

**EFFECT OF ULTRASOUND ON ESTER
HYDROLYSIS IN AQUEOUS ETHANOL**

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LIST OF ORIGINAL PUBLICATIONS

The thesis consists of three articles listed below and a review. The articles are referred in the text by Roman numerals I–III. The review summarizes and supplements the articles.

- I. Tuulmets, A., Salmar, S. Effect of ultrasound on ester hydrolysis in aqueous ethanol. *Ultrason. Sonochem.*, **2001**, 8, 209–212, doi:10.1016/S1350-4177(01)00078-5
- II. Tuulmets, A., Salmar, S., Hagu, H., Effect of ultrasound on ester hydrolysis in binary solvents. *J. Phys. Chem., B* **2003**, 107, 12891–12896, DOI: 10.1021/jp035714l.
- III. Salmar, S., Cravotto, G., Tuulmets, A., Hagu, H. Effect of ultrasound on the base-catalyzed hydrolysis of 4-nitrophenyl acetate in aqueous ethanol. *J. Phys. Chem., B* **2006**, 110, 5817–5821, DOI: 10.1021/jp057405w

Author's contribution

Paper I: Responsible for all performing experimental work and calculations. Helped to prepare the manuscript.

Paper II: Responsible for around half of performed experiments and calculations. Helped to prepare the manuscript.

Paper III: Main person responsible for planning and writing. Performed almost all experimental work and calculations.

ABBREVIATION

BuOAc	butyl acetate
<i>t</i> -BuCl	<i>tert</i> -butyl chloride
<i>s</i> -BuOH	<i>sec</i> -butanol
DMSO	dimethyl sulfoxide
EtOAc	ethyl acetate
GLC	gas-liquid chromatography
HPLC	high-pressure liquid chromatography
NMR	nuclear magnetic resonance
4-NP	4-nitrophenol
4-NPA	4-nitrophenyl acetate
PrOAc	propyl acetate
SCW	supercritical water
$\Delta V^\ddagger$	volume of activation
X_{EtOH}	molar ratio of ethanol

1. INTRODUCTION

Ultrasound can affect a wide range of chemical and physical processes, [1–7] and this has been used by chemists and chemical engineers for a variety of purposes in areas as diverse as electrochemistry, food technology, synthetic chemistry, materials design, nanotechnology and sewage treatment. Most often, ultrasound has been employed to accelerate reactions and this effect has been found to be especially useful in synthetic chemistry.

The origin of the sonication effect on heterogeneous processes seems to be well understood. Here the reaction is influenced primarily through the mechanical effects of cavitation. Sonication is able to initiate or accelerate many homogeneous and also heterogeneous systems, which proceed *via* radical intermediates through the generation of free radicals.

However, the relevant mechanisms have not been sufficiently clarified for reactions in homogeneous media, particularly for ionic reactions, which cannot be switched to a radical pathway. Many examples of homogeneous heterolytic reactions accelerated by ultrasound have been described. This provides a challenging puzzle for sonochemistry.

Therefore, the main goal of present study was to obtain more experimental data for sonication effect on homogeneous polar reactions and in this way to gain a better insight into the matter. We have undertaken ultrasonic kinetic investigations of two mechanistically complementary model reactions *viz.* the acid-catalyzed hydrolysis of aliphatic esters and the base-catalyzed hydrolysis of 4-nitrophenyl acetate in ethanol-water binary mixtures.

In this Thesis we have questioned the feasibility of application of the cavitation theory in the case of ultrasound effect on these non-radical reactions, and have pointed to the possible explanation of the data by effects taking place in the bulk solution. We suggest that pressure waves, associated with the propagation of the ultrasound, as well as the shock waves generated during the bubble collapse, can affect reactions in the bulk medium by changing the translational energy of species and the solvent structure, shifting the solvation equilibria and affecting the hydrophobic interactions. Most likely, different combination of all these mechanisms may occur. In other words, the effect of ultrasound on a polar reaction could be related to destruction of the molecular structure of the solvent-solute system and to perturbation of hydrophobic solute-solvent interactions.

If this is the case, ultrasound may become a useful tool for physicochemical control of the chemical reaction. Moreover, as ultrasound can affect weak interactions in solution, the impact of ultrasound on living organisms may be more complex than simple mechanical influence caused by cavitation phenomena.

2. ULTRASOUND EFFECT ON POLAR HOMOGENEOUS REACTIONS

Since Thorneycroft and Barnaby characterized the cavitation phenomenon towards the end of the 19th century [4], and since Richards and Loomis published the first report describing the influence of ultrasound on reaction rate in 1927 [8], ultrasound has been widely employed in chemistry and chemical technology, and the physical background of its influence has been widely discussed. A large number of exhaustive monographs [1–5] and reviews [6, 7] have been published, especially during the last 20 years, few of which are referred to in this Thesis. Therefore it was not necessary to recapitulate the general principles of the topic in the present work. However, a short explanation of the current conceptions of sonochemistry was found to be relevant for understanding the content of this Thesis.

It is certain that sonochemical effects cannot be caused by direct influence of the sound field on the reacting species on the molecular level, since the energy of ultrasound is too low to alter electronic, vibrational, or rotational states of reacting molecules [1–7]. Therefore the effect of ultrasound has been explained by the “hot spot” theory, assuming involvement of *cavitation bubbles*. Like any kind of sound, ultrasound is transmitted via waves that alternately compress and stretch the structure of the medium through which it passes. During a rarefaction cycle, when a large negative pressure is applied to a liquid, intermolecular forces are not strong enough to maintain cohesion and small gas-filled cavities, so-called *cavitation bubbles* are formed. The rapid nucleation, growth and collapse of these bubbles constitute the phenomenon of *cavitation*. The “hot spot” theory suggests that each cavitation bubble acts as a localized micro-reactor which, if formed in aqueous system, generates high temperature and pressure, reaching within the “hot spot” to several thousand degrees and hundred atmospheres.

On the basis of this concept, the nature of the sonication effect on heterogeneous processes seems to be well explained, as the cavitation phenomenon brings about mechanical effects responsible for mass transfer, the activation of the surface of solid reagents or catalysts, the dispergation of particles, and so forth. Many homogeneous and heterogeneous reactions can be initiated or accelerated by ultrasound through the generation of free radicals that give rise to chain reactions in solution. Moreover, in some cases ultrasound has been found to change the reaction mechanism from polar to radical [1–7].

Following these explanations, it can be concluded that an ionic reaction, which is not switchable to a radical pathway, should not be susceptible to ultrasound effects. However, several examples of homogeneous polar reactions, accelerated by ultrasound, have been found. These are mostly hydrolysis and

solvolysis reactions, which have been kinetically investigated for sonication effects, be reviewed below.

In the first paper [9] of this kind, published already in 1953, the acid-catalyzed hydrolysis of ethyl acetate (EtOAc) in aqueous solution was studied at three frequencies, 400, 700 and 1500 kHz, and at various energy levels. The sonication effect was as small as few percents, but in several cases it exceeded the experimental error.

Later, the acid-catalyzed hydrolysis of methyl acetate (MeOAc) has been investigated by three groups [10–12]. In all these works similar experimental conditions were used: 1M HCl and 0.6–1 M methyl acetate in 100–500 mL volume of the reaction mixture. Kinetics was followed by titrimetric determination of the formed acetic acid. The reaction was performed in water without sonication and under sonication at 23 kHz [10], at 27,5 kHz [11] and at 540 kHz [12], and in a water-acetone binary solvent at 540 kHz [12]. The sonication effect was from low to moderate, and rate enhancement was up to 60%.

Under conditions affording more pronounced sonication effects, a many-fold acceleration of the acid-catalyzed hydrolysis of EtOAc in water was attained at 22 kHz [13]. Kinetics of the hydrolysis reaction in 1M HCl solution was followed by gas-liquid chromatography (GLC), determining the ester concentration.

Still lower acceleration effect (14–15%) by ultrasound has previously been reported for the alkaline hydrolysis of 4-nitrophenyl esters of several aliphatic carboxylic acids in a water-acetonitrile mixtures (60:40, V/V) [14]. Reactions were conducted in THAM buffer (pH 8.0) in an ethylene glycol jacketed vessel with a 20 kHz transducer. Kinetics was followed spectrophotometrically at 35°C by periodical monitoring the formation of 4-nitrophenol (4-NP) at 400 nm.

The hydrolysis of phthalic acid esters in an aqueous solution by sonochemical action was performed at an ultrasonic frequency of 200 kHz [15]. Moderate ultrasonic accelerations were found over the pH range between 4 and 13.

In contrast to these findings, an ultrasonic acceleration by 2 orders of magnitude was found by Hua et al. [16] for the hydrolysis of 4-nitrophenyl acetate (4-NPA) in aqueous solution over the pH range of 3–8 at 25°C and at 20 kHz. In the presence of ultrasound, the observed rate constant for the hydrolysis of 4-NPA was found to be independent of pH and ionic strength.

Large sonication effects up to 20 times were observed for the solvolysis reaction of 2-chloro-2-methyl-propane in ethanol-water [17–20], *iso*-propanol-water [18] and *tert*-butanol-water [18] mixtures by Mason's group. Three different ultrasonic generators operating at 20 kHz [19, 20], 45 kHz [18] and 80 kHz [17] were used. Kinetics of solvolysis of *tert*-butyl chloride (*t*-BuCl) was followed conductometrically. Surprisingly, the effect of ultrasound showed nonlinear dependences on the composition of aqueous binary mixtures. For

example: at 10°C the solvolysis rate in 20 wt% of ethanol in the presence of ultrasound was twice that in the absence of ultrasound, whereas in 40%wt and 60% of ethanol the rate increases were six- and 20-fold, respectively.

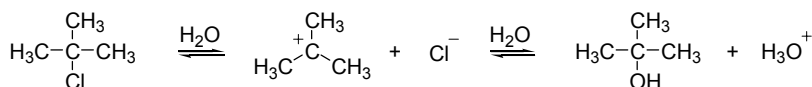
The solvolysis of 1-bromo-1-phenylethane in ethanol-water mixtures have been studied by another group [21] and also an ultrasonic acceleration of the reaction was observed. An immersion horn system operating at 20 kHz was used in this study.

For polar reactions, the solvation of reactants is one of the most important factors governing the rates of the reactions [22]. In binary solvents, the situation is complicated by the selective solvation of species. This means that the composition of the solvation shell around reacting species is different from the bulk solvent composition. In solvents capable of hydrogen bonding, the structure of the medium is also of great importance [23]. Explanations of the sonochemical effects based on the idea of perturbation of the molecular organization of the solvation shell of the reaction system have been suggested [20, 24]. Thus, the results of kinetic measurements in binary solvents should be informative in this context.

