Influence of Conformational Equilibria upon the Self-Diffusion of the Conformers in Neat Liquids

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The self-diffusion coefficients D of the isomers of liquid N-isopropyl-N-methylacetamide (IPMAA) and acetylacetone (ACAC) are studied as functions of temperature. For ACAC also pressure dependent studies were undertaken. In IPMAA the cis and trans conformers have almost identical D. In liquid ACAC, D_{Keto} is always smaller than D_{enol}, this difference being 15% around 300 K.

Key words: Conformers; Self Diffusion; Neat Liquids; Pressure.

Introduction

High resolution NMR is one of the two spectroscopic methods that can quantitatively describe conformational equilibria in liquids, provided the life time of the conformers is long on the HRNMR time scale. Thus this technique has been used on many classes of compounds for the characterisation of the thermodynamics and kinetics of these equilibria [1]. Among the group of compounds studied thoroughly are the substituted amides [2]. For many amides and their solutions also high pressure HRNMR data were obtained [3, 4], from which the reaction- and activation volumes could be derived. In none of these older studies the self-diffusion of the individual conformers was determined.

In [5] we reported the first experimental observation of different self-diffusion coefficients D of the conformers in a neat liquid: The cis and trans conformers in neat liquid N-methylformamide. For this compound the self-diffusion coefficient of the cis-conformer D_{cis} was found at $T \leq 280$ K to be 17% lower than D_{trans}, the difference becoming smaller with increasing temperature.

Conformational equilibria are found in most larger molecules, and it appears of interest to look for more examples of this new dynamic effect in order to learn which types of structural differences between the conformers lead to measurable differences of D.

In the following we present ambient pressure data for the unsymmetrically substituted N-isopropyl-N-methylacetamide (IPMAA) where a cis-trans equilibrium can be observed in the proton NMR spectra, and for acetylacetone (ACAC), which occurs in a temperature dependent keto-enol equilibrium.

Experimental

Substances

N-Isopropyl-N-methylacetamide (IPMAA) was prepared from acetylchloride and N-isopropyl-N-methylamine by standard methods. The byproduct N-isopropyl-N-methyl-ammoniumchloride partially precipitated and was filtered off. To the remaining liquid a surplus of diethyl ether was added, and the liquid phase washed with water. After drying over a molecular sieve 3 Å, the solvent was distilled off and the amide was obtained by vacuum distillation. The proton NMR spectrum was free of impurities. Acetylacetone (p. a.) 99.5% was purchased from E. Merck (Darmstadt, FRG), stored over a molecular sieve 3 Å and distilled prior to use.

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Methods

The self-diffusion coefficients were measured in a strengthened glass cell (o.d. 7 mm, i.d. 1.2 mm), a modification of the cell type introduced by Yamada [6]. Details of the apparatus used for the filling of the cells and the whole pressure setup have been published [7, 8].

A Bruker MSL 300 spectrometer operating at 300 MHz in combination with a home built probe head was used for the measurements.

The self-diffusion coefficients were determined from a Hahn-spin-echo experiment by application of a pulsed field gradient [9]. For this pulse sequence the amplitude A of the echo after a waiting period τ between the 90°- and 180°-pulse is given by

$$A(2\tau)=A(0)\exp(-2\tau/T_2)\exp(-(\gamma\delta g)^2D(\Delta-\delta/3)), \qquad (1)$$

where T_2 is the spin-relaxation time of the nucleus under study, γ its gyromagnetic ratio, and δ is the length of the field gradient pulse. Its strength is given by $g = K \cdot I$ with K the coil constant and I the pulse current. D is the self-diffusion coefficient to be measured and Δ the time between the two gradient pulses. The self-diffusion coefficients of the two conformers were determined from the amplitude of the two N-methyl signals of the Fourier transformed second half of the spin echoes. D was derived from a series of 10 to 12 spin echoes at increasing coil currents I, while keeping all other parameters in (1) constant. The gradient coil constant K was calibrated with water at 293 K [10], the calibration being controlled with a second substance. For these control experiments usually cyclooctane was used [11]. The temperature was controlled by a metal sheathed thermocouple to ± 1 K. The pressures were measured with Bourdon gauges (Heise/Connecticut) to ± 1 MPa. The overall error of the self-diffusion coefficients is estimated to be ± 5%, the reproducibility was better than ± 2%.

