H/D-EXCHANGE REACTIONS OF EUGENOL AND 2-METHYLNAPHTHALENE IN DEUTE-RIUM OXIDE AT HIGH TEMPERATURES AND PRESSURES

Jarno Kalpala, Kari Hartonen and Marja-Liisa Riekkola
Laboratory of Analytical Chemistry, Department of Chemistry, University of Helsinki
P.O. Box 55, FIN-00014 University of Helsinki, Finland

The dramatic changes in properties of water (H_2O) near the critical point make high temperature water an interesting alternative for organic solvents as a reaction medium. In this paper, deuterium oxide (D_2O) at high temperature (200-450°C) was used to study the deuteration of eugenol and 2-methylnaphthalene. Reactions were carried out in bomb-type reactors made of stainless steel and Hastelloy® C-22. Reaction product were analysed with gas chromatograph-mass spectrometry (GC-MS). Deuteration of eugenol and 2-methylnaphthalene was examined in pure D_2O and in D_2O with several acid, base, salt and metal catalysts. Also deuterated acid and base catalysts, deuterium chloride (DCl) and sodium deuteroxide (NaOD) were used, respectively. At its best, high (100%) deuteration efficiencies with different deuteration states were achieved with 2-methylnaphthalene. With eugenol, relatively good deuteration efficiency was achieved at lower temperatures using only D_2O without any catalyst. Occasionally only insignificant amounts of by-products were detected in GC-MS -analysis.

1. Introduction

Water at room temperature is a very polar solvent with high dipole moment and dielectric constant. These parameters are greatly affected by temperature. Increase in temperature of H_2O will decrease the dielectric constant and solubility parameter values and result in lower viscosity and surface tension, less hydrogen bonding and generally better solubility of less polar compounds and to same extent, worse solubility of more polar compounds. Near the critical temperature of H_2O, there are also dramatic changes in density and in water's ionic dissociation constant. Below the critical temperature K_w increases at the constant pressure, as temperature increases (Marshal and Franck, 1981). On the contrary, beyond critical temperature K_w decreases as temperature increases (Marshal and Franck, 1981). These changes in water's properties, as temperature increases, makes organic compounds and gases fully soluble in supercritical water, i.e. $T>T_c$ (374.1^{o}C) and $P>P_c$ (218.3 atm), which makes possible to conduct reaction in one phase. There are also few weaknesses when using water at high temperature. Of course higher the temperature is the more oxidative conditions we have in water. Additionally, corrosion is one thing that should not be forgotten. High temperature water itself is corrosive, but especially very basic or acidic conditions, high concentration of dissolved

oxygen or presence of inorganic species like Cl⁻-ions makes water a very corrosive environment at high temperature and pressure (Gloyna and Li, 1995)

Similarly to H_2O, deuterium oxide (D_2O) at high temperature and pressures can be used as a reaction solvent. D_2O has slightly higher melting and boiling points (3.8^oC and 101.4^oC respectively) than H_2O, but lower critical temperature (371.5^oC) and pressure (214.4 atm). Concentrations of the DO^- and D_3O^+ ions are increased with the temperature (Yao and Evilia, 1994), and therefore certain acid or base catalysed reactions, that are not possible in normal conditions, can be done in supercritical or near critical conditions (Yao and Evilia, 1994). For example, H-D exchange reactions can be easily performed in pressurised hot deuterium oxide and supercritical deuterium oxide (Yao and Evilia, 1994). In supercritical or high temperature D_2O, it is possible to selectively deuterate (Boix and Poliakoff, 1999) or perdeuterate (Junk et al., 1997) different organic compounds in high yield with insignificant by product formation (Boix and Poliakoff, 1999). Also it is possible to affect to reaction efficiency, reaction rate and selectivity by adjusting temperature (Yang and Evilia, 1999), pressure, pH (Yao and Evilia, 1994 and Yang and Evilia, 1999) or by using catalyst (Junk and Catallo, 1997).