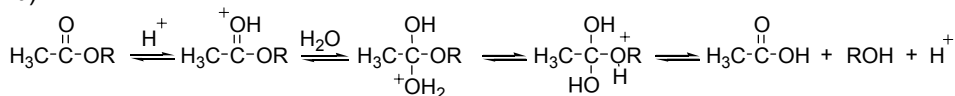
As mentioned above, Mason et al. [17–20] studied the effect of ultrasound on the kinetics of *t*-BuCl solvolysis in alcohol-water mixtures (Scheme 1, a). The acceleration effect observed in this reaction was not linear with the increase in the ethanol or *tert*-butanol content of the reaction mixture. However, in this case the possibility of the sonication-induced radical processes cannot be excluded that hampers explicit analysis of the results.

To avoid the problems of shift of the reaction pathway, the acid-catalyzed hydrolysis of alkyl esters in water-ethanol binary mixtures were studied in this work (Scheme 1, b), with the aim to elucidate more details of the sonication effect on polar reactions. Furthermore, experiments carried out in 1 M HCl solutions prevent possible pH changes due to water sonolysis or nitrogen oxidation products [25, 26].

a)

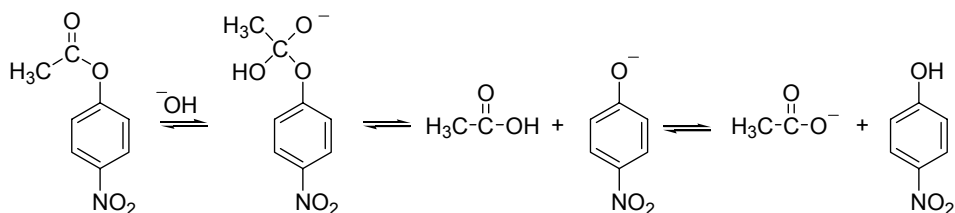


b)



Scheme 1. a) Solvolysis of 2-chloro-2-methyl-propane and b) acid-catalyzed hydrolysis of alkyl ester

Further, we extended our kinetic investigation to a mechanistically complementary reaction, viz. the base-catalyzed hydrolysis of esters. As indicated above, two laboratories have reported different ultrasound effects on base-catalyzed hydrolysis of 4-NPA (Scheme 2) in aqueous media [14, 16]. In the present work we also used 4-NPA as a model ester and ethanol-water binary mixtures as the reaction medium. Unlike aliphatic esters, 4-NPA is ideally suitable for spectrophotometric kinetic measurements, affording reagent concentrations several orders of magnitude lower than those required for GLC determinations. The complications that may arise from the well-studied sonolytic degradation of 4-NP [16, 27–30] or the radical-induced decomposition of 4-NPA [30] will be discussed below.



Scheme 2. Base-catalyzed hydrolysis of 4-nitrophenyl acetate.

The effect of ultrasound on this model reaction was investigated over the 0–50 wt % range of ethanol concentration and over the pH range from 7.5 to 9.

A specific feature of the present work consisted in the comparative use of two different immersion horns for sonication. A quartz probe avoided the well-known problems arising from the erosion of titanium horns and made unnecessary to filter the samples. The titanium probe was still used to reproduce the experiments published by Hua et al. [16]. A comparison of results obtained with the quartz and titanium horns enabled us to rationalize the sonication effects reported by the authors [16].

3. METHODS OF KINETIC MEASUREMENTS

3.1. Acid-catalyzed hydrolysis of aliphatic esters

The kinetics of the acid-catalyzed hydrolysis of esters was followed by GLC determinations of the ester concentration in 1 M HCl solutions. The apparatus for ultrasonic measurements consisted of a stainless steel reaction vessel provided with a cooling jacket and equipped with an electronic thermometer and a titanium sonication horn (with 14.5-mm tip diameter) reproducibly immersed into the reaction solution. Ultrasound was generated by a UZDN-2T probe (400 W) disrupter operating at 22 kHz. Its energy output was 55 W in water, estimated calorimetrically in the same reaction vessel.

For kinetic measurements, 80 mL of the solution was transferred into the reaction vessel, 1 mL of *sec*-butyl alcohol was added as the internal standard for GLC analyses, and the ultrasound was switched on. The reaction temperature was maintained at $18.3 \pm 0.3^\circ\text{C}$ by regulating the water circulation in the cooling jacket of the apparatus. After the temperature was equilibrated in the whole system, 0.5 mL of an ester (initial concentration 0.05–0.06 M) was injected into the solution to start the reaction. Aliquots of 0.5 mL were withdrawn at appropriate time intervals and treated three times with 0.2 mL of hexane. The joint hexane extracts were analyzed by GLC. The ratios of peak areas for the ester and the internal standard were plotted against time, and first-order kinetic constants were calculated from the obtained kinetic curves by means of a differential method, the error in the rate constants being $\pm 0.3\%$ or less.

Measurements without sonication were performed similarly in a reaction cell thermostated at 18.3°C and equipped with a magnetic stirrer.

Ethanol-water binary mixtures were prepared by weighing of necessary amounts of commercially available ethanol (analytical grade) and bi-distilled water. Density data were taken from ref [31].

3.2. Base-catalyzed hydrolysis of 4-nitrophenyl acetate

Ethanol-water mixtures in the 0–50 wt% concentration range and pH values ranging from 7.5 to 9 were prepared with phosphate and Borax buffers by weighing calculated amounts of reagents according to standard procedures [32]. Density data were taken from ref [31]. The ionic strength of all solutions was made up to $\mu = 0.045$ M with NaCl. The pH of the reaction mixtures, measured before and after each run, did not vary by more than 0.01 units (Orion Model pH Meter 420A).

4-NPA was first dissolved in ethanol and then diluted to a 0.1 mM concentration with thermostated ethanol-water buffer immediately before starting the

reaction. When no ethanol was present in the buffer, 4-NPA was dissolved in water by stirring overnight at room temperature.

Sonication was performed with two different direct immersion probe systems. One sonicator was an UZDN-2T cell disrupter described in previous section. Another unique apparatus developed in Prof. Giangarlo Cravotto's lab in University of Turin was a probe operating at 21.1 kHz, equipped with a quartz sonication horn (tip diameter 15 mm). Its average power delivery to water, estimated calorimetrically, was 9.4 W. The sonication horns were always immersed 2.5 cm below the liquid surface.

The ultrasonic experiments were performed under argon atmosphere in a 100-mL glass cell sealed with an elastomeric septum. The cell, equipped with an electronic thermometer and a magnetic stirrer, was cooled in a water-ice bath so that the temperature in the reaction vessel was maintained at $20 \pm 0.5^\circ\text{C}$ during all measurements.

The kinetics of the base-catalyzed hydrolysis of 4-NPA was followed spectrophotometrically with a Varian Cary 50 Scan UV-visible spectrophotometer. Spectrophotometric calibrations were preliminarily carried out to determine in the 230–550 nm range the molar absorptivities of 4-NPA and 4-NP in buffered ethanol-water mixtures at pH 7.5, 8.0, and 9.0.

All hydrolysis reactions were performed without sonication and under ultrasound. Aliquots of 0.5–1 mL were withdrawn from the reaction mixtures at appropriate time intervals and the formation of the 4-nitrophenolate ion or the consumption of 4-NPA was monitored at 400 and 272 nm, respectively.

The hydrolysis of 4-NPA with a titanium probe was carried out in aqueous phosphate buffer ($\text{KH}_2\text{PO}_4/\text{K}_2\text{HPO}_4$, $\mu = 0.045\text{ M}$) at pH 7.5. Aliquots were withdrawn with a syringe equipped with $0.2\text{ }\mu\text{m}$ HPLC filter to remove Ti particles released from erosion of the sonication horn. Spectra were recorded immediately, while some samples were analyzed by HPLC (Waters 6000 HPLC pump and 440 UV detector at 254 nm) on a reversed-phase column to detect products of OH-radical-induced reactions. Water/methanol/acetic acid (60:40:1) was used as eluent.

The sonolytic degradation of 4-NP was monitored in identical fashion and under the same conditions as the hydrolysis of 4-NPA. 4-NP (100 mL, 0.1 mM) in aqueous phosphate buffer was sonicated and the absorbance of the 4-nitrophenolate ion was measured at 400 nm.

In a similar way the kinetic measurements of 4-NP degradation and the base-catalyzed 4-NPA hydrolysis were carried out with the probe equipped with a quartz horn in 0–50 wt % aqueous ethanol buffered with phosphate salts at pH 8.0 and with Borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}/\text{HCl}$) at pH 9.0. At appropriate time intervals, 0.5–1 mL aliquots were withdrawn with a syringe and their spectra were recorded immediately at 230–550 nm; preliminary filtration was found to be unnecessary. Rate constants for the reactions were likewise determined from the decrease of 4-NPA absorption at 272 nm and the increase of the 4-nitrophenolate absorption at 400 nm. In standard experiments these

absorbances were registered simultaneously and rate constants were calculated from both sets of data; averages of the resulting values are presented in the following tables and figures. All runs were carried out at least in triplicate. The standard deviations of mean values did not exceed 5% for experiments with the Ti horn and 0.8% for experiments with the quartz horn.

4. ULTRASONIC POWER MEASUREMENTS

(Carried out in collaboration with Hannes Hagu)

Nonlinear dependences involving extreme points were found for the effect of ultrasound on the rate of the reaction in ethanol-water mixtures. Because many physicochemical properties of binary systems depend on the composition nonlinearly, it should be clearly determined how much of the ultrasonic energy is absorbed by the system at any component ratio to ensure a confident interpretation of the results.

Several methods are available to estimate the amount of ultrasonic power entering a sonochemical reaction [2, 33]. Many authors have suggested determining the thermal effect of ultrasound as a means of obtaining the effective power. This is based on the assumption that almost all the cavitation energy produces heat, and thus the output power can be obtained *via* calorimetry. The other method involves a chemical dosimeter, which monitors the sonochemical generation of a chemical species. The yields of the reaction after an adequate sonication time are regarded as a measure of the power of the ultrasound.

Although chemical dosimetry is generally believed to be the most straightforward method of determining the ultrasonic power in a sonochemical reaction, it cannot be applied to binary solvent systems, because the reaction rate as well as the ultrasonic acceleration probably depends on the solvent composition. However, many authors [34–37] have shown that the results from a chemical dosimeter were directly and linearly related to the calorimetrically determined ultrasonic power. In addition, it is important to notice that a chemical dosimeter may not describe the true acoustic power but describes the sonochemical efficiency for the reaction induced under certain experimental conditions [37].

