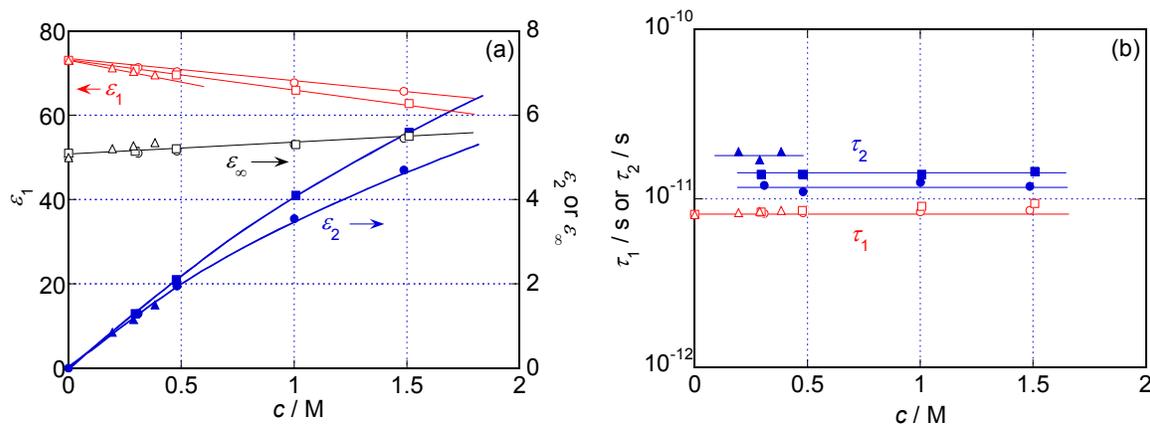


Figure 4. The c dependencies of ϵ_j ($j = 1, 2$, and ∞) (a) and τ_j ($j = 1$ and 2) (b) of constituent Debye-type relaxation modes for aqueous solutions of AcCN (circles), PrCN (squares) and BuCN (triangles) at 25 °C. The lines are guides for the eyes.

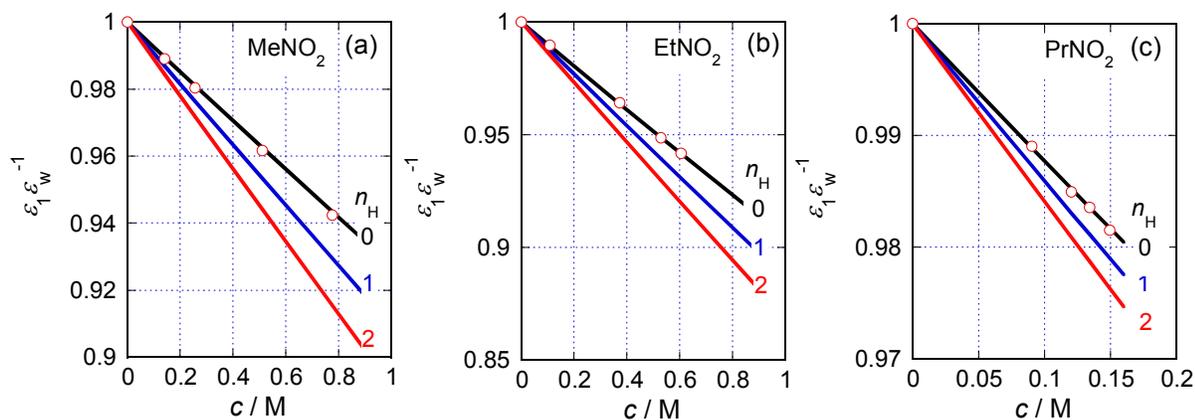


Figure 5. The c dependence of the depression ratio, $\epsilon_1 \epsilon_W^{-1}$, for aqueous solutions of MeNO₂ (a), EtNO₂ (b) and PrNO₂ (c).

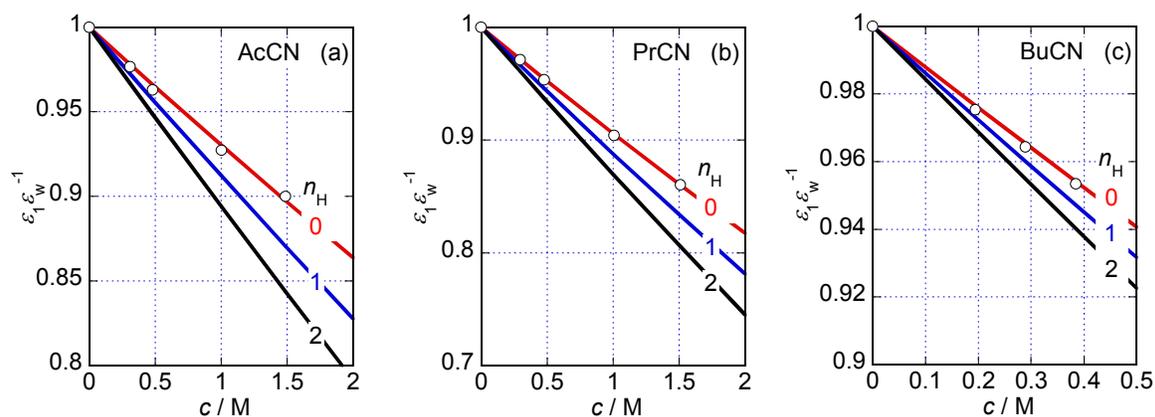


Figure 6. The c dependence of $\epsilon_1 \epsilon_W^{-1}$ for aqueous solutions of AcCN (a), PrCN (b) and BuCN (c).

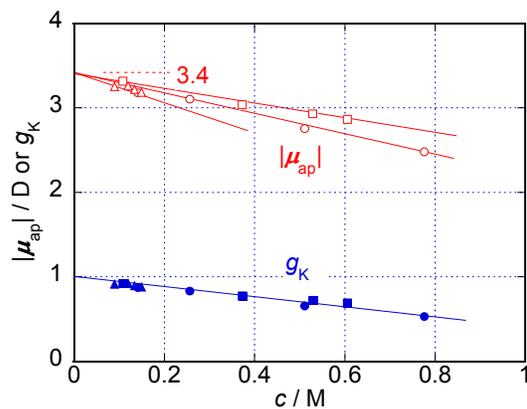


Figure 7. The dependencies of the g_K and $|\mu_{ap}|$ values on c for aqueous solutions of MeNO₂ (circles), EtNO₂ (squares) and PrNO₂ (triangles).

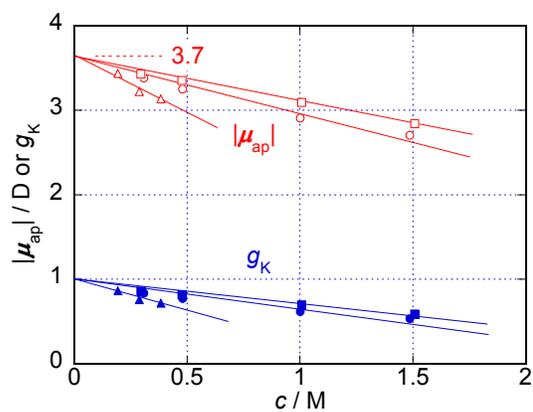


Figure 8. The c dependencies of the g_K and $|\mu_{ap}|$ values for aqueous solutions of AcCN (circles), PrCN (squares) and BuCN (triangles).