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Journal Name

ARTICLE

Influence of the medium´s viscosity on the kinetics of hydrogen atom self-exchange for N-hydroxy phtalimide/ piperidine-N-oxyl (NHPI/PINO•) measured by CW-ESR spectroscopy

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CW-ESR line broadening experiments are used to investigate the kinetics of fast hydrogen atom self-exchange reactions. The system NHPI/PINO• was studied in five different aprotic organic solvents at room temperature with a focus on the influence of the viscosity of the medium. Our findings support theoretical descriptons derrived from statistical dynamics on the impact of the reorganization of the medium. In an Arrhenius type description the influence appears in the preexponential factor as a linear dependence on the dynamic viscosity.

Introduction

The process of hydrogen atom transfer (HAT) is the simplest kind of proton coupled electron transfer (PCET) which plays an important role in a wide range of chemical, biological and industrial processes. These include basic reactions in the interconversion of chemical and electrical energy, water splitting and in fuel cells.[1] This triggered an intensive and currently ongoing research on such processes in the fields of chemical kinetics and theory, in order to understand their chemical mechanisms and fundamental physics.[2-5]

These theoretical approaches are inspired by the concept of Marcus Cross Relation which was postulated first in Marcus Theory on electron transfer. Experimental proof that the rates and activation parameters of cross reactions agree with ones calculated from corresponding self-exchange - an isoenergetic process of two reactants of equal structure that differ only by one hydrogen atom - reactions was reported.[6,7] Therefore studies of self-exchange enable us not only to predict cross reactions but also help to understand the physics of a single reactant.

Since hydrogen atom self-exchange is an isoenergetic process with a driving force $\Delta G^0 = 0$, there are only a few experimental methods available to measure corresponding rates. These include magnetic resonance spectroscopy, tracer methods or optical detection of chiral compounds. Moreover these rates can differ by several orders of magnitude. Most research was done on relatively slow reacting metal complexes which react within the time scale of the applied methods such as NMR line broadening.[8-11]

In our work we focus on the radical PINO•, which is known as

effective organo-catalyst for hydrogen abstraction.[12] This radical is generated from the industrial product NHPI. Both
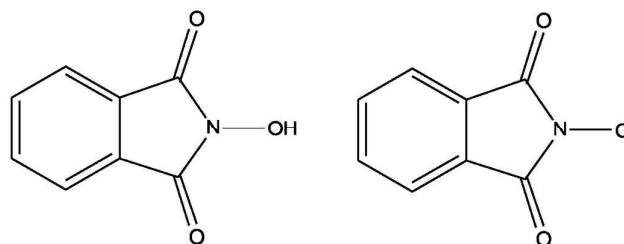
structures are displayed in figure 1.
Fig 1 Structures of NHPI (left) and PINO• (right)

There are many reports on the kinetics of cross reactions of PINO• with a variety of reactants. Since most of these reactions are fast methods such as Laser Flash Photolysis[13,14] or stopped-flow UV-VIS spectroscopy[15] were applied. Further there has been work on so called pseudo self-exchange, a process with a driving force close to zero, between two derivatives of NHPI studied by a UV-VIS spectroscopy. In this work the authors present quite conclusive evidence that the observed process is HAT.[16]

HAT is not only the simplest form of PCET, but also one of the simplest chemical processes, like electron self-exchange. It involves the simultaneous transfer of two particles, an electron and a proton. In contrast to a stepwise mechanism of PCET this process is much simpler. For example there is a report for p-quinones in buffered aqueous solution were protons are transferred about ten times faster than electrons.[17] Effects like this complicate a theoretical interpretation of stepwise mechanisms significantly, therefore we focus on HAT.

The fastest rates reported for NHPI/PINO• are in the order of 10^8 M^{-1} s^{-1}, which is out of the time resolution of usually applied methods to measure self-exchange reactions.

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Therefore, there is no report on real hydrogen atom self-exchange so far for this system.