In this work, the acoustic power entering the systems was determined by calorimetry. Three direct irradiation systems (probe systems) were used. Two different sonicators from Bandelin Electronic (Sonoplus HD 2070, 20 kHz, 70 W and Sonoplus HD 2200, 20 kHz, 200 W) were connected with a standard 500-ml calorimetric system equipped with a mechanical stirrer, a heating system, and a thermocouple. Both sonicators were set to equal output power. The irradiation horns with 12.7-mm tip diameter were immersed reproducibly (1.5 cm below the solution surface) into the sample.

Because of technical reasons, the UZDN-2T probe could not be used in a standard calorimetric system; therefore, for the sake of certainty, calorimetric measurements were also carried out in the stainless steel cell used for the kinetic studies described above, equipped for this work with a magnetic stirrer, a heating system and a thermocouple. For calorimetric measurements, the thermostating jacket was empty to minimise heat losses. Similarly with kinetic measurements, 80 ml samples were used. The temperature was monitored with an EVIKON E6011 temperature registration device.

The water equivalent of the calorimeter and the heat capacities C_p for solutions were determined using all of the equipment in parallel. Before heating or sonication, the solution inside the reactor was thermostated at an appropriate temperature close to ambient temperature (usually about 20°C). Temperature monitoring was started 90 seconds before and stopped 90 s after the heating or sonication period, which lasted 120 s. For the determination of ΔT (1.7–2.4 K) the temperature drifts were extrapolated to the midpoint of the energizing period.

The ultrasonic power that entered into the system was calculated by the following equation:

$$\text{power(W)} = \left(\frac{\Delta T}{\Delta t} \right) C_p \cdot M,$$

where C_p is the heat capacity of the solution ($\text{J}\cdot\text{g}^{-1}$) and M the mass of the sample (g). ($\Delta T/\Delta t$) is the temperature rise per second.

Ultrasonic power determinations were carried out in the 0–60 wt % region of ethanol-water binary mixtures. Calorimetrically measured specific heat capacities were in agreement with literature data [31] within $\pm 2.2\%$. The results of measurements with different equipment agreed within 0.5 to 1.5%.

Our ultrasonic power determinations were performed in the 0–60 wt.% region of ethanol-water binary mixtures. The relative power of ultrasound in the systems is presented in Table 1, with the calorimetric power in pure water taken for a unit. It appears that the calorimetric sonication effect depends insignificantly on the solvent composition. The relative data in Table 1 can be considered to be correction coefficients by which the ultrasonic acceleration ratios in this work or published in papers [19, 20] should be divided to normalize the data. However, the values in Table 1 are definitely bracketed with the experimental uncertainty limits of these studies and need not be applied.

Table 1. Relative power of ultrasound in ethanol-water binary mixtures.

X , wt. %	$X = \text{EtOH}$	Z_{rel}^a
0 ^b	1 ^c	1 ^d
10	1.013	1.038
20	1.016	1.066
30	1.014	1.046
40	1.007	0.989
50	1.003	0.923
60	0.990	0.860

^a relative acoustic impedance of EtOH-H₂O system at 20°C, from Ref. 38. ^b pure water

^c 39.5 W in the 500 cm³ calorimeter, and 55 W in the cell for kinetic measurements. ^d $1.48 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$

The power output of a sonicating horn will depend on the acoustic load, which can be expressed by the acoustic impedance

$$Z = \rho \cdot C,$$

where ρ is the density of the medium and C is the speed of sound in the fluid. It appears (Table 1) that the delivered power correlates well with the acoustic impedance of the noncavitating system.

If the assumption that almost all the cavitation energy produces heat that is measurable via calorimetry is valid, it follows that at least for the solvent systems under consideration the solvent properties have an insignificant effect on the number of cavitation events as well as the cavitation intensity. This result is somewhat unexpected in the context of the complexity and microheterogeneity of alcohol-water binary systems (Chapter 4); however, the total number of bubbles and the energy dissipated per bubble can change as the composition of the solution changes. Hence, the total amount of cavitation energy may remain constant if changes in these two variables counteract each other. However, our results indicate that dependences of the ultrasonic rate enhancement on solvent composition do describe changes in the sonochemical efficiency.

5. ULTRASOUND EFFECT ON ACID-CATALYZED HYDROLYSIS OF ALIPHATIC ESTERS

The kinetics of the hydrolysis reaction was followed by gas-liquid chromatography. An advantage of the GLC method is the direct analysis of reaction products. No sonolytic degradation products except those from the hydrolysis of esters were detected. Although the rate constants were calculated as a rule from the disappearance of the ester, in some test experiments peaks of the alcohol that was formed in the process were used for calculations. The results agreed within experimental error.

Nonsonic and ultrasonic rate constants for ester hydrolyses in water and ethanol-water binary mixtures are presented in Table 2. Although the nonsonic reaction rates gradually decrease with the increase in ethanol content, the ultrasonic reactions show complicated dependences on the solvent composition as is seen in Figure 1 and Figure 2 for hydrolysis of EtOAc.

Table 2. Results of kinetic measurements in ethanol-water binary mixtures.

Ester	% w/w (X) ^a ethanol in water	Rate constant $k \times 10^5 \text{ s}^{-1}$		Ultrasonic acceleration
		Nonsonic	Sonic	
EtOAc	0 (0)	9.56	12.40	1.30
	9.1 (0.038)	6.91	8.01	1.16
	18.2 (0.08)	5.62	5.80	1.03
	27.8 (0.131)	5.00	6.78	1.36
	40.0 (0.207)	3.23	7.48	2.32
	50.0 (0.281)	2.37	5.76	2.43
PrOAc	10 (0.042)	1.53	5.36	3.50
	20 (0.089)	1.22	3.19	2.61
	30 (0.144)	1.16	2.24	1.93
	40 (0.207)	0.805	1.44	1.79
	50 (0.281)	0.59	1.05	1.78
BuOAc	10 (0.042)	9.06	24.2	2.67
	20 (0.089)	7.77	17.4	2.24
	30 (0.144)	5.50	9.50	1.73
	40 (0.207)	4.76	7.41	1.56
	50 (0.281)	3.99	5.52	1.38

^a molar fraction of ethanol

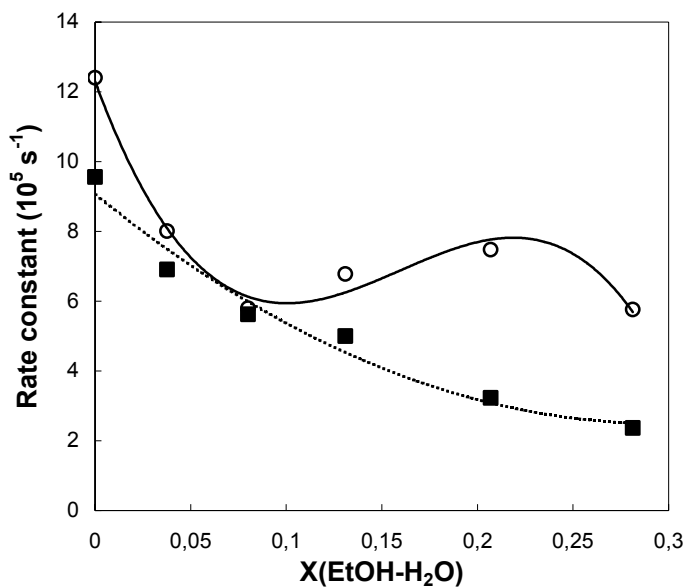


Figure 1. Rate constants for the hydrolysis of EtOAc: (■) nonsonic, (○) sonic.

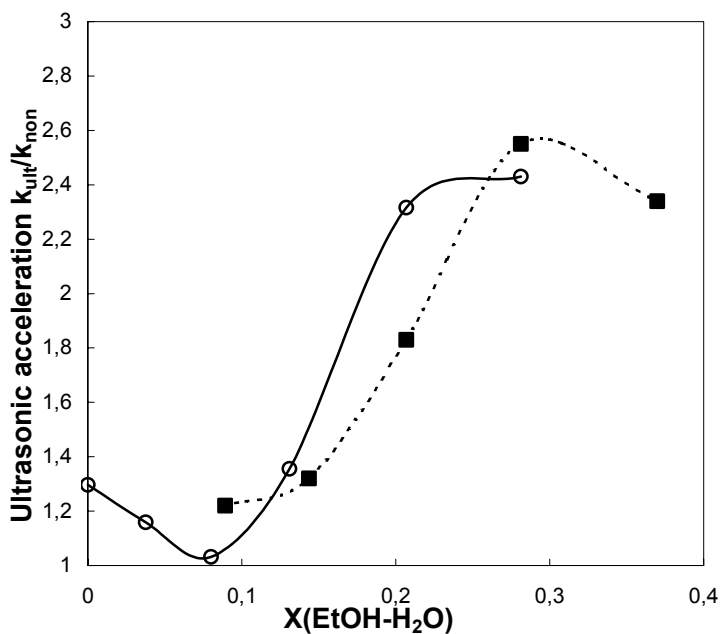


Figure 2. Rate enhancements induced by ultrasonic irradiation in ethanol-water binary mixtures: (○) acid-catalyzed hydrolysis of EtOAc at 18.3°C (22 kHz) and (■) solvolysis of *t*-BuCl at 20°C (20 kHz; from Ref. [20])

Both our data for the hydrolysis of EtOAc and the data from Mason's group [19, 20] for the solvolysis of *t*-BuCl at 20°C show a distinct maximum in the region of about 50 wt % ethanol (Figure 2). Mason et al. [19, 20] have pointed out a coincidence of the maximum in their data with the maxima found in the viscosity, enthalpy of mixing, and sound absorption versus solvent composition curves. [23] These properties of the binary liquid mixture show the existence of a structurally critical region at 0.2–0.3 mol fraction (40–50 wt %) of ethanol. This is also reflected in the volumes of activation $\Delta V^\ddagger$. All of the available data for a variety of solvolysis reactions in ethanol-water mixtures show a decrease in $\Delta V^\ddagger$ when passing from water to ethanol-water mixtures and a minimum in the region between 0.2 and 0.3 mol fraction of the alcohol [39].

Recent spectroscopic, X-ray diffraction, and mass spectrometric investigations have shed light on the structure of ethanol-water solutions [40–42]. It has been concluded that small additions of ethanol in the range of $0 < X_{\text{EtOH}} < 0.08$ (X_{EtOH} is the ethanol molar ratio) exert a strong structure-making effect accompanied by an increase in the self-association of water molecules. Indeed, the partial molar volume of ethanol is a minimum at $X_{\text{EtOH}} = 0.08$ [43], and the excess solvatochromic parameters distinctly show an enhancement in the structure of water in this region [44].