Results and Discussion

N-isopropyl-N-methylacetamide

The self-diffusion of this compound was studied at ambient pressure only. The data are compiled in Figure 1. The structure of the two conformers is shown in this figure. In the temperature range studied (242 - 298 K) the conformer equlibrium is constant within experimental accuracy. K = [trans]/[cis] = 0.83±0.04 [3]. The trans-form has at all temperatures a self-diffusion coefficient that is by 2.5% lower than the value found for the cis-conformer. This difference is within experimental error, but as inspection of Fig. 1 shows it is seen in all 4 data sets. For N-methylformamide a difference of 17% was obtained, the cis-conformer showing the lower translational mobility [5]. This was explained by the formation of a compact local structure through strong electrostatic O···H-N interactions between the cis and trans conformers that was evident from MD simulations. Obviously the three voluminous alkyl groups do not permit a sufficiently close contact between the dipole moments of the IPMAA molecules, and minor differences in the geometrical arrangements of the alkyl groups become responsible for the small effect observed.

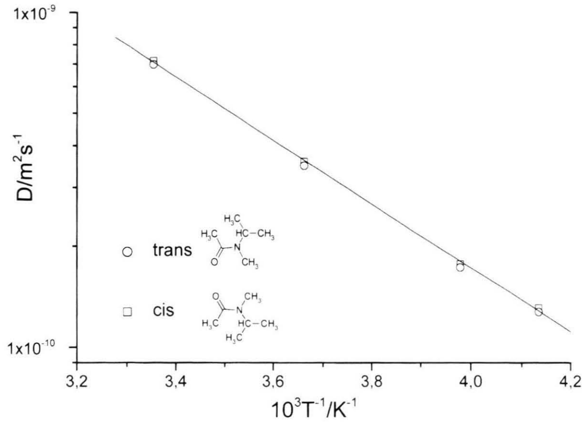
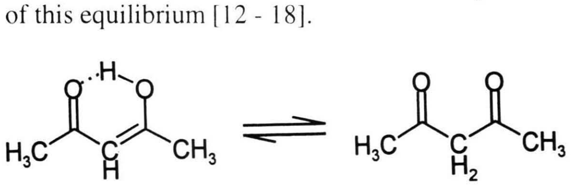


Fig. 1. T-dependence of the self-diffusion coefficients of the cis and trans conformers in neat liquid IPMAA.

Acetylacetone

ACAC is one of the often cited textbook examples for intramolecular exchanges in the the keto-enol tautomerism. Several authors studied the T-dependence of this equilibrium [12 - 18].



The studies of v. Jouanne et al. [12] and Wallen et al. [13] included also the pressure dependence. The older publication, reaching $p_{\max}$ = 40 MPa [12], arrived at

Table 1. T, p-dependence (K, MPa) of the mole fractions and self-diffusion coefficients observed for the keto / enol tautomers in neat liquid ACAC.

T	$x_{(\mathrm{keto})}$	K = [keto]/[enol]	— D (10^{-9} $m^2 \cdot s^{-1}$) —					
			$p = 0.1$	$p = 10$	$p = 50$	$p = 100$	$p = 150$	$p = 200$
423	0.496	0.98	– / –	5.20 / 5.72	4.22 / 4.62	3.36 / 3.69	2.76 / 3.01	2.38 / 2.59
373	0.388	0.63	3.65 / 4.09	3.41 / 3.85	2.71 / 3.02	2.19 / 2.45	1.81 / 2.00	1.51 / 1.70
334	0.284	0.40	2.43 / 2.80	2.31 / 2.64	1.85 / 2.11	1.47 / 1.68	1.19 / 1.34	0.98 / 1.10
297	0.179	0.22	1.57 / 1.79	1.51 / 1.68	1.12 / 1.29	0.88 / 1.00	0.69 / 0.80	0.55 / 0.63
274	0.143	0.17	1.03 / 1.21	0.96 / 1.13	0.76 / 0.90	0.58 / 0.68	0.45 / 0.52	0.35 / 0.42
257	0.134	0.15	0.74 / 0.89	0.67 / 0.81	0.52 / 0.63	0.39 / 0.48	– / –	– / –
243	0.112	0.13	0.55 / 0.66	– / –	0.39 / 0.46	– / –	– / –	– / –

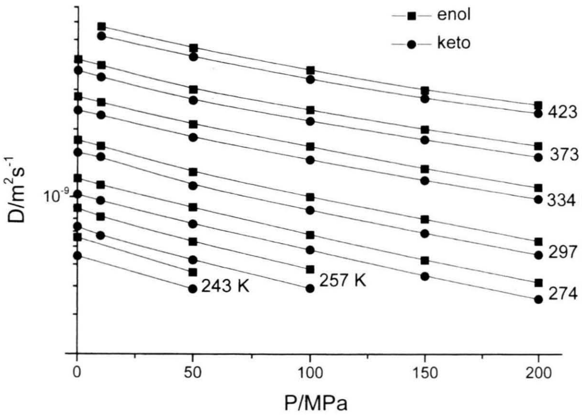


Fig. 2. Isotherms of the self-diffusion coefficients D_{enol} and D_{keto} of the two tautomers of neat liquid ACAC.