However, rates that fast are conveniently within the time resolution of a CW-ESR line broadening experiment. This type of experiment was introduced in the 1950s[18] to study electron self-exchange reactions and is currently used in this field.[19-21]

To our knowledge we report the first successful CW-EPR line broadening experiment to obtain kinetics of a real hydrogen atom self-exchange with $\Delta G^0=0$. PINO• is prone to self-decomposition, with a lifetime of minutes.[22] Therefore we electrochemically oxidized NHPI to the corresponding radical PINO•, as displayed in equation (1) in Lewis-basic aprotic organic solvents. We used a flow-through electrochemical cell mounted directly before the ESR-resonator. This radical generation is already described in literature.[23,24]

$$NHPI \xrightarrow{-e^-} NHPI^+ \xrightarrow{-H^+} PINO \qquad (1)$$
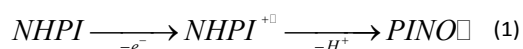
Aprotic media was chosen in order to favour the simpler HAT process.

Most current theoretical approaches indicate strong medium effects on the rates. There are little systematic studies on those in literature.[25] Therefore we varied the dynamic viscosities η and found a η^{-1} dependence of the measured hydrogen self-exchange rates k_H. This was predicted theoretically from statistical dynamics.[26]

Theory

A general mechanism for the hydrogen atom self-exchange we observe in aprotic solvents is displayed in figure 2.
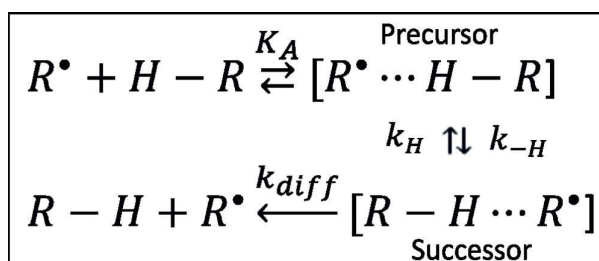

Fig 2 Proposed mechanism

There K_A denotes the association constant and k_{diff} the dissociation of the products. k_H is the rate of the actual transfer of the hydrogen atom from one complex to the other, which will be called precursor and successor complex. This is an activated process with a rate described by the Arrhenius type equation 2.

$$k_H = \nu_{ex}\, e^{-\frac{E_A}{RT}} \qquad (2)$$

E_A denotes the activation barrier, R the gas constant and T the absolute temperature. Due to the fact that we are comparing self-exchange rates we assume the exponential part to be constant in our further discussion. For an elementary chemical process following a mechanism as given in figure 1 a detailed description of the preexponential factor ν_{ex} was derived theoretically by Alexandrov and Gol´danskii. In their approach they consider the reorganization of the medium which has to correspond to the change of volume and shape of the reactants inside the reaction cage. Their description of ν_{ex} is given in equation 3.

$$\nu_{ex} = \frac{1}{2\pi\tau_c}\sqrt{\frac{E_R^{''}}{\Gamma}} \qquad (3)$$

Γ describes the interaction of the corresponding electronic states of precursor and successor complex. For self-exchange reactions we assume this term to be constant. $E_R^{''}$ is the activation energy required to reorganize the medium, which is computed from the time-evolution of the potential functions of all heavy particles in the electronic states of precursor and successor complex. Since we expect these values to be similar and only the square root of $E_R^{''}$ is effective on ν_{ex} it is negligible for our purpose. Thus τ_c remains as single effective variable. It is defined as the relaxation time of all the motions necessary in order to rearrange the particles of the medium to the reactant´s change in shape and volume during the transfer process. Thus the physical interpretation of τ_c relates it to the translational and rotational diffusion of these particles, thus τ_c is proportional to the dynamic viscosity η.[26] Therefore a η^{-1} dependence is predicted for k_H, which was found in this work.

This is similar to solvent friction effects known from electron transfer theory, which are reflected by the dependence of the preexponential factor on τ_L^{-1}, the longitudinal relaxation time.[27-29] This quantity τ_L is defined for processes with constant but non-zero charge. In our process neither reactants nor the transferred hydrogen atom are charged, thus the dynamic viscosity affects the rates.