Further additions of the alcohol begin to prevent water from organizing into 3D structures. The structural behavior of these solutions is strongly modified at $X_{\text{EtOH}} > 0.2$. In this region, a large number of ethanol-water bonds are formed, and water-water bonds are broken. All of these results have led to a cluster model of a stacked ethanol core and a thin water shell [40, 41]. The observations for diluted aqueous solutions of ethanol suggested the evolution of an ethanol polymer structure and a complete breakdown of the bulk water structure at $X_{\text{EtOH}} > 0.1$.

On the basis of these findings, the application of ultrasound to the reaction would, by disrupting the binary solvent structure, permit more favorable solvation and result in enhanced rates of reaction. The negligible effect of ultrasound at 18 wt % ($X_{\text{EtOH}} = 0.08$) ethanol can be assigned to the rigidity of the solvent structure.

However, solute-solvent interactions in these complicated systems can be particularly important (e.g., the replacement of EtOAc by more hydrophobic esters changed beyond recognition the dependence of the sonication effect on the solvent composition).

Taking stock of cluster formation in ethanol-water mixtures, we wished to study the effect on the hydrolysis rate of the inclusion of a substrate in the hydrophobic interior of clusters, and to this end, we experimented with propyl and butyl acetates. Indeed, sonication effects in the region $0.2 < X_{\text{EtOH}} < 0.3$ agreed well with the order of hydrophobicity of these esters (Table 2, Figure 3). BuOAc should be the most powerfully held by clusters, and sonication was actually the least efficient in this case (Figure 4).

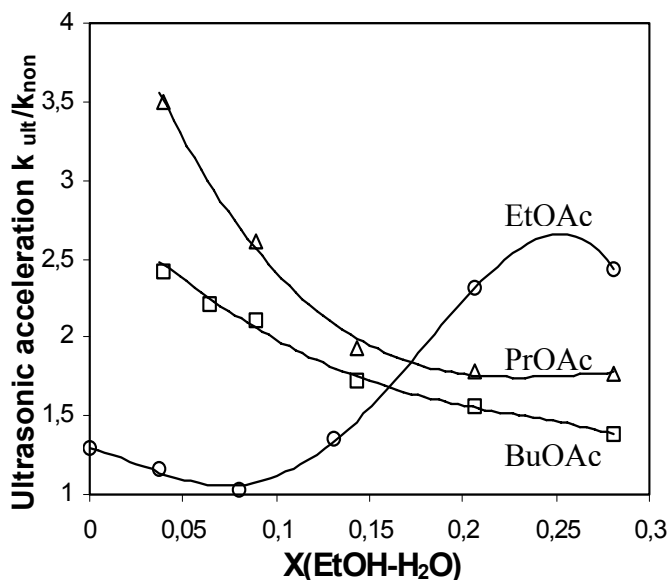


Figure 3. Rate enhancements of ester hydrolyses induced by ultrasonic irradiation in ethanol-water binary mixtures.

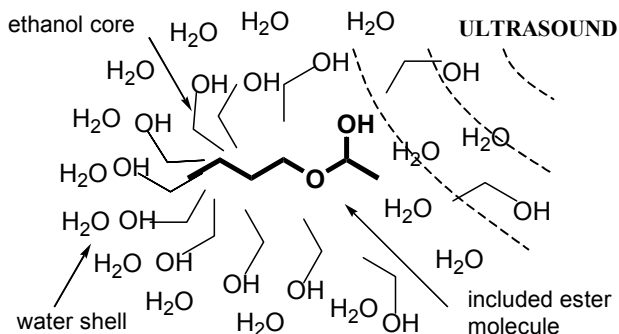


Figure 4. Schematic representation of the impact of ultrasound on ethanol-water clusters.

Engberts et al. [45–47] have developed a versatile quantitative approach to reactions in binary solvent systems, including ester hydrolyses based on an idea about the equilibrium formation of encounter complexes between reactants and hydrophobic cosolvents. The more hydrophobic the reagents and the cosolvents (e.g. alcohols), the more extensively the reagents are included in the encounter complexes and thus rendered unreactive. From the rate constants for the neutral hydrolysis of *p*-methoxyphenyl-2,2-dichloroalkanoates in dilute aqueous

solutions of short-chain alcohols, the molar energies of hydrophobic interactions between the components of the solutions have been estimated to be as small as 1 kJ or less [47]. Nevertheless, 2-fold and greater rate decreases in solutions that are about 2 mol % in alcohol and 10^{-5} M in ester were plausibly assigned to hydrophobic interactions.

The complicated features of the sonication effects in the regions up to 15 mol % ethanol cannot be interpreted as straightforwardly. Obviously, the perturbing effects of ultrasound on the solvent structure, on solute-solvent interactions, and also on possible solute-solute interactions at low cosolvent content may be involved (Chapter 6.3).

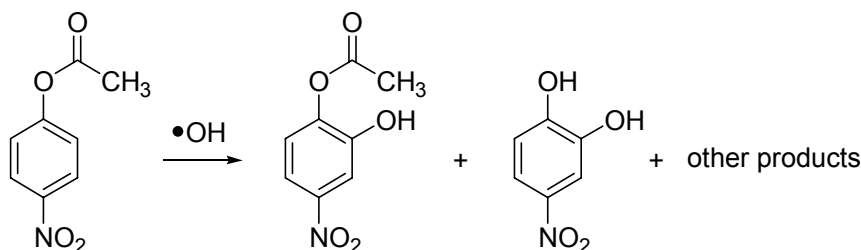
In contrast to the sonication effects and despite considerable changes in the solvent structure, rate constants for the hydrolyses without ultrasonic irradiation decrease slightly and monotonically with increasing organic cosolvent content (Table 2). The same was observed for the solvolysis of *t*-BuCl in ethanol-water mixtures [19, 20, 48]. Winstein and Fainberg [48] have shown that the activation free energy of *t*-BuCl solvolysis increases smoothly with increasing ethanol content and that the enthalpy and entropy of activation manifest clearly extremes in the region of 15 mol % ethanol. This is also the region of the maximum solvation energy of the initial reagent, *t*-BuCl [49]. A similar compensation effect has been observed for the hydrolysis of EtOAc in water-DMSO and water-acetone systems [50].

Thus, ultrasonication is able to reveal subtle interactions and particular effects of an entropic or enthalpic origin, which remain hidden in conventional kinetics.

6. ULTRASOUND EFFECT ON BASE-CATALYZED HYDROLYSIS OF 4-NITROPHENYL ACETATE

6.1. Sonolytic degradation of the ester

Ester hydrolysis under ultrasound in aqueous media can be accompanied by side reactions, mainly because of the activity of hydroxyl radicals generated from the decomposition of water. In such systems, cavitation bubbles are filled with water vapor, dissolved gas, and other volatile materials. As bubble collapse creates extreme physical conditions (several thousand degrees and several hundred atmospheres), water vapor undergoes thermal decomposition to yield an OH radical and an H atom [1–7]. 4-NPA is liable to undergo OH-radical-induced reactions like the one shown in Scheme 3 [30].



Scheme 3.

The production of radicals depends primarily on the frequency of the ultrasound [51–54]. Tauber et al. [30] studied at 321 kHz the sonolysis of 4-NPA in an argon-saturated aqueous solution (pH 6.5, 25°C, the reaction vessel being immersed in a water-filled sonicator, 85 W). Under these conditions, OH-radical-induced products (e.g. 2-hydroxy-4-nitrophenyl acetate, Scheme 1) and pyrolytic products were found exclusively; hydrolysis, however, was extremely slow at this pH.

Yim et al. [15] studied the degradation of phthalic acid esters in aqueous solution under ultrasound at 200 kHz. Compared to hydrolysis, attack by OH radicals was found to predominate in the degradation of diethyl phthalate in the pH range 4–11. However, the contribution of hydrolysis increased appreciably with increasing pH.

Ando et al. [55] studied the decarboxylation of 6-nitrobenzisoxazole-3-carboxylic acid under ultrasound with a horn-type sonicator (20 kHz) in phosphate-buffered solutions, pH 7.0, under argon. The rate was unaffected by sonication, and no products of free-radical reactions were detected. However, this substrate might be less prone to enter a radical pathway.

Hua et al. [16] reported that ultrasound increased by 2 orders of magnitude the rate constant of 4-NPA hydrolysis in aqueous solution over the pH

range 3–8. In the presence of ultrasound, the observed first-order rate constant was independent of both pH and ionic strength and was equal to $4.6 \times 10^{-4} \text{ s}^{-1}$ at 25°C with Ar as cavitating gas (a direct-immersion Ti probe was used at 20 kHz and 115 W). The authors found that OH radical reactions were not contributing significantly to the sonolytic hydrolysis.

The generation of OH radicals is obviously much more intense at 321 or 200 kHz than it is at 20 kHz. Besides, above pH 6.5 the hydrolysis of 4-NPA is base-catalyzed and its rate is strongly pH-dependent. The reaction is very slow at pH 6.5 with a specific rate of $1 \times 10^{-6} \text{ s}^{-1}$, but it becomes 10-fold faster at pH 7.5 [16]. To observe the real effect of ultrasound on the base-catalyzed hydrolysis of 4-NPA, it was essential to find reaction conditions under which pyrolytic degradation and free-radical processes would be relatively slow or entirely suppressed.

6.2. Experiments with a titanium probe

Our aim was to reproduce in the first place the results published by Hua et al. [16] and then to extend our measurements to water-ethanol systems. To begin with, the sonolytic hydrolysis of 4-NPA was investigated in an aqueous solution at pH 7.5 with a direct-immersion Ti probe system. Furthermore, the sonolytic degradation of 4-NP was studied under these conditions. In accordance with findings [16, 27–30] we found it to be first-order as shown in Figure 5. The slope of this plot gave a first-order rate constant of $7.5 \times 10^{-6} \text{ s}^{-1}$. This was almost 2 orders of magnitude smaller than the value of $5.2 \times 10^{-4} \text{ s}^{-1}$ reported by Hua et al. [16], evidently because of the lower ultrasound power used by us. However, because the sonolytic degradation of 4-NP could not be ignored, for our kinetic calculations we quantitated 4-NPA at 272 nm rather than the formation of 4-nitrophenolate ion. The contribution to the absorbance at 272 nm made by 4-NP present in the solution was calculated from simultaneous measurements at 400 nm and subtracted from the total absorbance.

An additional feature of our experiment was to carry out kinetic measurements of base-catalyzed hydrolysis of 4-NPA with sonication and without ultrasound successively in the same reaction system. In Figure 6 the disappearance of 4-NPA is plotted vs time throughout a single experiment. The first-order rate constants presented in Table 3 were respectively determined from the plots for the silent reaction, for the reaction under ultrasound, and for the reaction after ultrasound was switched off.