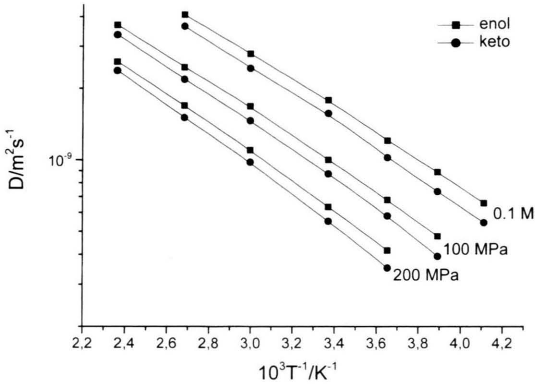


Fig. 3. Arrhenius plots of the isobars of D_{enol} and D_{keto} in neat liquid ACAC.

a significant shift of the equilibrium with pressure towards the enol-form, while Wallen et al. [13] (p_{max}: = 259 MPa] did not find any significant change in this equilibrium with pressure.

Our data are compiled in Table 1 and Figs. 2 and 3. In our experiments we did not observe any significant change of the keto-enol equilibrium with pressure. Thus the data collected in Table 1 give the average value of the mole fraction x for each temperature. These x-values were reproducible to ± 0.005.

The published thermodynamic data on the keto-enol equilibrium show a certain scatter. Our data agree for temperatures around 300 K with the older results [14 - 18] but show a significant deviation from the data published by Wallen et al. [13]. Also the change of the equilibrium constant K with temperature is in good agreement with the older results.

Since our equilibrium constants are independent of pressure and corroborate older data, we abstain from a detailed thermodynamic analysis. The reaction volume ΔV, defined by

$$\frac{\partial \ln K}{\partial p} = \frac{-\Delta V}{RT}, \tag{2}$$

is zero within experimental accuracy. This is a rather surprising result in view of the older data [13], and also considering the calculated molecular volumes [18] which yielded a difference between the keto and enol form of $\Delta V = +3\ \mathrm{cm^3 \cdot mol^{-1}}$. This discrepancy should be taken as a warning against the description of chemical equilibria in the condensed liquid phase by geometrical parameters derived for isolated molecules. One has rather to consider a combination of the local packing efficiency of the next neighbours and electrostatic as well as dispersion interactions in the mixed ensembles present in the fluid. Inspection of Figs. 2 and 3 shows that the keto-tautomer has lower self-diffusion coefficients at all temperature. The ratio $(D_{\mathrm{keto}}/ D_{\mathrm{enol}})_T$ is for any given temperature independent of pressure (all isotherms in Fig. 2 run parallel) and increases from 0.83 for $T \leq 257$ K to 0.91 for T = 423 K.

The rather weak temperature dependence of this ratio is in contrast to the effects observed for N-methylformamide (NMF) [5], in this liquid the difference of 17% for $T \leq 280$ K is reduced to less than 3% at $T \geq 320$ K. For NMF, the effects observed are ascribed to the stronger electrostatic interaction possible between the cis and trans conformers. Obviously this type of interaction becomes rapidly less effective when the thermal energy of the liquid is raised.

For the tautomers of ACAC, the found significant contribution to the differences of D results obviously from the overall shape of the molecule, the enol form being more compact than the extended keto tautomer, and thus more mobile. These sterical differences seem to be less sensitive to changes of T and density. The contribution of electrostatic interactions, considered important for the difference in the K values between the gas phase and the neat liquid [18], seems either to be of less importance or, when compared to NMF, to be less dependent on the specific preferred geometry between the neighbouring molecules.

Concluding Remarks

With the data presented here and in the previous paper [5] it was shown for the first time that in neat liquids simple conformeric and tautomeric equilibria can lead to significant differences in the translational molecular mobility for the conformers. In the case of the previously studied NMF, preferred local structures caused by strong electrostatic interactions seem to be the cause of the differences observed. The very similar amide IPMAA shows a very small difference between the self-diffusion coefficients of the cis and trans conformers. This is most probably to be explained by the bulky and unpolar alkyl groups covering most of the surface of the amide group proper and thus excluding close contacts between the dipole moments and / or local charges.

The keto and enol tautomers of ACAC show a fairly large difference in their self-diffusion coefficients. This difference shows a rather weak temperature dependence only. For this pair of tautomers obviously geometrical effects have the dominating influence on the translational molecular mobility.

It remains to be seen whether more systems suitable for NMR studies of the type proposed here can be found, permitting a more in depth analysis of these novel dynamical effects.

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