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On Sonochemical Effects on the Diels−Alder Reaction

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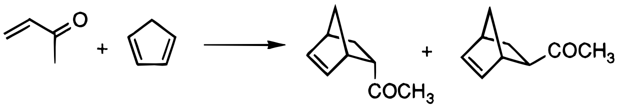
Introduction

The first published example of an ultrasound-assisted Diels−Alder reaction involved a nonvolatile quinone and various dienes.[1] The interpretation given by the authors has been recently criticized by Javed et al.[2] who pointed out that the reaction was performed on heterogeneous systems which means that mechanical effects of ultrasound could be at the origin of the observed optimization.

In homogeneous conditions, there are only two published cases[2,3] of Diels−Alder reactions accelerated by ultrasound whereas one reaction has been reported to be insensitive to ultrasonic irradiation.[4]

During our work, we studied the possible influence of ultrasound on the rate and the stereoselectivity of the classical cycloaddition reaction between cyclopentadiene (CPD) and methyl vinyl ketone (MVK).



Experimental Section

Solvents and reactants of the highest purity grade were purchased from Aldrich Chemical Co. excepting cyclopentadiene-*d*-6 which was synthesized following the procedure of Lambert and Finzel.[5]

The 20 kHz ultrasonic irradiation was performed by using a Chemsonic generator developed in our laboratory and equipped with a titanium immersion horn. During an additional experiment, a Deltasonic cleaning bath was used to generate a 28 kHz indirect irradiation.

The acoustic intensity, higher than the transient cavitation threshold, was carefully controlled, and the bulk temperature was adjusted at 10.0 °C. Initial concentrations of both diene and dienophile were 0.2 mol L^{-1}. Reactions were performed under air and in a 30 cm^3 glass vessel. Each experiment was repeated at least three times.

Yields and [endo]/[exo] ratios were measured by vapor phase chromatography, using a 5 m column filled with 10% carbowax 20M on chromosorb P (45−60 mesh).

Results and Discussion

As Table 1 shows, yield and stereoselectivity are increased by ultrasonic irradiation in chlorinated and brominated solvents whereas they are not affected in nonhalogenated solvents. Typical kinetic curves obtained from silent and sonochemical experiments in dichloromethane as solvent are given in Figure 1.

Table 1. Influence of Ultrasonic (US) Irradiation on the Yield and [Endo]/[Exo] Ratio in Various Organic Solvents

	yield[a] (%)		[endo]/[exo][a]	
solvent	silent	US	silent	US
CH_3OH	17 ± 1	17 ± 2	11.5 ± 0.5	11.5 ± 0.5
$C_6H_5CH_3$	3 ± 1	3 ± 1	5.0 ± 0.3	4.9 ± 0.3
$CHCl_3$	7 ± 1	15 ± 2	7.2 ± 0.4	12.7 ± 0.5
CH_2Cl_2	4 ± 1	18 ± 2	6.7 ± 0.3	15.5 ± 0.5
CH_2Br_2	7 ± 1	58 ± 3	6.5 ± 0.3	19.5 ± 0.6

[a] After 1 h at 10 °C.

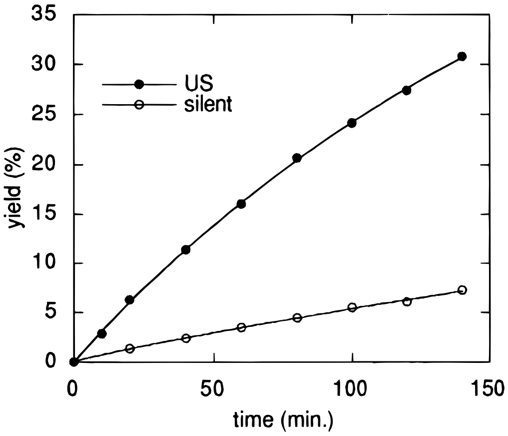


Figure 1. Reaction kinetics in CH_2Cl_2 as solvent in silent and sonochemical conditions (T = 10 °C).

Reactions were performed in strictly homogeneous solutions, and we are forced to conclude that we are in presence of clear-cut sonochemical effects in $CHCl_3$, CH_2Cl_2, and CH_2Br_2. The occurrence of these effects in halogenated solvents only suggests that solvent molecules take a prominent part in the sonochemical pathway. To confirm this assumption, additional experiments have been performed in dichloromethane.