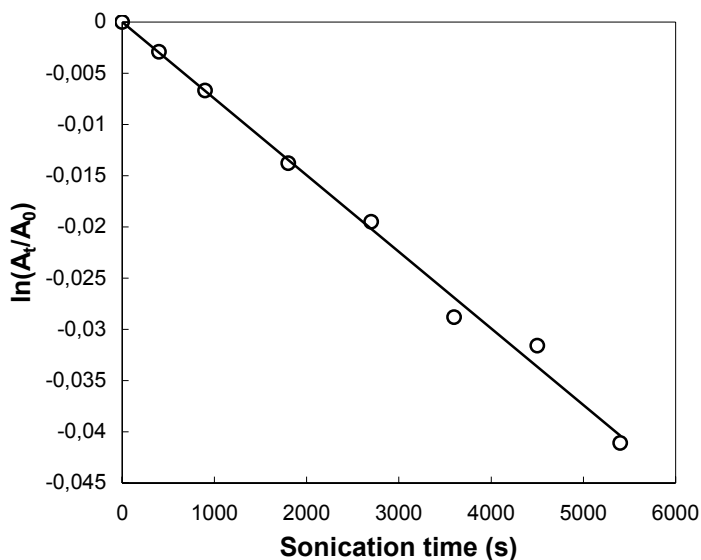


Figure 5. First-order plot of the sonolytic degradation of 4-NP in argon-saturated phosphate buffer, pH 7.5, at 20°C. A is the absorbance of 4-NP measured at 400 nm.

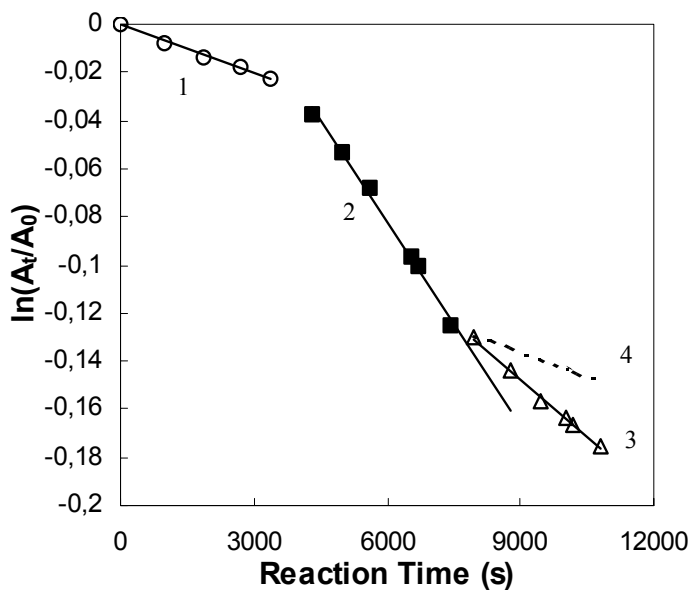


Figure 6. First-order plots for base-catalyzed hydrolysis of 4-NPA in argon-saturated phosphate buffer, pH 7.5: (1) without ultrasound, (2) under ultrasound, (3) successively without ultrasonic irradiation, and (4) (dashed line) calculated according to the rate of the reaction before sonication. A is the absorbance of 4-NPA measured at 272 nm.

Table 3: Results of kinetic measurements for base-catalyzed hydrolysis of 4-nitrophenyl acetate in water at pH 7.5

rate constant $k \times 10^5 \text{ s}^{-1} \text{ }^a$		
nonsonic 1	sonic 2	nonsonic 3
0.66±0.01	2.85±0.11	1.57±0.07

^a Values are averages from three parallel runs

Segments 2 and 3 in Figure 6 represent the kinetics of hydrolysis under irradiation and after ultrasound was switched off, respectively. The first-order rate constants from segments 1 and 2 reveal a considerable sonolytic acceleration, the ratio $k_{\text{ult}}/k_{\text{non}}$ being 4.3. This effect was not due to a loss of 4-NPA through OH-induced radical reactions [30], because after 1-h irradiation we could not detect by HPLC the products of such reactions at a level exceeding 2%. The rate constant for silent hydrolysis after previous sonication (segment 3 in Figure 6) was distinctly greater than that determined before irradiation (segment 1 in Figure 6), their ratio equaling 2.3, a result that clearly indicates a catalytic build-up during sonication. Although kinetic curves obtained under sonication do not show the expected autocatalytic shapes, data recorded within about 1 h might not necessarily reflect this pattern. Identification of the catalyst must await a separate investigation; a decisive role in its formation is most probably played by the metal traces from the immersed titanium horn in conjunction with sonolytic products deriving from the phenyl ester and the phenol. As a matter of fact, the kinetic anomaly was not present when a quartz horn was used, nor did our sonication experiments on alkyl esters with a titanium horn (Chapter 5) exhibit any catalytic phenomena.

We surmise that the entity of catalytic effects must depend on irradiation intensity. Judging from the relative rates of sonolytic degradation of 4-NP, the ultrasound power applied by Hua et al. [16] was almost 9 times greater than that emitted in the present experiments. Therefore, we suppose that the large sonication accelerations observed by Hua et al. [16] were not only caused by direct effects of ultrasound but also involved a considerable contribution from catalytic effects.

As a conclusive caveat, it is clear that an immersion titanium probe is not suitable for kinetic experiments with 4-nitrophenyl esters under ultrasound. In the following kinetic measurements we always used a quartz horn.

6.3. Experiments with a quartz probe

The experiments were carried out in water at pH 7.5, 8.0, and 9.0 and in aqueous ethanol over the range of 0.8–50 wt % at pH 8.0 and 9.0. Remarkably, no catalytic effect was observed (cf. 6.2, Figure 6) and no degradation of the 4-NP could be detected during 2 h irradiation in any of the solvent mixtures. Rate constants for the hydrolysis reaction could equally be determined, with coinciding results within the experimental error, from the disappearance of 4-NPA or from the formation of 4-NP.

Results are presented in Table 4 and Figures 7 and 8. It is noteworthy that the sonication effect was virtually independent of pH, while the reaction rate increased 12 times with the pH change from 7.5 to 9.0.

Table 4: Results of kinetic measurements for base-catalyzed hydrolysis of 4-nitrophenyl acetate in ethanol-water binary mixtures with the quartz horn

% w/w (X) ^a ethanol in water	rate constant $k \times 10^5 \text{ s}^{-1}$						ultrasonic acceleration		
	pH=7.5 ^b		pH=8.0 ^b		pH=9.0 ^c		pH=7.5 ^b	pH=8.0 ^b	pH=9.0 ^c
	non-sonic	sonic	non-sonic	sonic	non-sonic	sonic			
0 (0)	0.66	0.73	2.48	2.78	8.12	8.90	1.10	1.12	1.10
0.8 (0.003)			2.07	2.28	8.02	8.46		1.10	1.06
5 (0.020)			2.30	2.74				1.19	
10 (0.042)			2.10	3.01	8.10	12.07		1.43	1.49
15 (0.065)			1.79	2.87				1.61	
20 (0.089)			1.50	2.42	6.75	11.06		1.61	1.64
25 (0.115)			1.35	1.95				1.45	
30 (0.144)			1.15	1.51	4.48	6.17		1.31	1.38
40 (0.207)			0.82	0.97	3.03	3.36		1.18	1.11
45 (0.243)			0.53	0.56				1.05	
50 (0.281)			0.29	0.32	1.30	1.36		1.09	1.04

^a Molar fraction of ethanol, ^b phosphate buffer, ^c borax buffer

In water or in the presence of minor additions of about 1 wt % ethanol, the sonication effect did not exceed 10%. With a further increase in the alcohol content, the ultrasonic acceleration increased rapidly, reaching a maximum at $X_{\text{EtOH}} \approx 0.08$; thereafter, it dwindled gradually and became almost negligible at $X_{\text{EtOH}} \approx 0.25$.

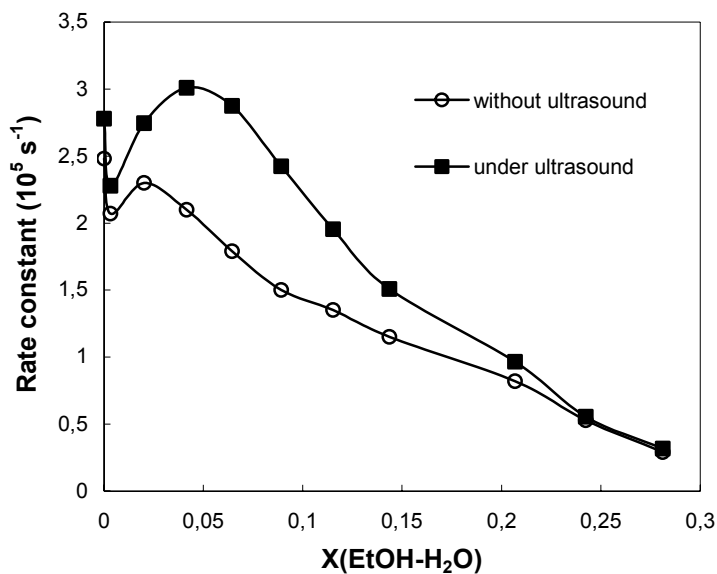


Figure 7. Rate constants for the hydrolysis of 4-NPA in ethanol-water binary mixtures at pH 8.0: (○) without ultrasound and (■) under ultrasound.

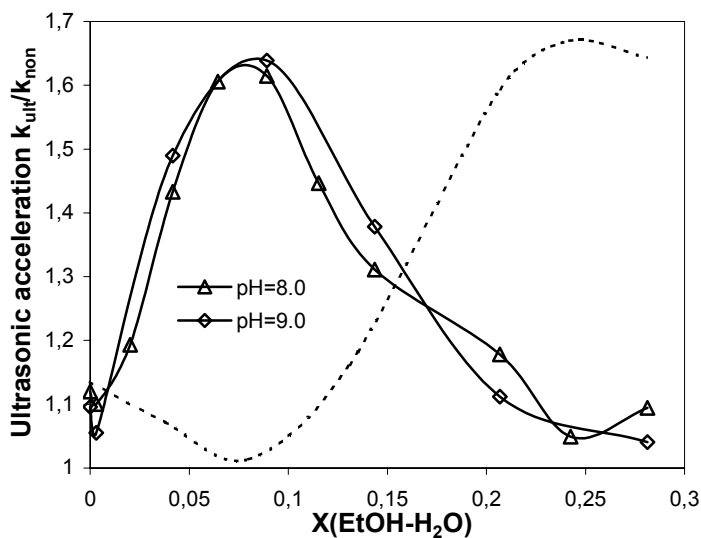


Figure 8. Ultrasound-induced rate enhancements of the hydrolysis of 4-NPA in ethanol-water binary mixtures at pH 8.0 and 9.0. For comparison, the dashed line presents the rate enhancement for acid-catalyzed hydrolysis of EtOAc (in arbitrary units) (from Chapter 5).

