Thermophoresis and Thermodiffusion

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Motivation:

It turns out that a simple nonequilibrium environment created by a temperature gradient can be used to monitor the reaction kinetics of large proteins with small substrate molecules. This is probably caused by a change in the hydration layer of the protein which is influenced by subtle conformations changes induced by the binding substrate molecule. The underlying effect is thermophoresis or thermal diffusion, which is the mass transport induced by a temperature gradient applied to a liquid mixture. The resulting separation of the components causes a concentration gradient parallel or antiparallel with respect to the temperature gradient. Beside the recently detected biophysical applications it is relevant in polymer characterization, and analysis of petrol reservoir characterization. Additionally the effect is also discussed as an accumulation mechanism for a hydrothermal emergence of life in the early stage of the earth and in the deep sea close to black smokers.

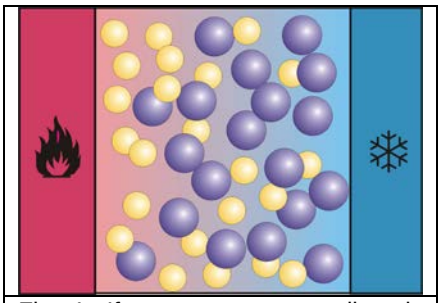

Fig. 1: If a temperature gradient is applied to a mixture, this results in a concentration gradient.

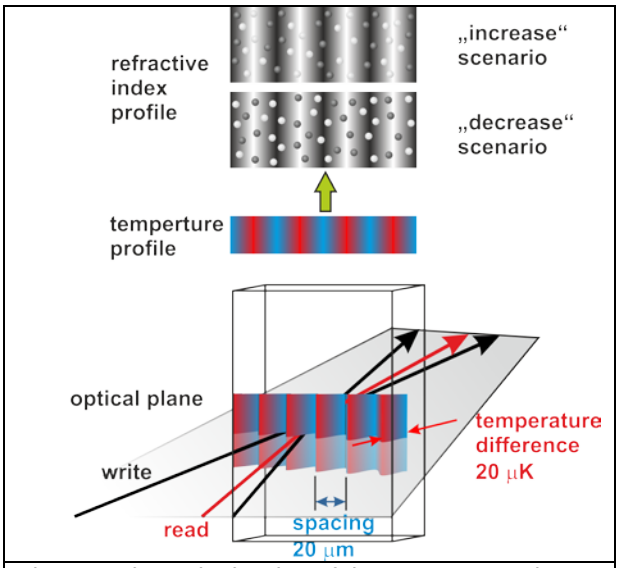

Fig. 1: Schematic drawing of the TDFRS experiment. The two IR-beams (black) intersect in the sample cell and create a sinusoidal interference grating with a fringe spacing on the order of 20 µm and a temperature amplitude of approximately 20 µK due to absorption of the laser light. The temperature grating causes a refractive index grating. After temperature equilibration the diffusion process starts. This leads depending on the movement of the components to an increase or decrease of the refractive index contrast of the grating. The buildup and contrast variation of the grating is probed by a read-out laser beam (red).

The investigation of the thermophoresis and thermal diffusion in liquid mixtures is based on the determination of the transport coefficients D (mutual diffusion coefficient), D_T (thermal diffusion coefficient) and S_T (Soret coefficient). Experimentally we are determining these properties by **T**hermal **D**iffusion **F**orced **R**ayleigh **S**cattering (**TDFRS**) [1-3] and, hence, to provide a "thermophoretic scale", enabling a comparison with values obtained, by means of **M**olecular **D**ynamic (MD)-simulations and empirical parameters such as the log P, a partition coefficient describing the hydrophilicity of a compound.

References:

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2. Wiegand, S., H. Ning, and H. Kriegs, J. Phys. Chem. B, **111**(2007) 14169-14174.
3. Wiegand, S., in *Functional Soft Matter*, J.K.G. Dhont, et al., Editors. 2015, Forschungszentrum Jülich: Jülich. p. F4.1-F4.24.

Accumulation of formamide in hydro-thermal pores to form prebiotic nucleobases

Formamide is one of the important compounds from which prebiotic molecules can be synthesized, provided that its concentration is sufficiently high. For nucleotides and short DNA strands, it has been shown that a high degree of accumulation in hydrothermal pores occurs, so that temperature gradients might play a role in the origin of life [Baaske P, et al. (2007) Proc Natl Acad Sci USA 104(22): 9346−9351].We show that the same combination of thermophoresis and convection in hydrothermal pores leads to accumulation of formamide up to concentrations where nucleobases are formed. The thermophoretic properties of aqueous formamide solutions are studied by means of Infrared Thermal Diffusion Forced Rayleigh Scattering. These data are used in numerical finite element calculations in hydrothermal pores for various initial concentrations, ambient temperatures, and pore sizes. The high degree of formamide accumulation is due to an unusual temperature and concentration dependence of the thermophoretic behavior of formamide. The accumulation fold in part of the pores increases strongly with increasing aspect ratio of the pores, and saturates to highly concentrated aqueous formamide solutions of ~85 wt% at large aspect ratios. Time-dependent studies show that these high concentrations are reached after 45–90 d, starting with an initial formamide weight fraction of 10^{-3} wt % that is typical for concentrations in shallow lakes on early Earth.