Experimental

N-hydroxy pthalimide (NHPI: Sigma Aldrich 97%) was recristallized from distilled water. The obtained yellow needles were dried over P_4O_{10} under reduced pressure.

All solvents - acetonitrile (MeCN: J.T. Baker 99.8%), nitromethane (MeNO$_2$: Aldrich 96+% HPLC grade), propylene carbonate (PC: Sigma Aldrich 99% reagent grade), dimethyl sulfoxide (DMSO: Sigma Aldrich ≥99.9%), propionitrile (EtCN: Sigma Aldrich 99%), acetone (Ac$_2$O: Merck 99%) - were dried by the corresponding molecular sieve, distilled and stored under nitrogen atmosphere.

The supporting electrolytes tetrabuthylammonium tetrafluoroborate (Fluka 98% purum) and sodium perchlorate (Fluka 98% puriss. p.a.) were dried at 350K under vacuum for at least 8h and stored under nitrogen atmosphere.

Properties of the solvents containing 0.1 M of supporting electrolyte were determined at 295K from three individual measurements with an error <1% on the final values. The temperature was controlled by a home build external thermal bath. Density was measured with a L-Dens density transmitter from Anton Paar Company (Graz, Austria) and kinematic

viscosity with a Ubbelohde viscosimeter Type 50103/0c from Schott Company (Germany).

EPR Spectra are recorded with an ELEXSYS E-500 spectrometer from Bruker equipped with a cylindrical HSW10010 high resolution resonator, a digital temperature control unit and an electrochemical flow through system. Inside the resonator a quartz capillary with an inner diameter of 0.8 mm is mounted. The thermo-sensor is placed directly at the glass capillary´s surface.

Our cylindrical two-electrode electrochemical cell is positioned between the magnet´s pole gaps, directly before the ESR-resonator. It is equipped with a flexible carbon mesh counter electrode and a carbon fibre working electrode which are contacted by a tungsten wire. To fill the cell with a supporting electrolyte solution before starting any experiment, the outer camber is contacted to a peristaltic pump that can be disconnected by two simple valves.

Both storage flasks - one for the solution to fill the outer chamber and one containing the sample - can be degassed before the measurements by bubbling nitrogen through the solutions. The nitrogen is saturated with solvent vapour before entering the flask to avoid concentration changes in the samples by evaporation of the solvent.

All tubing is made from Teflon with very low oxygen permeability. Moreover, the tube connecting storage flask and electrochemical cell is mantled by a silicon tube. A stream of dry nitrogen in between these two tubes minimizes oxygen diffusion through the Teflon-tube itself.

Constant nitrogen pressure is used to press the solution through the system. The actual flow rate is adjusted with a screw valve and monitored by a shielded GF-2060 flowmeter from Gilmont Instruments.

All measurements were performed at 295K at X-Band (approx. 9.3 GHz) with a modulation amplitude of 0.5 G and repeated at least three times.

In each solvent we started from 0.5 mM NHPI. The potential is chosen to ensure almost quantitative conversion for this starting point. Now the flow rate was optimized to get the maximum ESR-signal, which was obtained with flow rates of around 0.5 ml/min. This optimal flow rate was kept constant in all experiments in one specific solvent. For higher concentrations of NHPI the concentration of PINO• was controlled upon adjusting the potential. The concentration of the electro-generated radical [PINO•] in [mol l^{-1}] is determined by Faraday´s law which is given in equation 4.

$$[PINO] = \frac{1}{6*10^4 \, nF} * |I| * \frac{1}{u} \quad (4)$$

Here n is the number of electrons transferred per molecule, F the Faraday constant in [A s mol^{-1}], I the current in [A] and u the flow rate which is usually measured in [cm^3 min^{-1}]. The factor $6 * 10^4$ transfers u in SI units. Due to self-decomposition [PINO•] is decreasing with time.[22] The concentration we detect is a compromise between the generation of radical (proportional to I and u^{-1}) and its decay, which is not appearing in Faraday´s law, but dependent on the flow rate nonetheless.

