p, T-Dependence of the Molecular Dynamics in a Hydrophobic Model System: 2,2-Dimethyl-1-propanol / D_2O

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Aqueous solutions of 2,2-dimethyl-1-propanol were studied as a model system for the *p, T*-dependence of the hydrophobic interaction at pressures up to 200 MPa and between 273 K and 403 K. The liquid/liquid phase separation of this alcohol in light and heavy water is described. As expected for aqueous solutions of hydrophobic substances, the solubility of the alcohol is larger in light than in heavy water.

The *p, T, c*-dependence of the self diffusion coefficients and of the rotatoric mobility, as given by the deuteron spin lattice relaxation times, of the water and alcohol molecules are studied in the one phase region.

The translational and the rotational mobility of the water molecules in the binary solution show at low temperatures the anomalous pressure dependence typical for neat water.

Introduction

Apolar molecules in aqueous solution are surrounded by hydration shells in which the water molecules possess a reduced mobility, and, at least around 300 K, the total entropy of the solution is lowered compared to the bulk phase [1, 2]. This phenomenon is called hydrophobic hydration, and the formation of this hydration structure has been baptized "iceberg-formation" by Frank and Evans [3].

It is generally agreed upon that at higher concentrations of the apolar solute in water these isolated structures tend to associate. This association process releases some of the water of hydration into the bulk phase, and this increases the entropy of the solution. The entropy driven association is named hydrophobic interaction.

Both of these processes and their pressure and temperature dependence are of fundamental importance for the formation of the native functional structures of biopolymers like proteins or nucleic acids in aqueous solution [4].

In the following it will be attempted to characterize the translational and rotational dynamics of a hydrophobic model system over a wide range of temperatures and pressures in order to contribute to the still controversial discussion about the pressure dependence of the hydrophobic interaction [5].

Since purely apolar solutes are only very sparingly soluble in water, it is customary to study compounds carrying, attached to a large apolar hydrocarbon moiety, a polar group like a hydroxylamino- or carboxyl group. These polar groups enhance the solubility, and it is assumed that at least the qualitative *p, T*-dependence of hydrophobic hydration and interaction can be studied in these systems at sufficiently high concentrations [6]. In the following the dynamics of 2,2-dimethyl-1-propanol (DMP) will be studied. In Fig. 1 the van der Waals surface of this molecule is scetched. It shows clearly that most of the surface is hydrophobic. For NMR studies this alcohol has the advantage of conformational rigidity and almost spherical shape of the hydrocarbon moiety, and it also provides a fairly simple and intense proton NMR spectrum. In the following the pressure dependence of the liquid/liquid miscibility gap of this system will be described and the concentration, temperature and pressure dependence of the dynamics of the two compounds will be discussed.

Experimental

DMP (99%) and D_2O (100.0% D) were purchased from Aldrich Chemicals (D-7924 Steinheim, FRG) and used without further purification. Partially deuterated DMP ($(CD_3)_2CD_2HCCD_2OD$) was prepared by a standard Grignard synthesis and purified by preparative gas chromatography.

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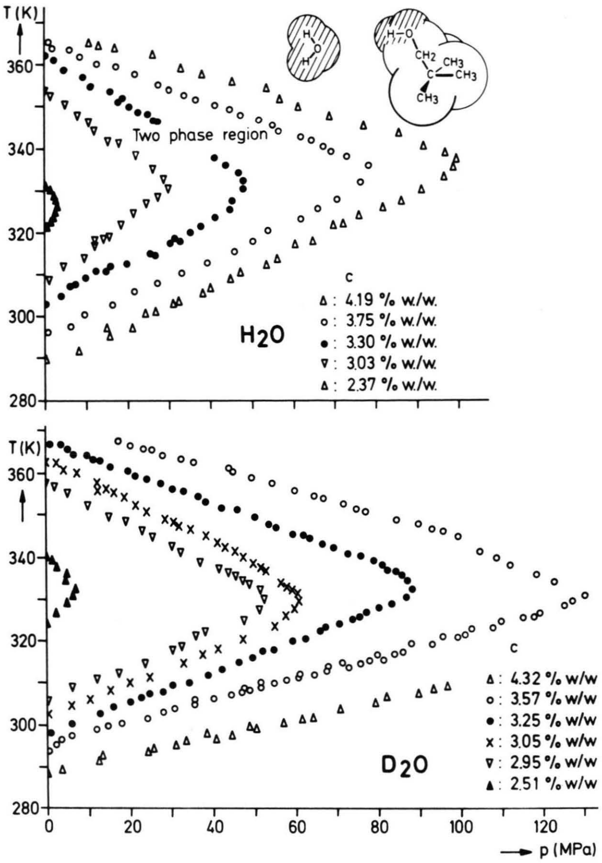