Thermophoresis has been suggested as an active transport mechanism to reach high concentrations of prebiotic molecules to culminate in the formation of RNA. A still open question is whether thermophoresis can also be a possible mechanism to form prebiotic nucleobases from simple molecules such as hydrogen cyanide (HCN) and formamide (FA). Already for almost 50 years, FA has been discussed as an important compound from which prebiotic molecules originate. It has been shown that all known nucleobases can be synthesized from aqueous FA solutions. In diluted HCN solutions, polymerization of HCN to form nucleobases becomes favoured over hydrolysis of HCN at concentrations of 0.03–0.3 wt%(8). To our knowledge, there are no similar studies of diluted FA solutions. Taking into account the faster hydrolysis of FA (3), we estimated that a 100-times higher concentration between 3 wt % and 33 wt % should be sufficient for the synthesis of prebiotic molecules in aqueous solutions. In the ocean during the early stages of Earth, the natural occurring concentrations at a low temperature (10 °C) and a pH between 6 and 8 are estimated to be only on the order of 10−9 wt %, whereas, in shallow lakes (depth 10 m), due to vaporization and FA input from the atmosphere, higher concentrations of about 10^{-3} wt % are possible. Still, these natural concentrations are far too small compared with those required for the formation of nucleobases.

We performed numerical calculations for the spatial and time dependence of the concentration of aqueous FA solutions in hydrothermal pores exposed to a temperature gradient to investigate whether it is possible to reach sufficiently high FA concentrations that are necessary to initiate the synthesis of prebiotic nucleobases. The dependence of the highest FA concentration in part of the pore is analysed as a function of the initial FA concentration, which is the reservoir concentration within the shallow lake, at various ambient temperatures, initial concentrations, and aspect ratios of the pores. The highest FA concentration within the pore relative to the initial FA concentration defines the so-called accumulation fold. The concentration dependence and temperature dependence of the thermodiffusion and mass diffusion coefficients of FA in aqueous solutions as determined by means of Infrared Thermal Diffusion Forced Rayleigh Scattering (IR-TDFRS), as well as other relevant physical properties of FA solutions, are used as an input to these calculations. In contrast to the previous study for nucleotides and short DNA fragments, we do not find an exponential increase of the accumulation fold with increasing pore aspect ratio. Instead, the accumulation fold increases exponentially only at relatively small aspect ratios, sharply increases at intermediate aspect ratios, and, finally, saturates to highly concentrated FA solutions on the order of 85 wt % at relatively large aspect ratios. The sharp increase of the accumulation fold with increasing pore size is found to be essentially independent of the initial, shallow lake concentration.

Fig. 1 shows a contour plot of the concentration profile in a pore with aspect ratio 10 in the stationary state. At the top of the pore, the FA concentration is constant, reminiscent of the concentration in a shallow lake. This is also the initial concentration within the pore, before the temperature gradient is switched on. The right side of the pore is warmer compared with the left side, with a temperature difference of 30 K for all calculations. The maximum concentration in the stationary state within the dark red-coloured region at the bottom corner of the pore

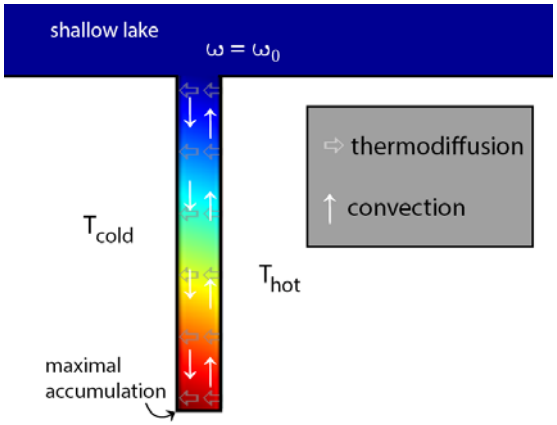

FIG. 1: Contour plot of the concentration profile in a pore with aspect ratio 10 connected to a reservoir in the stationary state. The vertical and horizontal arrows mark the convective and thermodiffusive flow, respectively..