At higher concentrations up to 20 mM of NHPI ultrasonic was used to dissolve it faster. The concentration of supporting electrolytes was always 0.1 M. Finally the radical concentration was checked by double integration of the first derivative spectra. Deviations of less than 5% on the double integral were tolerated. Under this condition the experimentally determined rates are independent of the actual radical concentration.

Results and discussion

A typical resolved EPR-Signal of PINO• consists of nine lines. The obtained hyperfine splitting constants are shown in table 1.

Table 1 Obtained hyperfine splitting constants

Solvent	a_{1N} [G]	a_{2H} [G]
Ac$_2$O	4.72	0.44
DMSO	5.04	0.46
EtCN	4.78	0.47
MeCN	4.77	0.46
MeNO$_2$	4.83	0.49
PC	4.85	0.48

They vary little with the solvent and are comparable to previously published ones.[22,30,31]

In DMSO and PC we observed additional inhomogeneous broadening from rotational anisotropy. The high field line in these spectra is approximately 50 mG broader than the low
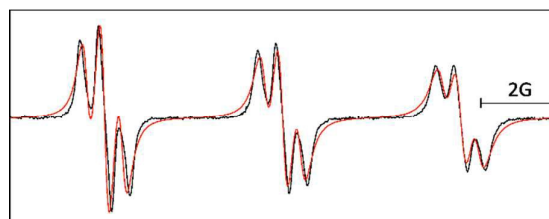
field one. An exemplary spectrum in DMSO is displayed in figure 3.

Fig 3 ESR spectra of 0.5 mM PINO in PC with 0.1 M TBA BF$_4$ (black) and corresponding simulation (red)

According to the Heisenberg uncertainty principle excess of NHPI broadens the lines, since the lifetime of the observed excited spin states decreases with increasing hydrogen atom
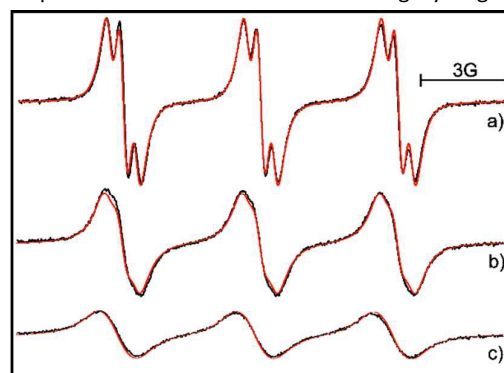
transfer rates. The largest effect was found in MeCN/NaClO$_4$ which is displayed in figure 4.

Fig 4 ESR spectra (black) of a) 0.5 mM PINO in MeCN with 0.1 M NaClO$_4$ b) with 10 eq. NHPI and c) with 20 eq. NHPI and corresponding simulations (red)

In order to obtain the peak to peak line widths ΔB_{PP} experimental spectra were fitted with fixed hyperfine couplings and the assumption of perfect Lorentzian line shape. For inhomogeniously broadened spectra each line was analysed individually. Subtracting the line width of the spectrum without excess of NHPI ΔB_{PP}^0 from the line width of the broadened ones yields the additional broadening. This is plotted versus the concentration of NHPI in figures 5 and 6. Figure 5 shows the data from a series of experiments in different solvents, figure 6 from experiments in MeCN with different supporting electrolytes.
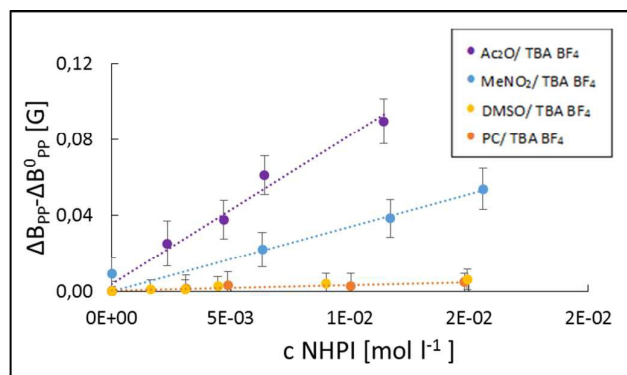