Surprisingly, the plots for 4-NPA in Figure 8 are mirror images of the one found for acid-catalyzed hydrolysis of ethyl acetate Figure 2 and their extremes lie at the same alcohol mole fractions. At $X_{\text{EtOH}} \approx 0.08$, ultrasound exerts a most pronounced effect on the hydrolysis of 4-NPA but has almost no influence on the rate of hydrolysis of ethyl acetate. At the same time in the region $0.2 < X_{\text{EtOH}} < 0.3$, the sonication effect of the hydrolysis of ethyl acetate is a maximum while it is nearly negligible for the hydrolysis of 4-NPA.

In Chapter 5 we interpreted the results for ethyl acetate hydrolysis following the current conception for the structure of ethanol-water solutions. Considering the cluster formation in ethanol-water solutions, propyl and butyl esters were used as probes of the possible inclusion of a reagent in the hydrophobic interior of clusters. Indeed, the sonication effect in the region $0.2 < X_{\text{EtOH}} < 0.3$ correlates with the order of hydrophobicity of the esters (Figure 3). The most hydrophobic ester should be the most powerfully held by clusters, and sonication is the least efficient in this case.

With the hydrophobic propyl and butyl esters the hydrolysis reaction exhibited considerable sonication effects in the region $0.05 < X_{\text{EtOH}} < 0.15$, where 4-NPA hydrolysis has a distinct maximum of ultrasonic acceleration. In that experiment (Chapter 5), because we resorted to a GLC method for kinetic measurements, large concentrations of the esters, close to solubility limits, had to be used. Experiments in water could not be carried out and results in the region up to $X_{\text{EtOH}} \sim 0.05$ might have been influenced by the presence of *s*-BuOH as an internal standard ($X = 0.002$). Nevertheless, although no maxima were detected, hydrolyses of propyl and butyl esters, like that of the more hydrophobic 4-NPA, showed enhanced susceptibilities to ultrasound irradiation in the region of $X_{\text{EtOH}} \leq 0.1$, where water structure-making occurs.

We tend to interpret these experimental data as evidence for the inclusion of ester molecules in the solvent framework, which would make them less reactive. Sonication can increase the translational energy of molecules in the liquid phase, thus leading to a breakdown of solvent structure and/or a shift of solvation equilibria.

The more hydrophobic a substrate, the more weakly it should be held by the solvent structure and the greater should be the sonication effect, except the region of cluster formation (*vide supra*). In fact, Figure 7 shows a relatively fast decrease of the silent reaction rate in the region up to $X_{\text{EtOH}} \sim 0.09$, at which value the sonication effect is most pronounced. This fall is followed by a slower decrease up to the region of cluster formation where the drop becomes faster again and the sonication effect negligible, evidencing the remarkable hydrophobicity of the ester.

These findings lead us to attribute the observed differences in the reaction rate to the changes of solvent structure and confirm our suggestion that sonication effects on polar homogeneous reactions primarily arise from a perturbation of weak solute-solvent interactions (Chapter 5).

While an interrelation between sonication effects and reaction mechanism cannot be entirely ruled out, it is, however, self-evident that low-frequency ultrasound is not able to interact with a transition state or to interfere with the solvation process of the transition state. Moreover, in the present case, sonication effects were unrelated to pH while reaction rates changed considerably with small changes in pH. On the other hand, sonication effects were similarly interconnected with solvent structure changes for both acid-catalyzed and base-catalyzed hydrolysis of esters.

7. MODE OF ULTRASOUND ACTION

The question “How ultrasound acts upon homogeneous ionic reactions?” still needs to be answered.

Cavitation is now generally accepted as the origin of the chemical effects of ultrasound. The sonochemical reaction is thought to occur in the cavitation bubble or in its immediate vicinity [1–7]. Extremely harsh conditions are produced by the collapse of a cavitation bubble. This collapse generates transient hot spots with local temperatures and pressures of several thousand Kelvin and hundreds of atmospheres [56, 57]. Under these conditions, standard solvents are in the supercritical state, thus providing a promoting medium for certain reactions [16, 58].

Three regions in which a reaction can take place exist in a cavitating liquid: the gaseous phase inside the bubble, the limit shell around it, and the bulk solution [58, 59]. Therefore, a cavitating reaction medium should be considered to be a pseudo-heterogeneous system, and the term “homogeneous sonochemistry” has been claimed to be misleading [60]. This is an expression of the concept that sound energy is focused in small regions and is not able to process into the rest of the material, and thus its effect is felt only at certain points in the medium.

As the sonochemical acceleration or promotion of a reaction presumably occurs in the cavitation microheterogenities of the reaction medium, the intrinsic rate enhancement of the reaction at this site should be most informative for the investigation and understanding of sonication effects.

The rate of a first-order reaction under sonication can be expressed as follows:

$$v = k_{son,obs} [c] = k_{silent} [c] + x k_{son}^o [c],$$

where x is the fraction of the reaction medium under perturbation by cavitation at any instant.

Thus, the intrinsic sonochemical rate constant can be calculated as

$$k_{son}^o = \frac{k_{son,obs} - k_{silent}}{x}.$$

Accordingly, whereas the observed sonochemical acceleration is

$$a_{obs} = \frac{k_{son,obs}}{k_{silent}},$$

the intrinsic sonochemical acceleration is

$$a^o = \frac{k_{son}^o}{k_{silent}} = \frac{1}{x} \left(\frac{k_{son,obs}}{k_{silent}} - 1 \right).$$

Whereas rate constants $k_{son,obs}$ and k_{silent} can be routinely determined, the values for x are not available in most cases. Hua et al. [16] have suggested that transient supercritical water (SCW) occurs during ultrasonic irradiation in water, and a heat-transfer model for the estimation of the lifetime and spatial extent of SCW during the cavitation bubble collapse was presented. On the basis of semiquantitative calculations, a value for x equaling 0.0015 in pure water was proposed [16, 61, 62].

Using the value for x , intrinsic sonochemical acceleration effects can be estimated from experimental data. However, it should be noted that the value for x by Hua et al. [16] concerns the integral volume of the transient SCW. If a reaction cannot be promoted in SCW and requires more rigorous conditions, which are provided in deeper layers of the shell or inside the gaseous phase of the bubble, the value for x is considerably smaller. The numbers in Table 5 are presented to depict the range of intrinsic accelerations required to produce the given observed rate enhancements. Obviously, the actual values for x fall in the range $0.001 > x > 0.0001$.

Table 5. Intrinsic sonochemical accelerations, a^o , for fractions of the reaction medium under perturbation, X , and for observed rate enhancements by sonication, a_{obs} .

X	a^o	
	$a_{obs} = 2$	$a_{obs} = 11$
0.01	100	1000
0.001	1000	10000
0.0001	10000	100000

It follows from Table 5 that a reaction moderately accelerated by sonication but located in the cavitation sites has to proceed up to several thousands times faster than in the bulk solution. Such rate enhancements have been reported for only a few reactions and require substantial changes in solvent properties [22].

Although the intra-bubble gas phase is an inconceivable site for ionic reactions to proceed, the liquid shell, particularly in the supercritical state, can provide a favorable medium for reactions. However, the low density, low polarity, and cluster formation indigenous to SCW [63] counteract ester hydrolysis reactions. The bubble-bulk interface can also be a site of accumulation for hydrophobic molecules [30, 52, 58]; however, estimated concentration limits of species are far too low to provide the required rate enhancements. Moreover, the

observed sonication effect increases in the opposite direction to the hydrophobicity of the esters.

Although an extension of the linear Arrhenius equation up to the SCW or hot-spot region temperatures may be acceptable in the case of cleavage or degradation reactions, the same approach is not valid for extremely solvation-dependent solvolysis or hydrolysis reactions. Moreover, the occurrence of high-temperature zones in a cavitating solution provides no adequate explanation of the observed effects in polar reactions because the absence of a sonication effect for a reaction with a positive activation energy has been documented [55] and has also been found in this work (Table 2). Besides, no correlation between ultrasound efficiency and activation energy for the solvolysis of *t*-BuCl in ethanol-water mixtures can be observed [20, 48].

From the definition of the activation volume of the reaction,

$$\left(\frac{d \ln k}{dP} \right)_T = - \frac{\Delta V^\ddagger}{RT},$$

the acceleration caused by pressure can be calculated. Assuming an activation volume equal to $-20 \text{ cm}^3 \text{ mol}^{-1}$, the rate of the reaction can be doubled by applying a pressure of 800 atm to the reaction solution at the standard temperature. At higher temperatures (e.g., in the cavitation bubbles), considerably greater pressure must be applied. If the reaction is accelerated only at cavitation sites with $x = 0.001$, then the same rate increase can be attained under a pressure greatly exceeding 7500 atm, which is hardly accessible even in the hot spots. Thus, the kinetic pressure effects should also be ruled out.

It follows that the observed acceleration ratios for polar homogeneous reactions, particularly those for ester hydrolysis, cannot be accounted for directly by the phenomena occurring in the cavitation bubbles. It seems to be necessary to take into consideration the bulk solution or at least an essential part of it.

Evidently, ultrasonic waves passing through the medium cause changes in the translational energy of species. The same may occur because of shock waves produced by collapsing cavitation bubbles in the medium. An acoustically induced motion of the water of crystallization in the crystal lattices leading to changes in the melting points of compounds has been pointed out [64]. The perturbation of normal molecular motion in the liquid phase by ultrasound has been detected through its effects on NMR spin-lattice relaxation times [65, 66]. From NMR spectra, it has been found that the introduction of 20 kHz ultrasound to a liquid sample induces conformational changes to appropriate constituent molecules of the sample [66]. It has been accepted for a long time that the equilibria involving aggregates present in solution are perturbed by pressure changes produced by sound waves [67] and that extensively exploited relaxation processes in liquids are caused by the

re-establishment of the equilibria perturbed by sound waves [68, 69]. Our results only corroborate this concept pointing at a highly probable action of ultrasound in the bulk solution.

However, our results do not permit us to discern the true acoustic field effects from those caused by pressure waves due to the cavitation phenomena. In many cases, the contribution of cavitation is evident because the efficiency of ultrasound increased when hydrolysis was performed under argon [13, 16] or decreased with the elevation of the reaction temperature [19, 20].

8. CONCLUSIONS

In the present Thesis the effect of ultrasound on homogeneous ionic reactions was studied. Kinetics of the acid-catalyzed hydrolysis of ethyl, propyl, butyl acetates and base-catalyzed hydrolysis of 4-nitrophenyl acetate in aqueous binary mixtures of ethanol without sonication and under ultrasound was investigated. Also the effective power of ultrasound was calorimetrically determined in ethanol-water binary mixtures.