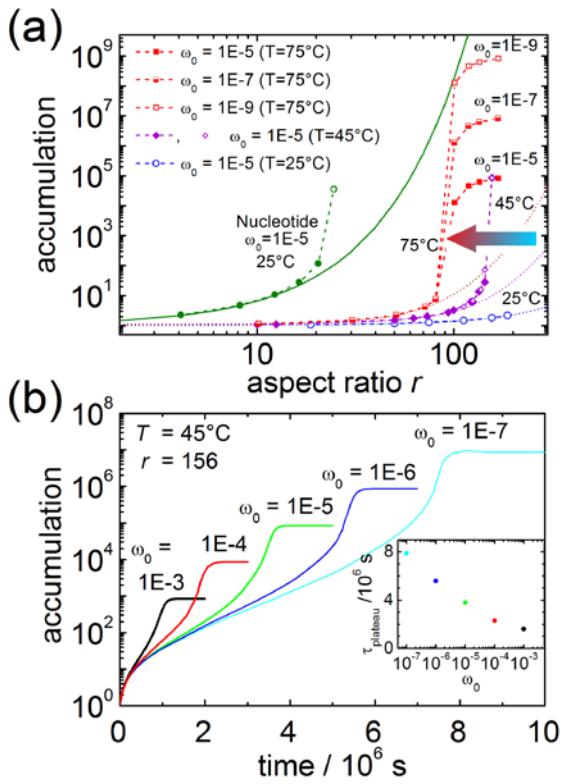

FIG. 1: (A) Accumulation fold of FA as a function of the aspect ratio r for various initial weight fractions, ω_0, and temperatures as indicated in comparison with the accumulation fold for a single nucleotide. The solid line has been calculated using equation 1 in ref. 1, and the dots refer to COMSOL simulations using the physical chemistry properties of water. The accumulation fold of FA at 25 °C, 45 °C, and 75 °C has been determined at an optimal width of 180 µm,160 µm, and 100 µm, respectively. All curves show an initial exponential increase, which levels of if the accumulation becomes so strong that it is close to the pure component. (B) Time-dependent study of the accumulation as a function of time for various initial concentrations,ω0, at a width of 160 µm and a height of 25 mm. (Inset) Time to reach the concentration plateau, τplateau, as a function of the dependence of the accumulation for different initial concentrations ω_0.

defines the accumulation fold that is of interest here. This is the region where possible formation of nucleobases from FA will take place. Fig. 2a shows the accumulation fold as a function of the height to width aspect ratio *r*. For comparison with literature results, we first performed calculations for an aqueous nucleotide solution (see Fig. 2, the green solid dots), with an initial concentration of $\omega_0 = 10^{-5}$. In this calculation for the nucleotide, literature values for $S_T = 0.015\ K^{-1}$, as well as for $D = 400\ \mu m^2/s$ were used, whereas the physicochemical properties of pure water were used for the solvent properties, as done in ref. 1. For low aspect ratios, we find good agreement with the exponential function (see Fig. 2a, solid line), as proposed in ref. 1 to describe the aspect ratio dependence of the accumulation fold. At high accumulation folds, however, we find the expected deviations from an exponential accumulation as the nucleotide concentration approached 100% saturation. The concentration and temperature dependence of the Soret coefficient and the mass diffusion coefficient of nucleotide solutions for somewhat elevated concentrations is not known. Additionally the solubility of nucleotides is limited, therefore the last data point in Fig. 2a, corresponding to a concentration of 35 wt %, is marked as an open circle to indicate the uncertainty of this data point. In contrast to nucleotides, FA and water are miscible at any fraction, so that the entire concentration range is accessible. We studied three different mean temperatures, T_{mean} = 25 °C, 45 °C, and 75 °C, for the optimal pore widths of 180 µm, 160 µm, and 100 µm, respectively, to achieve an efficient accumulation. The initial concentration was varied between $\omega_0 = 10^{-9}$ and $\omega_0 = 10^{-5}$, corresponding to FA concentrations as predicted for oceans and shallow lakes under early Earth conditions [2]. After an initial exponential increase of the accumulation fold with the pore aspect ratio, we observe, for all studies, a steep increase followed by a plateau when the accumulation fold reaches $1/\omega_0$ of a pure FA solution, as can be seen from Fig. 2a. This saturation plateau is approached at lower aspect ratios for larger temperatures, thus favouring an accumulation in wider pores at lower ambient temperatures. Fig. 2b shows the time dependence of the accumulation fold for three initial concentrations ω0, for the same temperature of T_{mean} = 45 °C and the same pore aspect ratio of 156. For an initial concentration $\omega_0 = 10^{-5}$, the saturation plateau is reached 45 d after switching on the temperature gradient. Reducing the initial concentration to $\omega_0 = 10^{-7}$ prolongs the saturation time to 90 d. These are reasonable time ranges to establish regions of sufficiently high FA concentration to synthesize nucleobases.

Further details can be found in Ref. 2.

[1] Baaske P, Proc Natl Acad Sci USA **104** (2007) 9346−9351.

[2] D. Niether, D. Afanasenkau, J. K. G. Dhont and S. Wiegand, Proc Natl Acad Sci USA, **113** (2016) 4272-4277.