

CHLORINATION OF 2,3-DICHLOROTETRAHYDROFURAN

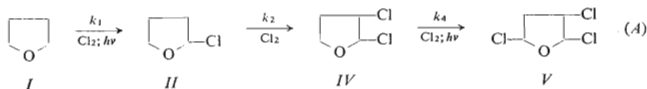
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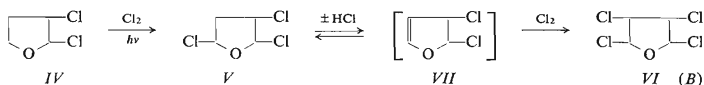
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The comparison of chlorination kinetics of 2,3-dichlorotetrahydrofuran and tetrahydrofuran at 20°C–80°C using gas-liquid chromatography proved the formation of 2,3,5-trichlorotetrahydrofuran to be a consecutive radical process which in a further step gives rise to 2,3,4,5-tetrachlorotetrahydrofuran. The overall reaction rate, as well as the activation energy, enthalpy and entropy for the individual reaction steps were determined.

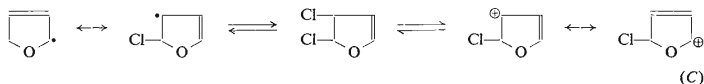
The factors determining substitution of hydrogen atoms in the radical chlorination of ethers, first of all the effect of temperature (*e.g.* in dialkyl ethers^{1,2}, or cyclic ethers, such as 1,4-dioxane³, 1,3-dioxolan⁴ and tetrahydropyran⁵) operate also in the polychlorination⁶⁻⁸ of tetrahydrofuran (*I*). Since 2,3-dichlorotetrahydrofuran (*IV*) is an intermediate in the formation of 2,3,5-trichlorotetrahydrofuran (*V*) by radical chlorination of *I*, we studied the course of the photochlorination of *I* to *V* via *IV* in tetrachloromethane at 20°C and 40°C (Scheme *A*). This reaction was compared with an independently studied analogous chlorination of *IV* to 2,3,4,5-tetrachlorotetrahydrofuran (*VI*) at 20°C–80°C via *V*. The chlorination of *I* at temperatures above 20°C gives practically no 2,5-dichlorotetrahydrofuran (*III*) which at lower temperatures accompanies the product *IV* and in certain cases even predominates in the reaction mixtures. It was proved⁹ that compound *IV* arises from 2-chlorotetrahydrofuran (*II*) by elimination of HCl, *i.e.* via 2,3-dihydrofuran on which chlorine is added. Analogously, we may anticipate that the chlorination of compound *IV* proceeds according to Scheme *B*.



* Part XII in the series Reactions of Chlorinated Furanidines; Part XI: This Journal 37, 1908 (1972).



Naturally, the course of the chlorination of *IV* as depicted by Scheme *B* is not the only possibility. Another possible way may be *e.g.* simple radical substitution of hydrogen in the position 4 in compound *IV*. On the basis of labelling with ^{36}Cl we have shown that chlorination of *V* resulted in a predominant retention of ^{36}Cl in the compound whereas the arising HCl contained only small amount of the radioactive chlorine. The suggested reaction course of the type *B* is supported by the fact that the structure *VII* (Scheme *B*) may split off the quasi-allylic chlorine since the arising radical (or ion) can be stabilized by non-bonding orbital delocalisation (Scheme *C*). This process can lower the overall activation energy E_5 (the reaction *V*–*VI*) as compared with E_2 (reaction *II*–*IV*); this is evident from the results of the measurements.



The unequivocal course of chlorination of the compound *IV* to *V* under described conditions is indicated also by comparison with the other position isomers of trichlorotetrahydrofuran by means of IR and NMR spectroscopy and also by a chemical proof. The IR-spectra of *V*, 2,3,4-trichlorotetrahydrofuran and 2,3,3-trichlorotetrahydrofuran (prepared according to ref.¹⁰) differ substantially in the C—H and C—C region, as well as in the 600–800 cm^{-1} region where the influence of halogen atoms on the skeletal vibrations¹¹ is usually observed. The hydrolysis of *V* gave no α -chloro- γ -butyrolactone, excluding thus the 2,2,3-trichlorotetrahydrofuran structure. The structure of compound *VI* was confirmed by the identity of its IR-spectrum with the spectrum of the compound prepared by chlorination of *I* to *III* and further to *VI* at higher temperature⁹. Also the results of gas-liquid chromatographic analysis were relevant (Kovats' index 1280, the isomers were not separated under conditions of measurement). Thus, the structures of compounds *V* and *VI*, anticipated in a series of previous papers, are confirmed, as well as their supposed mode of formation^{7,9,12}.

The photo-catalyzed chlorination of compound *IV* to *VI* via *V* was followed experimentally at 20°C–80°C. The experimental conditions, kinetic analysis and mathematical description of the changes of this system are described in a previous communication⁹; the recent treatment is simpler in that it does not involve the competitive

reaction leading to the compound *III*. The obtained values of the overall reaction rate are listed in Table I. The ratio of the reaction rates, $p = k_4/k_5$, was calculated from the determined maximum content of the compound *V* using the equation (I).

$$([V]/[IV]_0)_{\max} = p^{1/(1-p)}. \quad (I)$$

The difference between the activation energies of the chlorinations $IV \rightarrow V$ and $V \rightarrow VI$: $E_5 - E_4 = 3.5 \pm 0.3 \text{ kcal mol}^{-1}$, was obtained from the modified Arrhenius equation.