Ultrasonic power as an essentially cavitation effect appeared to be affected negligibly if at all by changes in the solvent structure. As an important conclusion it can be inferred that an interpretation of sonochemical effects must not be simplistically confined to cavitation phenomena particularly when polar homogeneous reactions are being considered.

The results of our work, together with literature data, allow us to conclude that the sonochemical acceleration of polar homogeneous reactions takes place mostly in the bulk reaction medium. Pressure waves associated with the propagation of the acoustic waves or essentially the shock waves generated during the cavitation bubble's collapse affect reactions in the medium. Evidently, sonication can cause changes in the translational energy of species, thus leading to a solvent structure break or to a shift of solvation equilibria or likely to both. The ultrasonic acceleration of ester hydrolysis in ethanol-water binary systems can be largely related to the perturbation of hydrophobic solute-solvent interactions. This implies the presence of acoustic field sonochemistry besides the generally accepted hot-spot sonochemistry.

This conclusion, which apparently applies to both acid-catalyzed and base-catalyzed hydrolysis, can be helpful in rationalizing the influence of solvent-solute interactions on these reactions. Because ultrasound seems to be able to control the kinetics of ionic reactions by affecting weak interactions between the species in the bulk solution, the impact of ultrasound on living organisms may be more complex than simple mechanical effects due to cavitation phenomena. We also believe that the field sonochemistry approach may have technological and biotechnological implications, providing unique possibility of control of the polar reactions like hydrolysis and aminolysis in water-solvent systems.

REFERENCES

1. *Ultrasound: Its Chemical, Physical, and Biological Effects*; Suslick, K. S. Ed., VCH: New York, 1988.
2. Mason, T. J., Lorimer, J. P. *Sonochemistry: Theory, Applications and Uses of Ultrasound in Chemistry*; Ellis Horwood: Chichester, England, 1988.
3. Mason, T. J. *Practical Sonochemistry*; Ellis Horwood: Chichester, England, 1991.
4. *Advances in Sonochemistry*; Mason, T. J. Ed., JAI Press, London and Greenwich, CT, 1990 (Vol. 1), 1991 (Vol. 2), 1993 (Vol. 3), 1996 (Vol. 4), 1999 (Vol. 5), 2001 (Vol. 6, ed. T. J. Mason and A. Tiehm).
5. *Synthetic Organic Sonochemistry*; Luche, J. L. Ed., Plenum Press: New York, 1998.
6. Cravotto, G.; Cintas, P. *Chem. Soc. Rev.* **2006**, 35, 180.
7. Mason, T. J. *Chem. Soc. Rev.* **1997**, 26, 180.
8. Richards, W. T., Loomis, A. L. *J. Am. Chem. Soc.*, **1927**, 49, 3086.
9. Thompson, D., Vilbrandt, F. C.; Gray, W. C. *J. Acoust. Soc. Am.* **1953**, 25, 485.
10. Chen, N., Kalback, W. M. *Ind. Eng. Chem. Fundam.* **1967**, 6, 175.
11. Fogler, S., Barnes, D. *Ind. Eng. Chem. Fundam.* **1968**, 7, 222.
12. Couppis, E. C., Klinzing, G. E. *AIChE J.* **1974**, 20, 485.
13. Tuulmets, A., Raik, P. *Ultrason. Sonochem.* **1999**, 6, 85.
14. Kristol, D. S., Klotz, H., Parker, R. C. *Tetrahedron Lett.* **1981**, 22, 907.
15. Yim, B.; Nagata, Y.; Maeda, Y. *J. Phys. Chem. A* **2002**, 106, 104.
16. Hua, I., Höchemer, R. H., Hoffmann, M. R. *J. Phys. Chem.* **1995**, 99, 2335.
17. Lorimer, J. P.; Mason, T. J. *J.C.S. Chem. Comm.* **1980**, 1135.
18. Mason, T. J.; Lorimer, J. P.; Mistry, B. P. *Tetrahedron Lett.* **1982**, 23, 5363.
19. Mason, T. J.; Lorimer, J. P.; Mistry, B. P. *Tetrahedron* **1985**, 41, 5201.
20. Lorimer, J. P.; Mason, T. J.; Mistry, B. P. *Ultrasonics* **1987**, 25, 23.
21. Broekaert, L.; Reisse, J. *Abstracts of the Fourth Meeting of the European Society of Sonochemistry*; Blankenberge, Belgium, 18–22 September, 1994; p 49.
22. Reichart, C. *Solvents and Solvent Effects in Organic Chemistry*, 2nd ed.; VCH: Weinheim, Germany, 1988.
23. Franks, F.; Ives, D. J. G. *Q. Rev.* **1966**, 20, 1.
24. Tuulmets, A. *Ultrason. Sonochem.* **1997**, 4, 189.
25. Suslick, K. S. *Science* **1990**, 247, 1373.
26. Huang, J. L.; Feng, R.; Zhu, C. P.; Chen, Z. H. *Ultrason. Sonochem.* **1995**, 2, S93.
27. Kotronarou, A.; Mills, G.; Hoffmann, M. R. *J. Phys. Chem.* **1991**, 95, 3630.
28. Hoffmann, M. R.; Hua, I.; Höchemer, R. *Ultrason. Sonochem.* **1996**, 3, 165.
29. Tauber, A.; Schuchmann, H.-P.; von Sonntag, C. *Ultrason. Sonochem.* **2000**, 7, 45.
30. Tauber, A.; Schuchmann, H.-P.; von Sonntag, C. *Chem. Eur. J.* **1999**, 5, 2198.
31. *Handbook of Chemistry*, Nikol'skiy, B., P., Ed. 2nd ed.; Khimiya: Moscow, 1965; (in Russian) Vol. 3.
32. *Determination of pH Theory and Practice*; Bates, R. G., Ed. 2nd ed.; J. Wiley & Sons: New York, 1973.
33. Berlan, J.; Mason, T. J. *Adv. Sonochem.* **1996**, 4, 1.
34. Mason, T. J.; Lorimer, J. P.; Bates, D. M.; Zhao, Y. *Ultrason. Sonochem.* **1994**, 1, 91.

35. Ratoarinoro; Contamine, F.; Wilhelm, A. M.; Berlan, J.; Delmas, H. *Ultrason. Sonochem.* **1995**, 2, 43.
36. Kimura, T.; Sakamoto, T.; Leveque, J. M.; Sohmiya, H.; Fujita, M.; Ikeda, S.; Ando, T. *Ultrason. Sonochem.* **1996**, 3, 157.
37. Koda, S.; Kimura, T.; Kondo, T.; Mitome, H. *Ultrason. Sonochem.* **2003**, 10, 149.
38. Nozdrev, V. F.; Larionov, N. *Dokl. Akad. Nauk SSSR* **1953**, 92, 991.
39. Asano, T.; Le Noble, W. J. *Chem. Rev.* **1978**, 78, 407.
40. Nishi, N.; Takahashi, S.; Matsumoto, M.; Tanaka, A.; Muraya, K.; Takamuku, T.; Yamaguchi, T. *J. Phys. Chem.* **1995**, 99, 462.
41. Matsumoto, M.; Nishi, N.; Furusawa, T.; Saita, M.; Takamuku, T.; Yamagami, M.; Yamaguchi, T. *Bull. Chem. Soc. Jpn.* **1995**, 68, 1775.
42. Egashira, K.; Nishi, N. *J. Phys. Chem. B* **1998**, 102, 4054.
43. Franks, F.; Johnson, H. H. *Trans. Faraday Soc.* **1962**, 58, 656.
44. Buhvestov, U.; Rived, F.; Ra'fols, C.; Bosch, E.; Rose's, M. *J. Phys. Org. Chem.* **1998**, 11, 185.
45. Blokzijl, W.; Engberts, J. B. F. N. *Angew. Chem., Int. Ed. Engl.* **1993**, 32, 1545.
46. Engberts, J. B. F. N.; Blandamer, M. J. *J. Phys. Org. Chem.* **1998**, 11, 841.
47. Buurma, N. J.; Pastorello, L.; Blandamer, M. J.; Engberts, J. B. F. N. *J. Am. Chem. Soc.* **2001**, 123, 11848.
48. Winstein, S.; Fainberg, A. H. *J. Am. Chem. Soc.* **1957**, 79, 5937.
49. Arnett, E. M.; McKelvey, D. R. *J. Am. Chem. Soc.* **1965**, 87, 1541.
50. Tommila, E.; Murto, M. L. *Acta Chem. Scand.* **1963**, 17, 1957.
51. Jiang, Y.; Petrier, C.; Waite, T. D. *Ultrason. Sonochem.* **2006**, DOI: 10.1016 / j.ultsonch. 2005.07.003
52. Mark, G.; Tauber, A.; Rüdiger, L.; Schuchmann, H.-P.; Schultz, D.; Mues, A.; von Sonntag, C. *Ultrason. Sonochem.* **1998**, 5, 41.
53. Petrier, C.; Jeunet, A.; Luche, J.-L.; Reverdy, G. *J. Am. Chem. Soc.* **1992**, 114, 3148.
54. Entezari, M., H.; Kruus, P. *Ultrason. Sonochem.* **1992**, 1, S165.
55. Ando, T.; Fujita, M.; Kimura, T.; Kondo, Y. *J. Org. Chem.* **1998**, 63, 6048.
56. Noltingk, B. E.; Neppiras, E. A. *Proc. Phys. Soc., London, Sect. B* **1950**, 63, 674.
57. Flint, E. B.; Suslick, K. S. *Science* **1991**, 253, 1397.
58. Henglein, A. *Adv. Sonochem.* **1993**, 3, 17.
59. Riesz, P. *Adv. Sonochem.* **1991**, 2, 23.
60. Reisse, J.; Caulier, T.; Dekercheer, C.; Kegelaers, Y.; Segebarth, N.; Bartik, K. In *Sonochemistry and Sonoluminescence*; Crum, L. A. et al. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999.
61. Burdin, F.; Tsochatzidis, N. A.; Guiraud, P.; Wilhelm, A. M.; Delmas, H. *Ultrasonics Sonochem.* **1999**, 6, 43.
62. Birkin, P. R.; Leighton, T. G.; Power, J. F.; Simpson, M. D.; Vincotte, A. M. L. *J. Phys. Chem. A*, **2003**, 107, 306.
63. Brennecke, J. F.; Chateauneuf, J. E. *Chem. Rev.* **1999**, 99, 433.
64. Homer, J.; Howard, M. J.; Gooda, S. C. *Ultrason. Sonochem.* **1995**, 2, 71.
65. Homer, J.; Patel, S. V. *J. Chem. Soc., Faraday Trans.* **1990**, 86, 215.
66. Homer, J.; Paniwnyk, L.; Palfreyman, S. A. *Adv. Sonochem.* **1996**, 4, 75.
67. Storey, L. R. O. *Proc. Phys. Soc., London, Sect. B* **1952**, 65, 943.
68. Eigen, M.; Kurtze, G.; Tamm, K. *Z. Elektrochem.* **1953**, 57, 103.
69. Eigen, M. *Faraday Soc. Discuss.* **1954**, 17, 194.