Fig. 1. Water rich part of the phase diagrams of DMP in light (top) and heavy water (bottom). The "Van der Waals contours" of the molecules (given in the top diagram) show the large hydrophobic surface of the alcohol molecules (white area in the drawing).

The NMR measurements were performed on a Bruker MSL 300 spectrometer operating at a B_0 field of 7.046 Tesla, in home built probeheads [7]. Great care was taken in the design to improve the thermal insulation of the probe volume and to reduce the temperature gradients over the sensitive volume. Temperatures were adjusted with the commercial Bruker variable temperature unit and controlled by a metal sheathed Chromel/Alumel thermocouple to ± 0.5 K. The high pressure NMR-glass cell was a modification of the strengthened glass cell design introduced by Yamada [8, 9].

These cells were also used for the determination of the liquid/liquid phase separations. The phase boundaries were either determined by very slow variation of the temperature in a thermostated bath or by gentle variation of the hydrostatic pressure. The first onset of a turbidity was taken as a sign for phase separation. Visual observation allowed this to be determined to ± 0.5 K and ± 1.0 MPa.

The self diffusion coefficients were determined by the pulsed field gradient method introduced by Stejskal and Tanner [10]. They are judged reliable to $\pm 5\%$. The reproducibility was better than $\pm 3\%$ except for the alcohol in the very dilute solutions, where poor signal to noise ratios reduced the reproducibility to $\pm 5\%$.

The spin lattice relaxation times of the deuterons were determined by the standard inversion recovery pulse sequence.

Results and Discussion

Liquid/Liquid Phase Separation

In Fig. 1 the water rich part of the phase diagrams for DMP (OH/OD) in light and heavy water are given. Application of pressure increases for all solutions studied the solubility of the alcohol in water. All mixtures studied here became homogeneous at pressures $p \geq 125$ MPa and remained clear at pressures up to 200 MPa, no high pressure demixing was observed up to this maximal pressure. Comparison of the two data sets shows that the solubility of DMP is larger in H_2O than in D_2O. This is the normal behaviour for the aqueous solutions of hydrophobic molecules [11], and is usually explained by the higher strength and concentration of the hydrogen bonds in heavy water. The determination of the spin lattice relaxation times of the deuterons and the self diffusion coefficients were confined to the one phase region of the binary system to alcohol concentrations $\leq 2.36\%$ w/w.

Self Diffusion Coefficients of the Two Compounds

In Figs. 2 and 4 the self diffusion coefficients D of the heavy water and the alcohol molecules are given as functions of concentration for three pressures: The data for neat heavy water were taken from the literature [12, 13]. The self diffusion coefficients of D_2O (Fig. 2) are almost independent of concentration; they show a very slight decrease with increasing alcohol concentration that is most pronounced at low temperatures. The pressure dependence of D of D_2O as function of alcohol concentration is given in Figure 3. This graph shows that the addition of the alcohol reduces for the translational mobility the anomalous increase