A possible explanation could be that direct sonication of halogenated molecules by a titanium horn leads to the formation of Lewis acids ($TiCl_4$, $TiBr_4$) known to catalyze the studied Diels−Alder reaction.[6] In a control experiment, a sealed tube was immersed in a thermostated cleaning bath in order to avoid direct contact between the solution and the ultrasonic transducer. In these conditions, increases of rate and stereoselectivity are still observed, precluding the hypothesis of an artefact due to an in situ generation of a Lewis acid derived from the titanium horn.

Then, a set of experiments was performed in presence of 2,2-diphenyl-1-picrylhydrazyl (DPPH). This stable free radical has often been used to scavenge radicalar species generated under ultrasonic irradiation.[7] Our experimental results are listed in Table 2.

In sonochemical conditions, the reaction rate and stereoselectivity are strongly reduced in presence of DPPH and fall down to the values observed in silent conditions for the highest DPPH concentration. We can therefore conclude that, in halogenated solvents, sonication promotes the generation of free radicals which affect the Diels−Alder reaction rate. In our experimental conditions, this alternative sonochemical route is faster

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Table 2. Influence of DPPH on the Yield and [Endo]/[Exo] Ratio in CH_2Cl_2 as Solvent

[DPPH] (mmol L^{-1})	yield[a] (%)		[endo]/[exo][a]	
	silent	US	silent	US
0	4 ± 1	18 ± 2	6.7 ± 0.3	15.5 ± 0.5
0.8	4 ± 1	15 ± 1	6.4 ± 0.2	14.5 ± 0.4
8	4 ± 1	4 ± 1	6.5 ± 0.2	6.5 ± 0.3

[a] After 1 h at 10 °C.

Table 3. Influence of Hydrogen Chloride on the Silent Yield and [Endo]/[Exo] Ratio in CH_2Cl_2 as Solvent

solvent treatment	yield[a] (%)	[endo]/[exo][a]
1 h presonication	15 ± 1	13.5 ± 0.3
+ HCl (5×10^{-3} mol L^{-1})	10 ± 1	12.6 ± 0.4

[a] After 1 h at 10 °C.

and more stereoselective than the silent one, giving rise to a global increase of the yield and of the [endo]/[exo] ratio.

It is well known that the sonolysis of haloalkanes leads to the homolytic cleavage of C−X bonds.[8] Taking into account the small amount of DPPH (less than 1% of the reactants concentration) which is sufficient to quench the sonochemical effect, it was tempting to imagine a radical chain pathway, activated in sonochemical conditions only, involving a two-step addition of a cyclopentadienyl free radical[9] on MVK. To make a long story short, this assumption was rejected on the basis of experiments performed with perdeuterated CPD.

We finally considered the possibility of an acid catalysis of the Diels−Alder reaction by the hydrogen halide coming from the sonolysis of the solvent molecules followed by a hydrogen abstraction.[10] The kinetic and stereochemical aspects of the acid catalysis of Diels−Alder reactions involving the protonation of dienophiles possessing carbonyl groups can be rationalized on the basis of the frontier molecular orbital theory.[11] Results listed in Table 3 fully confirm the catalytic effect of hydrogen chloride on the reaction under study. Indeed, the presonication of the solvent or the solubilization of a small quantity of gaseous HCl in CH_2Cl_2 before starting the reaction led to kinetic and stereochemical effects similar to those obtained by ultrasonic irradiation (see Table 1).

Conclusion

We have demonstrated a clear-cut effect of ultrasound on a Diels−Alder reaction in various halogenated solvents. Nevertheless, it must be pointed out that ultrasound does not affect the cycloaddition itself but promotes the in situ generation of a hydrogen halide which acts as catalyst. We suggest that the same interpretation must be tested in other cases described in literature.[2]

The sonochemical effect we observed is indirect and, in some way, trivial. A lot of work remains necessary to determine which reactions are sensitive to ultrasound. In many cases ultrasound acts by mechanical effects (which could be described as a very efficient stirring) or by generation of radicals acting as catalysts[12] or via the in situ formation of molecules which themselves are catalysts (the present case). If the yield of a silent reaction is n% after a definite period of time while the yield of the corresponding sonochemical reaction is m%, a ratio m/n higher than 1 is described as a sonochemical effect. It is interesting to observe that m/n depends on n. It means that if the silent reaction (especially a heterogeneous reaction) is performed without stirring or with an inefficient stirring (like those generally obtained with a magnetic stirrer) or if the silent reaction is performed in the absence of a catalyst which can be generated by ultrasound, it is obvious that a sonochemical effect must be observed. Nevertheless, in these two cases, the specificity of ultrasound must be questioned. A full paper on this important question in sonochemistry is in preparation.

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[9] Coming from an hydrogen abstraction by the halogen atom.

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