Fig 5 Plot of additional line broadening versus concentration of NHPI in different solvents with 0.1 M of TBA BF$_4$
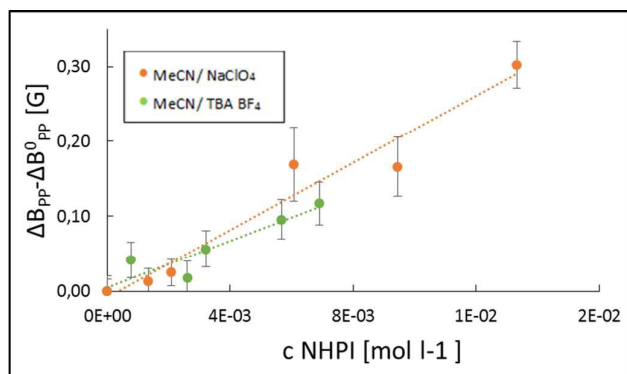

Fig 6 Plot of additional line broadening versus concentration of NHPI in MeCN with 0.1 M of different supporting electrolytes

The data shows a linear relation between the line broadening and the concentration of neutral NHPI. This is analysed by use of the modified Bloch equations.[32-34] From the slope of these plots an observed rate constant k_{obs} is obtained according to equation 5 which is valid in the region of slow exchange.

$$\Delta B_{PP} = \frac{(1-p_i)\,k_{obs}}{\pi\sqrt{3}\,\gamma_e}[NHPI] + \Delta B_{PP}^0 \quad (5)$$

γ_e denotes the gyromagnetic ratio of a free electron. The statistical factor p_i considers non-reactive collisions of equivalent spin states which is sufficiently approximated by 1/3.

Since k_{obs} is the rate of the overall process it must be corrected for diffusion to obtain real values of k_H. Solving the kinetic equations for the mechanism in figure 1 under the assumption of steady state conditions for precursor und successor complex and a non-zero rate constant for hydrogen atom back transfer k-H one yields equation 6. The resulting k_H is therefore independent of the activated process of association and dissociation.

$$\frac{1}{k_H} = \frac{1}{k_{obs}} - \frac{2}{k_{diff}} \quad (6)$$

k_{diff} was obtained from the simplified Smoluchowski equation 7. Hereby we assume that the change of the reactants radii due to one hydrogen atom for the comparably large molecule is not significant.

$$k_{diff} = \frac{8RT}{3\eta} \quad (7)$$

The dynamic viscosities η of the solvents containing supporting electrolyte were measured for the low viscous solvents – where a significant influence is expected - to get accurate values of k_{diff}. They were obtained from the quotient of the kinematic viscosity v and the density ρ. All measured and calculated values at 295K are summarized in table 2.

Table 2 Experimental density, kinematic and dynamic viscosity of solvents containing 0.1 M of supporting electrolyte

Medium	ρ [g/ml]	v [mm²/s]	η [Pa s]
MeCN/ NaClO$_4$	0.7857	0.4809	0.3779
MeCN/TBA BF$_4$	0.7512	0.5679	0.4266
Ac$_2$O/ TBA BF$_4$	0.7926	0.4410	0.3495
MeNO$_2$/ TBA BF$_4$	1.1280	0.5982	0.4150
DMSO/ TBA BF$_4$	1.0938	2.0138	2.2027
PC/ TBA BF$_4$	1.1966	2.3293	2.7873

The change of a solvent´s dynamic viscosity with the concentration of supporting electrolyte is described by the classical Jones-Dole equation.[35] Further we observed significant changes upon interchanging the supporting electrolyte in MeCN. Since diffusion can be interpreted as an activated process of changing place, this effect is readily explained by the significant difference in size of the cations. The more bulky TBA obstructs the solvent molecule´s motion more, thus the dynamic viscosity is larger.