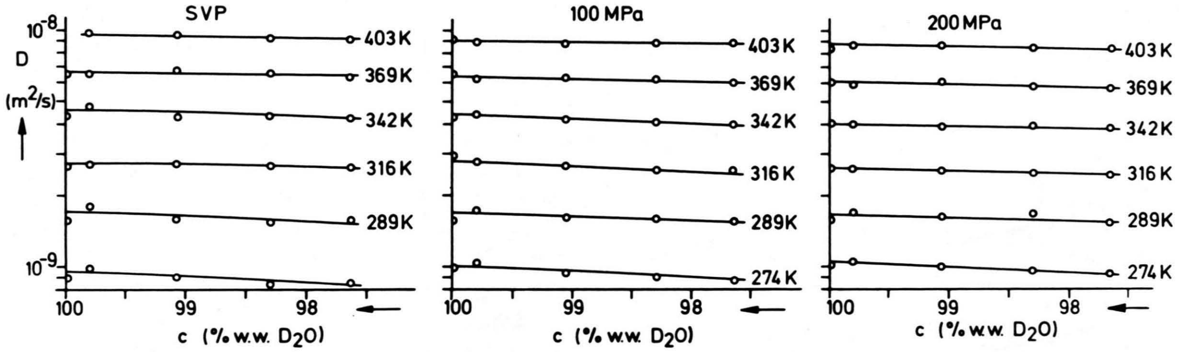

Fig. 2. Isotherms of the self-diffusion coefficients *D* of heavy water in aqueous DMP solutions as function of concentration at three pressures. SVP = Saturated Vapor Pressure.

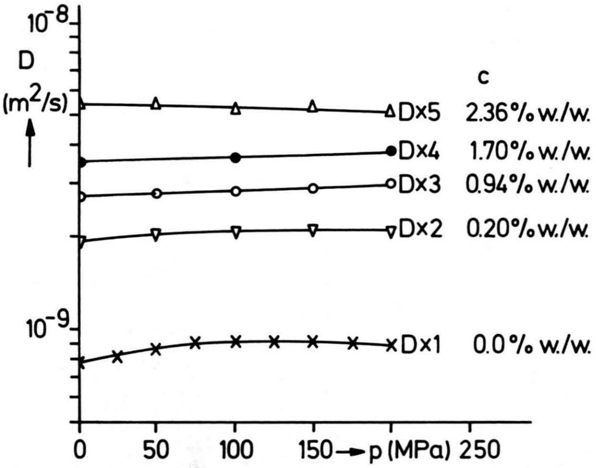

Fig. 3. Pressure dependence at 274 K of the self-diffusion coefficient of the water molecules in aqueous DMP solutions at various concentrations at 274 K.

of the fluidity of the D_2O molecules observed at the initial application of pressure.

This anomalous increase of the mobility, which is even more pronounced for the rotational mobility (compare Fig. 5), results from the open tetrahedral network structure of cold water. The water molecule participates with its two lone pairs and its two hydrogens in four hydrogen bonds and adopts an approximately tetrahedral local arrangement with rather poor packing efficiency. Removal of thermal energy forces the molecules into low-energy configurations which resemble local structures observed in the low-pressure polymorphs of ice and clathrates. The resulting quasitetrahedral force field presented by the surrounding network constrains a molecule to a few well-defined orientational states separated by relatively high potential barriers. The concentration of these fully H-bonded local structures must increase upon cooling with a consequent slowing down of diffusive modes. Compression of the sample brings next-nearest neighbours closer to a central molecule while nearest-neighbour correlations remain largely unchanged. The potential energy surface for rotation is thus less sharply defined and as a consequence rotation and translation is facilitated.

The mobility of the DMP molecules (Fig. 4) shows a stronger decrease with concentration than found for the heavy water. Also the pressure dependence of D for this compound is normal. Increasing pressure reduces the translational mobility, the effect becoming more pronounced with increasing temperature.

Considering the very specific interactions possible between the alcohol- and the water molecules, the attempt to derive from differences in the *c, p, T*-dependence of the self-diffusion coefficients the influence of pressure and temperature upon the hydrophobic association appears futile. Treating the molecules as spheres in a continuum would allow to derive from the Stokes-Einstein equation the molecular diameter, and to interpret relative changes as association dissociation effects. However, the ratio of the two diffusion coefficients at constant pressure and temperature shows a very weak concentration dependence only. Moreover the diffusibility of the alcohol increases faster with rising temperature than the mobility of water molecules. Hydrophobic association must increase with temperature and this should lead to a slower increase of D for the alcohol contrary to the effects observed.