In this study, deuterium oxide at high temperature (200-450^oC) was used to research the deuteration of eugenol and 2-methylnaphthalene. Deuteration of the two compounds was studied with pure D_2O and D_2O with several acid, base, salt and metal catalysts at different reaction conditions. Deuterated acid catalyst (deuterium chloride, DCl) and deuterated base catalyst (sodium deuteroxide, NaOD) were also. Two different self-made reactors were used during the research.

2. Experimental

Deuteration reactions were performed in self-made bomb-type reactors. Initially reactors were made of stainless steel and later Hastelloy® C 22 was used as a reactor material. Volumes of the reactors were approximately 3ml. Reactors with reagents were heated with a gas chromatograph oven. Oven temperature was monitored via two separate thermocouples, one connected to an empty reactor and another to one of the reactors with reagents inside.

To avoid very high pressures maximum amount of D_2O used was 45% of reactor volume. For the same reason, amount of D_2O and to same extent the amounts of other reagents were decreased to half (23%) in reactions made at 450 °C. Reaction time count was started after reactor reached reaction temperature and reactor (plus oven) temperature was kept constant during the whole reaction time. The pressure of reaction mixture at high temperature was evaluated with NIST/ASME Steam Properties program (Formulation for General and Scientific Use, Standard Reference Database 10 Version 2.01,USA).

After cooling down, eugenol was extracted and diluted with dichloromethane and 2-methylnaphthalene with n-heptane and both samples were dried with Na_2SO_4. Each experiment was repeated 3 times (n=3).

A gas chromatograph-mass spectrometer (GC-MS) equipment was used for reaction product analysis. Deactivated retention gap was used in front of the analytical column (25 m HP-5 with 0.2 mm i.d.). MS (EI) was operated in scan mode and ion chromatograms subtracted from TIC were used to calculate deuteration degree and TIC was used to estimate the amount of deuteration by-products.

3. Results and discussion

3.2. Eugenol

With eugenol, effect of reaction temperature, reaction time, different reactors and amount of D_2O on deuteration efficiency were examined. Reaction temperatures 200, 250, 300 and 350°C were investigated. Raising the reaction temperature clearly improved deuteration efficiency of eugenol and moved deuteration level distribution towards higher deuteration degrees At lowest temperature, at least monodeuterated eugenol was gained while at 250 and 300°C tri-and tetradeuterated eugenol were obtained. Although highest temperature (350°C) lead eugenol to decompose, 1-3 hydrogens could be easily exchanged selectively without any catalyst at lower temperature.

Reaction time had only small impact to deuteration efficiency. Also reactor material had only small effect on reaction efficiency of eugenol. Dideuterated eugenol was received as the main product with stainless steel and Hastelloy C 22. Unlike reaction time and reactor material, relative amount of D_2O was found to have a great effect on deuteration efficiency (Figure 1). With lower D_2O volumes, the amount of D_2O limits the equilibrium of the reaction and thus, the deuteration efficiency is low and deuteration distribution profile is descending. With higher D_2O volumes the profile changes to ascending and the distribution moves toward higher deuteration levels.
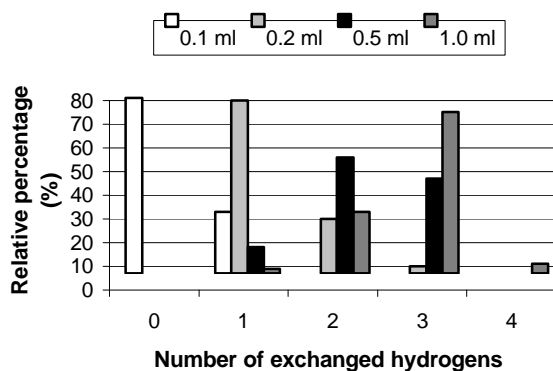

Figure 1. Effect of D_2O amount on deuteration distribution of eugenol. Reaction time 2h, m(eugenol)=50mg, T=250°C and n=3. Exceptionally, 2.2ml fully closed extraction vessel (Keystone Scientific, Bellefonte, PA, USA) was used as a reactor.