Table 3 summarizes the obtained rate constants.

Table 2 Experimental rate constants

Medium	k_{obs} [M^{-1} s^{-1}]	k_{diff} [M^{-1} s^{-1}]	k_H [M^{-1} s^{-1}]
MeCN/ NaClO$_4$	5.69E+08	1.73E+10	6.09E+08
MeCN/TBA BF$_4$	3.53E+08	1.53E+10	3.70E+08

Ac$_2$O/ TBA BF$_4$	1.80E+08	1.87E+10	1.84E+08
MeNO$_2$/ TBA BF$_4$	6.40E+07	1.58E+10	6.46E+07
DMSO/ TBA BF$_4$	9.14E+06	2.97E+09	9.19E+06
PC/ TBA BF$_4$	6.18E+06	2.35E+09	6.21E+06

The error on these was determined with values less than ±10%. The main source of error is attributed to the uncertainty in line width which is arising from several issues. There are additional dynamics that broaden the lines, such as Heisenberg exchange which is dependent on the radical concentration. As mentioned in the experimental section we have to measure and control I and u carefully in our experiments. Further the double integral as indicator for the concentration has its error due to integration over the noise on the baseline. Moreover the modulation itself has an impact on the observed line width. This is only problematic if the broadening effect is small. Finally solubility of the reactant is determining for the statistical significance of the results.

In figure 7 we plot the values of k_H versus η^{-1}. As discussed before the observed linear relation is expected since were comparing self-exchange rates of one reactant.
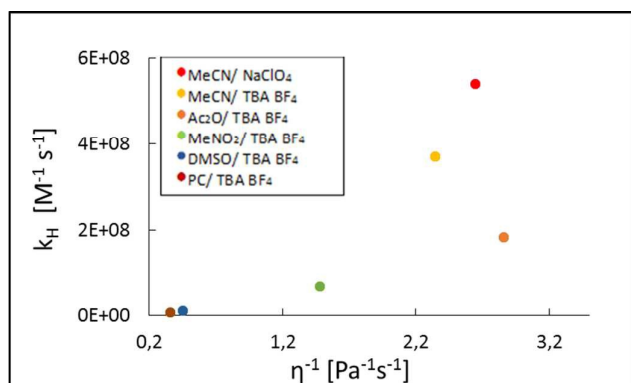

Fig 7 Plot of k_H versus η^{-1}

However, this data indicates that the dynamic viscosity is not the only factor influencing the rate, since the rates measured in acetonitrile are significantly faster than the ones in the other series of solvent. However, these rates appear to follow the same η^{-1} trend within each other. We tested bulkier supporting electrolytes such as tetraoctylammonium tetrafluoroborate, however the change of η was insignificant. We suggest that the chemical properties that determine interaction of medium and reactant are a factor that has to be considered as well.

Finally we tried to include more aprotic organic solvents. Within the limit of the solubility of NHPI we tested the following. In tetrahydrofurane and dimethylformamide no EPR-signal could be detected at all and in propionitrile insufficient signal-to-noise ratios were obtained.

Conclusions

We successfully demonstrated that CW-EPR line broadening experiment can be used to determine rate constants of hydrogen atom self-exchange. Due to the experiments time resolution it is especially useful to study highly reactive radicals that react in the fast regime >10^6 M^{-1} s^{-1} of hydrogen atom transfer reactions.

Further our data agrees with Alexandrov and Gol´danskii´s theory on the reorganization of the medium. The motions that adjust the medium to the change of the reactant´s size and volume are limited by its dynamic viscosity which appears in the preexponential factor.

Moreover we found a deviation from a strictly linear relation for the rates in acetonitrile compared to the other solvents. The explanation of this effect is subject of future work.

Acknowledgements

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