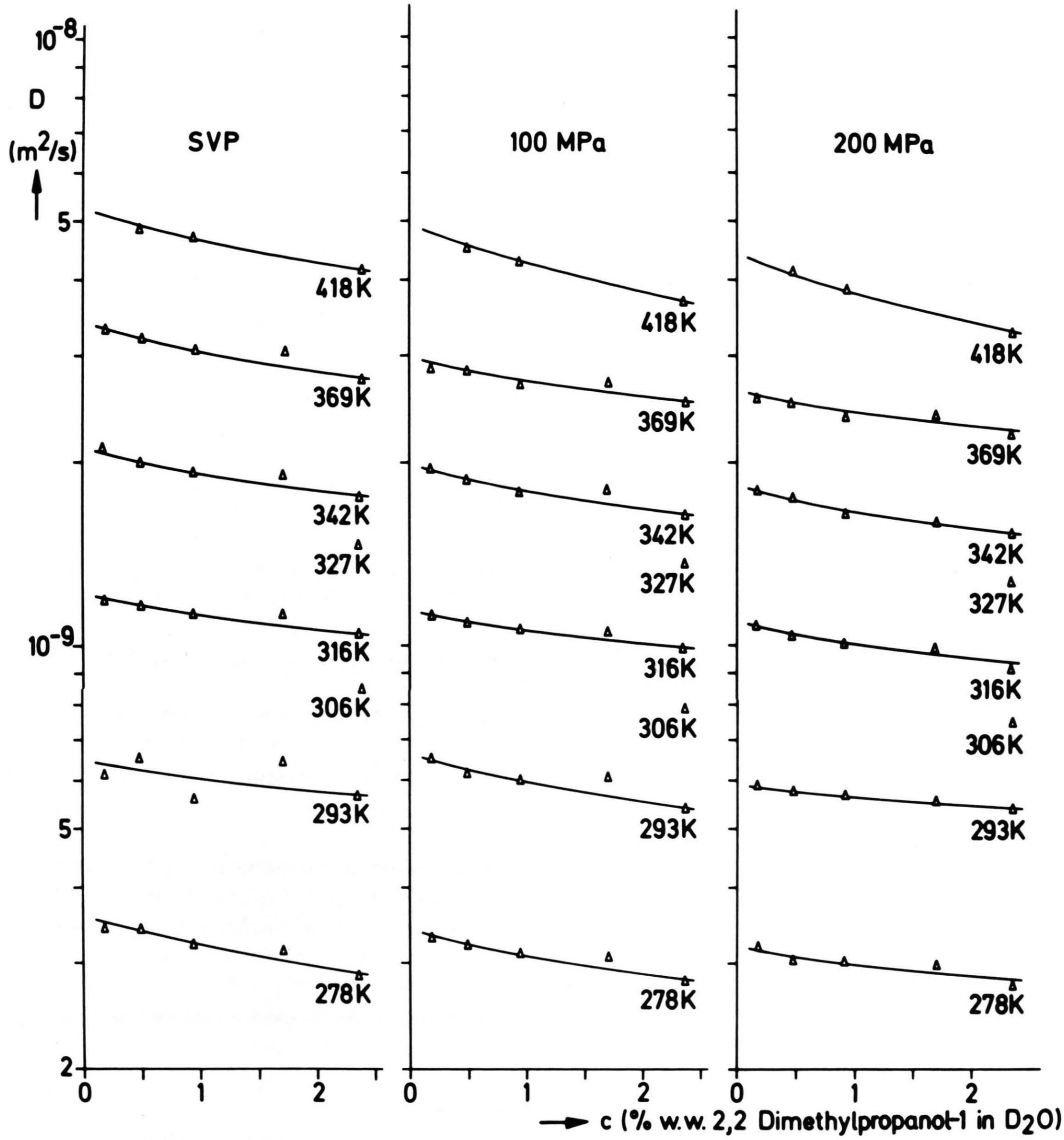

Fig. 4. Isotherms of the self-diffusion coefficients of the alcohol molecules in aqueous DMP solutions as function of concentration at three pressures.