For eugenol and with pure D_2O up to four hydrogens can be exchanged with deuterium. Using acid catalysts led eugenol to decompose. Basic catalysts were not studied in this research, but because eugenol is a fenolic (acidic) compound, these would certainly be

worthwhile of trying. %RSD-values were 1-11% with stainless steel reactors and 4-17% with Hastelloy® C 22 reactors.

3.3. 2-Methylnaphthalene

With 2-methylnaphthalene, effects of reaction temperature and reaction time were investigated. Also different acid, base, salt and metal catalysts as well as the amount 2-methylnaphthalene were examined.

As in reactions with eugenol, different reaction times (2, 4 and 6h), gave practically same kind of deuteration distribution in presence of HCl-catalyst, at 350ºC. With all reaction times, heptadeuterated 2-methylnaphthalene was main reaction product and octadeuterated 2-methylnaphthalene was the highest deuteration level. In all cases undeuterated and monodeuterated 2-methylnaphthalene were not gained. Unlike with eugenol, increase in temperature clearly improved deuteration efficiency of 2-methylnaphthalene and moved deuteration distribution towards higher deuteration levels (Figure 2).
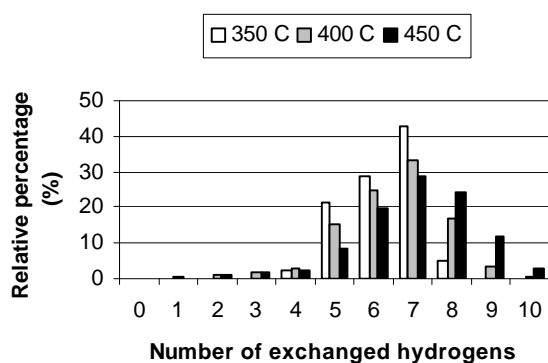

Figure 2. Effect of reaction temperature to deuteration distribution of 2-methylnaphthalene. At 350ºC and 400ºC t_r*=2h, m(2-methylnaphthalene)=68.2 mg, V(HCl)=6.8µl and V(D$_2$O)=1.36ml. At 450ºC reagent amounts were halved.* n=3.

Because deuteration reaction is an equilibrium reaction, it is conceivable that the amount of 2-methylnaphthalene relative to D_2O amount would affect deuteration efficiency. Using three different amounts, the effect of 2-methylnaphthalene amount on deuteration efficiency were explored. Decreasing the amount of 2-methylnaphthalene moves deuteration distribution (and reaction equilibrium) toward higher deuteration states in reactions without catalyst (Figure 3). The same phenomenon is also observed in minor scale with acid catalyst. With catalyst the difference between two lowest amount of 2-methylnaphthalene was very small, which indicates that the equilibrium cannot be pushed much further in these conditions by lowering the amount of 2-methylnaphthalene.

With Pt (8.2mg) catalyst, tetradeuterated 2-methylnaphthalene as a main product and heptadeuterated as highest deuteration degree were gained. Palladium might also be a good choice for catalyst, but unfortunately it was not available for this work
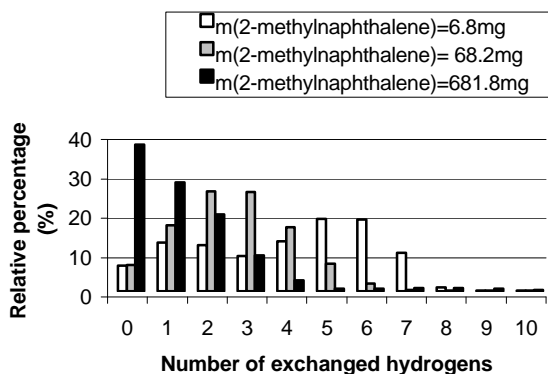

Figure 3. Effect of 2-methylnaphthalene amount on deuteration efficiency. T=350ºC, tᵣ=2h, n=3.