SUMMARY IN ESTONIAN

Ultraheli mõju estrite hüdrolüüsile vesi-etanool segudes

Teatavasti on ultraheli kasutades võimalik mõjutada mitmeid keemilisi ja füüsikalisi protsesse tänu ainulaadsele kavitatsioonifenomenile. Ultraheli efektide puhul heterogeensetes süsteemides on tegu kavitatsiooni mehhaaniliste mõjudega, mis võivad esile kutsuda massiülekande protsesse, aktiveerida tahkete reagentide või katalüsaatorite pindu, soodustada osakeste disperseerumist jne. Mitmeid homogeenseid ja heterogeenseid reaktsioone võib initsieerida või neid kiirendada vabade radikaalide genereerimisega ultraheli toimel, mis kutsub lahuses esile ahelreaktsioone. Samuti võib mõningatel juhtudel ultraheli tingida reaktsioonimehhanismi muutuse heterolüütilisest vabaradikaalseks. Siiski on teada mitmeid näiteid ultraheli toimel kiirenenud homogeensetest ioonilistest reaktsioonidest, mis pole võimalised ümber lülituma radikaalsele rajale ning seega ei peaks ultraheli neid mõjutama. Samas on vähe reaktsioone, mille ultraheliefekte on uuritud kineetiliselt. Valdavalt on need solvolüüsid või hüdrolüüsid ning ultraheli toimemehhanism taoliste reaktsioonidele pole kaugeltki selge.

Käesoleva töö eesmärgiks oligi saada rohkem eksperimentaalseid andmeid ning läbi selle leida vastuseid ultraheli efekti olemusele homogeensete iooniliste reaktsioonide korral.

Kineetilisteks ultraheli uuringuteks võeti alifaatsete estrite (etüül-, propüül- ja butüülatsetaat) happekatalüütiline ning 4-nitrofenüülatsetaadi aluskatalüütiline hüdrolüüs vesi-etanool binaarsetes segudes. Kõikide estrite korral kahanes hüdrolüüsi kiirus ilma ultrahelita ühtlaselt etanooli kontsentratsiooni kasvades, samas kui ultraheliga kiiritades näitas reaktsioonikiirus keerulisi sõltuvusi vesi-etanool segu koostisest.

Kuna mitmed binaarsete süsteemide füüsikokeemilised omadused sõltuvad koostisest mittelineaarselt, siis tulemuste interpretatsiooni huvides määrati, kuidas ultraheli energia neeldumine sõltub süsteemi koostisest. Kalorimeeriline mõõtmine näitas, et määratud ultraheli võimsus on väga vähe kui üldse mõjutatud muutustest solventstruktuuris.

Käesoleva töö kineetiliste uuringute ja kirjandusandmete põhjal järeldati, et homogeensete polaarsete reaktsioonide sonokeemiline kiirenemine leiab aset kogu reaktsioonikeskkonnas. Rõhulained, mis on seotud helilainete levimisega või veelgi tõenäolisemalt lööklained, mis tekivad kavitatsioonimulli kollapsi tagajärjel, võivad mõjutada reaktsiooni üle kogu süsteemi. Sonikeerimine võib põhjustada muutusi osakeste translatoorses energias, mis viib solventstruktuuri lõhkumiseni või solvatatsiooni tasakaalu nihkumiseni. Seega võib estri hüdrolüüsi kiirenemine ultraheli toimel vesi-etanool segudes suuresti olla seotud hüdrofoobsete solvent-soluut interaktsioonide häiritusega. See vihjab helivälja sonokeemia olemasolule lisaks üldiselt aktsepteeritud "hot-spot" sonokeemiale.

Järeldus, mis ilmselt kehtib nii happe- kui ka aluskatalüütilise hüdrolyüsi korral, võib olla kasulik ratsionaliseerimaks solvent-soluut interaktsioonide mõju sellistele reaktsioonidele. Kuna ultraheli tundub olema võimeline kontrollima iooniliste reaktsioonide kineetikat, mõjutades nõrku osakestevahelisi interaktsioone lahustes, siis ultraheli toime elusorganismidele võib olla komplitseeritum kui lihtsalt kavitatsiooni fenomenist tingitud mehhaanilised efektid.

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PUBLICATIONS

Tuulmets, A., Salmar, S. Effect of ultrasound on ester hydrolysis in aqueous ethanol. *Ultrason. Sonochem.*, **2001**, 8, 209–212, doi:10.1016/S1350-4177(01)00078-5

Tuulmets, A., Salmar, S., Hagu, H., Effect of ultrasound on ester hydrolysis in binary solvents. *J. Phys. Chem., B* **2003**, 107, 12891–12896, DOI: 10.1021/jp035714l.

Salmar, S., Cravotto, G., Tuulmets, A., Hagu, H. Effect of ultrasound on the base-catalyzed hydrolysis of 4-nitrophenyl acetate in aqueous ethanol. *J. Phys. Chem., B* **2006**, 110, 5817–5821, DOI: 10.1021/jp057405w

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2. Tuulmets, A., Salmar, S., and Hagu, H., Effect of ultrasound on ester hydrolysis in binary solvents. *J. Phys. Chem., B* **2003**, 107, 12891–12896
3. Hagu, H., Salmar, S., Tuulmets, A., Ultrasonic acceleration of ester hydrolysis in ethanol-water and 1,4-dioxane-water binary solvents. *Proc. Estonian Acad. Sci. Chem.*, **2002**, 51, 4, 235–239
4. Tuulmets, A., Salmar, S., Effect of ultrasound ester hydrolysis in aqueous ethanol. *Ultrasonics Sonochemistry*, **2001**, 8, 209–212

Reports on conferences

1. Tuulmets, A., Salmar, S., Talu, L. Ultrasonic Acceleration of Polar Homogeneous Reactions. *International Conference and Exhibition on Ultrasonics (ICEU-99)*, New Delhi, December 2–4, 1999, *Conference Papers*, 1999, **2**, 320–323 (Oral report)
2. Tuulmets, A., Salmar, S. Effect of ultrasound on ester hydrolysis in aqueous ethanol. *Abstracts 7th Meeting European Society of Sonochemistry*, May 14–18, 2000, Biarritz-Guéthary, France, 2000, 65–66 (Oral report)
3. Salmar, S., Tuulmets, A. Effect of ultrasound on the solvation of reagents. 26th Estonian Chemistry Days, Abstracts of Scientific Conference, Tallinn, 2000, 129 (Oral report)
4. Salmar, S., Hagu, H., Tuulmets, A. Effect of ultrasound on ester hydrolysis in aqueous ethanol. 27th Estonian Chemistry Days, Abstracts of Scientific Conference, Tallinn, 2001, 120–121 (Poster presentation)
5. Tuulmets, A., Salmar, S., Hagu, H. Sonochemistry of polar homogenous reactions. *Abstracts of the 8th Meeting of European Society of Sonochemistry*, (Villasimius, Italy September 14–19, 2002), 2002, 77–78 (Oral report)
6. Tuulmets, A., Salmar, S., Hagu, H. Ultrasound and hydrophobic interactions. *Abstracts of the 9th Meeting of European Society of Sonochemistry*, April 25–30, 2004, Badajoz, Spain, 2004, **P-15**, 151–152 (Poster presentation)
7. Tuulmets, A., Salmar, S., Hagu, H. Ultrasound and hydrophobic interactions. *COST D32: KICK-OFF MEETING, Workshop on Chemistry in High-Energy Microenvironments*, July 8–9, 2004, Alicante, Spain (Poster presentation)

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1. Salmar, S., Cravotto, G., Tuulmets, A., Hagu, H., Effect of ultrasound on the base-catalyzed hydrolysis of 4-nitrophenyl acetate in aqueous ethanol. *J. Phys. Chem., B* **2006**, DOI: 10.1021/jp057405w
2. Tuulmets, A., Salmar, S., and Hagu, H., Effect of ultrasound on ester hydrolysis in binary solvents, *J. Phys. Chem., B* **2003**, 107, 12891–12896
3. Hagu, H., Salmar, S., Tuulmets, A., Ultrasonic acceleration of ester hydrolysis in ethanol-water and 1,4-dioxane-water binary solvents. *Proc. Estonian Acad. Sci. Chem.*, **2002**, 51, 4, 235–239
4. Tuulmets, A., Salmar, S., Effect of ultrasound ester hydrolysis in aqueous ethanol. *Ultrasonics Sonochemistry*, **2001**, 8, 209–212

Konverentsid

1. Tuulmets, A., Salmar, S., Talu, L. Ultrasonic Acceleration of Polar Homogeneous Reactions. *International Conference and Exhibition on Ultrasonics (ICEU-99)*, New Delhi, December 2–4, 1999, Conference Papers, 1999, **2**, 320–323 (suuline ettekanne)
2. Tuulmets, A., Salmar, S. Effect of ultrasound on ester hydrolysis in aqueous ethanol. *Abstracts 7th Meeting European Society of Sonochemistry*, May 14–18, 2000, Biarritz-Guéthary, France, 2000, 65–66 (suuline ettekanne)
3. Salmar, S., Tuulmets, A. Effect of ultrasound on the solvation of reagents. *26th Estonian Chemistry Days, Abstracts of Scientific Conference*, Tallinn, 2000, 129 (suuline ettekanne)
4. Salmar, S., Hagu, H., Tuulmets, A. Effect of ultrasound on ester hydrolysis in aqueous ethanol. *27th Estonian Chemistry Days, Abstracts of Scientific Conference*, Tallinn, 2001, 120–121 (stendiettekanne)
5. Tuulmets, A., Salmar, S., Hagu, H. Sonochemistry of polar homogenous reactions. *Abstracts of the 8th Meeting of European Society of Sonochemistry, (Villasimius, Italy September 14–19, 2002)*, 2002, 77–78 (suuline ettekanne)
6. Tuulmets, A., Salmar, S., Hagu, H. Ultrasound and hydrophobic interactions. *Abstracts of the 9th Meeting of European Society of Sonochemistry, April 25–30, 2004, Badajoz, Spain, 2004, P-15*, 151–152 (stendiettekanne)
7. Tuulmets, A., Salmar, S., Hagu, H. Ultrasound and hydrophobic interactions. *COST D32: KICK-OFF MEETING, Workshop on Chemistry in High-Energy Microenvironments*, July 8–9, 2004, Alicante, Spain (stendiettekanne)