Rotational Correlation Times of the Compounds

The spin lattice relaxation of the deuterons in the two molecules is entirely due to the electric quadrupolar relaxation mechanism. In the whole p, T range studied, the mobility of the molecules is relatively high. The relaxation times can be described in the extreme narrowing limit. In this regime the deuteron spin lattice relaxation time $T_1(D)$ for an isotropically rotating molecule is given by [14]

$$\frac{1}{T_1} = \frac{3}{8} \frac{(e^2 q Q)}{h} \tau_2$$

with e^2qQ the quadrupole coupling constant (QCC) and τ_2 the rotational correlation time. The QCC for water was derived to 201 kHz [7, 15], and that for the deuterons in the deuteromethyl groups of the alcohol

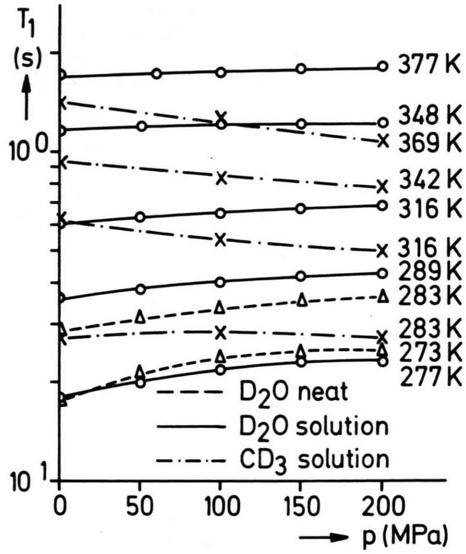

Fig. 5. Deuterium spin lattice relaxation times for heavy water and DMP. The anomalous behaviour of the rotational mobility of heavy water can be observed at all temperatures. For the alcohol the rotation is increasingly hindered with rising pressure. This effect becomes more pronounced with rising temperatures $c(\mathrm{DMP}) = 2.36\%$ w/w.

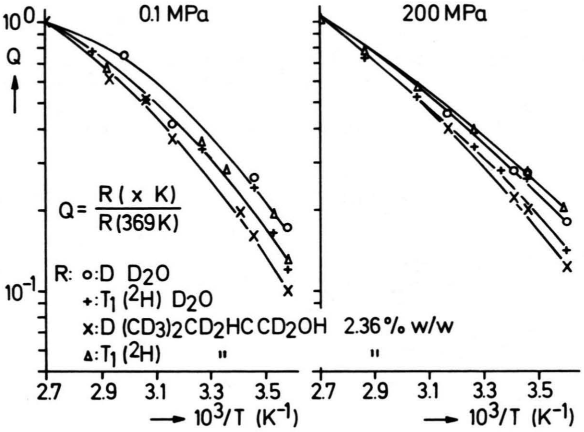

Fig. 6. Reduced isobars for the deuteron T_1 of water and the methyl deuterons of DMP and *D* of the two compounds. For comparison the *D*-values for neat D_2O are also included.

was estimated to 170 ± 10 kHz [16]. In the *p*, *T* range studied, the QCC's for both compounds should be practically constant, although for deuterons involved in hydrogen bonding the QCC is influenced by the geometry of these bonds.

In the following no attempt is made to derive rotational correlation times; rather the *p*, *T*-dependence of T_1 will be discussed qualitatively.

In Fig. 5 the T_1-isotherms of the deuterons in heavy water and of the methyl deuterons of DMP for the solution containing 2.36% w/w of the alcohol are given. For comparison the two T_1-isotherms for neat D_2O [7] at low temperatures are included. The anomalous and unique pressure dependence of the deuteron T_1 in neat water, were the application of hydrostatic pressure increases the rotational mobility of the water molecules to a larger extent than the translational mobility, is also seen in the alcohol solution. This anomaly becomes less pronounced with increasing temperature, but is still present in the 377 K isotherm. The qualitative molecular explanation for this effect has been given in the discussion of the self-diffusion coefficients.

The rotation of the alcohol molecules shows a more "normal" behaviour. Only for the lowest isotherm (283 K) a slight increase with pressure is seen. For all higher temperatures the normal decrease of the rotational mobility with pressure is found. The isotherms of the more dilute solutions behave qualitatively very similar.

In Fig. 6 reduced isobars for D and the deuteron-T_1 of the two compounds are presented. All these isobars are curved, the curvature decreasing with pressure. The differences in pressure and temperature dependence, however, are in our opinion too small for an attempt to describe the deviations by pressure and temperature influences upon the hydrophobic association of the unpolar molecule. This analysis should become possible when the proton spin lattice relaxation times of partially deuterated 2,2-dimethyl-1-propanol (i.e. $(CD_3)_2HCCD_2CD_2OD$) are measured.

Acknowledgement

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