With acid and base catalysts, one could easily affect to the reaction equilibrium and push it further to more complete deuteration. Reactions with base catalysts resulted more highly deuterated 2-methylnaphthalene than those with acid catalysts. Reactions with deuterated acid and base catalysts instead of the regular ones had same effect on deuteration distribution. With acid catalyst, the reaction occurs via arenium ion mechanism and with base reaction follows S_E1 mechanism (Smith, M.B. and March, J, 2001). With optimal reaction conditions and with NaOD as a catalyst, over 50% of initial 2-methylnaphthalene was perdeuterated (Figure 4). Identical deuteration distribution was gained with Na_2CO_3 as a catalyst already at 400ºC (Figure 4). This similarity in reaction efficiency with NaOH, Na_2CO_3 and NaOD arises from reaction of Na_2CO_3 with water where NaOH is formed as reaction product (Karamäki, E.M., 1983) and NaOH finally acts as a catalyst.

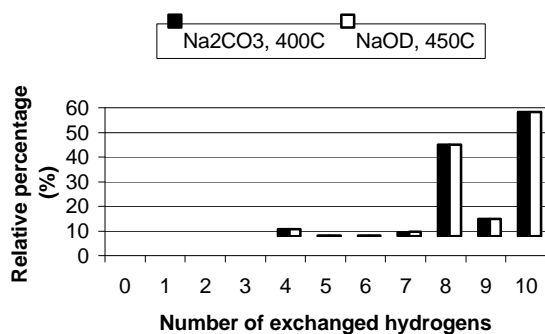*Figure 4. Deuteration distribution of 2-methylnaphthalene with NaOD and Na_2CO_3 catalyst. With Na_2CO_3,* T=400ºC, tᵣ=2h, V(D₂O)=1.36ml m(2-

methylnaphthalene)=68.2mg, V*(Na$_2$CO$_3$)=2.7mg and* n*=3. With NaOD,* T*=450ºC,* t$_r$*=2h,* V*(D$_2$O)=0.660ml* m*(2-methylnaphthalene)=3.4mg,* V*(NaOD$_{40\%}$)=22.3µl and* n*=3.*

4. Conclusions

Supercritical or pressurised hot water is an effective reaction media for acid-base reactions. Possibility to affect solvent properties, by controlling temperature and pressure enables adjusting reaction efficiency and selectivity with temperature and pressure. Fast deuteration with deuterium oxide at high temperature and pressure was achieved for eugenol and 2-methylnaphthalene. With eugenol, 1-3 hydrogens could be easily exchanged selectively without any catalyst. Basic catalysts were not investigated and acid catalysts caused eugenol to decompose. Deuteration of 2-methylnaphthalene was clearly enhanced by acid and base catalyst. Even better results could be obtained by using hydrogen free reagents like NaOD and DCl instead of NaOH and HCl. All hydrogen atoms can be easily exchanged with deuterium by using base catalyst. With both researched compounds, reaction time had only a small impact on deuteration efficiency and deuteration reaction reached equilibrium in less than two hours. Relative amount of 2-methylnaphthalene had a great effect on deuteration efficiency. Decreasing the amount of 2-methylnaphthalene moved reaction equilibrium toward higher deuteration levels. The average %RSD for reactions with eugenol in stainless steel reactor was 9% ranging from 1.0 to 52%. For 2-methylnaphthalene %RSD was 33%, ranging from 0.1% to 205%. Reactions in Hastelloy C 22 reactors gave 22% as average %RSD for 2-methylnaphthalene, ranging from 0.7% to 77%. For eugenol average %RSD was 10%, ranging from 4% to 58%. Since equilibrium of the reaction regulates reaction, it is not possible to perdeuterate 2-methylnaphthalene with 100% efficiency even under in optimal reaction conditions. For that reason we are going to concentrate on dynamic deuteration of eugenol and 2-methylnaphthalene in future.

5. Acknowledgements

6. References

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