In the analysis of the chlorination $I \rightarrow II \rightarrow IV \rightarrow V$ the new results were combined with the values obtained previously⁹. During the reaction the amount of the compound *II* increases till a maximum concentration is attained and then it decreases giving rise to the product *IV*, the concentration of which passes also through a maximum. This model can be described as a three-step consecutive competitive process with two intermediates which has been already mathematically treated¹³⁻¹⁶. The derivation of relations for the calculation of ratios of the reaction rates, $q = k_1/k_2$ and $s = k_2/k_4$, from the maximum concentration of intermediates, *i.e.* *II* and *IV*, has made it possible to calculate the numerical values of q and s . The mathematical relations are relatively complicated and therefore the calculations were carried out using a computer. The overall reaction rate constants k_1 , k_2 and k_4 are valid for the reaction steps shown in Scheme A, k_5 is the overall rate constant of the chlorination of compound *V*. The values k_1 and k_2 published previously⁹ for the temperatures 20°C and 40°C were used in the calculation of k_4 from the values s and of k_5 from

TABLE I

The Maximum Conversion of the Intermediate Based on the Starting Compound, and the Calculated Values of Rate Constants (min^{-1})

°C	$([V]/[IV]_0)_{\max}$ $([V]/[I]_0)_{\max}$	p	q s	$10^3 \cdot k_1$ $10^3 \cdot k_2$	$10^5 \cdot k_4$ $10^5 \cdot k_5$
20	0.750 ± 0.038	6.45 ± 0.32	0.780 ± 0.030	16.13 ± 1.48	65.39 ± 14.79
	0.85 ± 0.05		34.20 ± 11.22	20.70 ± 1.27	10.16 ± 1.54
40	0.739 ± 0.037	4.86 ± 0.24	0.193 ± 0.008	7.94 ± 0.80	92.11 ± 16.93
	0.75 ± 0.05		46.69 ± 11.63	41.19 ± 2.78	18.99 ± 2.34
60	0.707 ± 0.035	3.55 ± 0.18	—	—	131.4 ± 29.6
	—		—	—	33.7 ± 5.1
80	0.652 ± 0.033	2.22 ± 0.11	—	—	175.5 ± 39.5
	—		—	—	55.5 ± 8.4

$p = k_4/k_5$. The calculation was then extended to other temperatures using the Arrhenius relation. The overall activation energy for the step $IV \rightarrow V$ is $E_4 = 6.79 \pm 0.97$ kcal mol⁻¹ and for $V \rightarrow VI$ $E_5 = 9.22 \pm 0.50$ kcal mol⁻¹. The value of their difference is not far from the value obtained by calculation from p ($E_{5-4} = 2.74$ kcal mol⁻¹). For the individual reaction steps following thermodynamic values were found: $\Delta H_1^\ddagger = 7.56$ kcal mol⁻¹, $\Delta H_2^\ddagger = 24.34$ kcal mol⁻¹, $\Delta H_3^\ddagger = 8.83$ kcal mol⁻¹, $\Delta H_4^\ddagger = 6.21$ kcal mol⁻¹, $\Delta H_5^\ddagger = 8.64$ kcal mol⁻¹, $\Delta S_1^\ddagger = -45.1$ e.u., $\Delta S_2^\ddagger = -12.7$ e.u., $\Delta S_3^\ddagger = -41.5$ e.u., $\Delta S_4^\ddagger = -56.1$ e.u., $\Delta S_5^\ddagger = -51.5$ e.u. The values with the index 3 refer to the reaction $II \rightarrow III$ which was discussed in the previous communication⁹.

EXPERIMENTAL

Methods

The chlorination vessel, reaction conditions and analysis were described in the previous communication⁹. In the chlorination of *I* (105 ml, 1 mol) the chlorine was introduced at a constant rate 125 ml/min as a mixture with dried nitrogen. The samples were taken at 30 min intervals. The chlorination with radioactive ³⁶Cl was carried out at 140°C; chlorine was liberated from Na³⁶Cl by treatment of Na³⁶Cl with manganese dioxide and sulphuric acid. The chlorine was introduced by carbon dioxide through a drying tube with CaCl₂ into a flask containing compound *V* (1.5 ml). From this flask the gas was passed through a reflux condenser into an absorber containing Na₂CO₃ in which HCl was trapped. The ³⁶Cl activity measurements were carried out on liquid samples in glass ampoules using a Tesla NAG 232 counter with a well-type scintillation crystal NaI (Tl), and a VAM-15-D computer (Vakutronik, Dresden). The used Na³⁶Cl (The Radiochemical Centre, Amersham, England) had specific activity 0.036 mCi/g. A standard was prepared from 40 mg Na³⁶Cl, the counting rate of which was $3.0 \cdot 10^4$ c.p.m.; its solution in water (2 ml) had $1.8 \cdot 10^4$ c.p.m. The total amount used in an experiment was 1.2 g Na³⁶Cl with a counting rate $8.9 \cdot 10^5$ c.p.m. After carrying out the experiment, the counting rate of the aliquot parts of the liquid residue in the chlorine generator, chlorinating flask and absorber was measured. The respective counting rates based on the total volumes are $3.9 \cdot 10^5$, $2.2 \cdot 10^4$ and $6.0 \cdot 10^3$ c.p.m. The IR-spectra were taken on a UR 10 Zeiss spectrometer in the region 4000–400 cm⁻¹ in demountable cells (film). The NMR spectra were taken on a Tesla BS-478 A spectrometer (80 MHz) at 26°C, using hexamethyldisiloxane as internal standard. The compounds were measured in 10% tetrachloromethane solutions and the spectra were characterised by their shape as well as by the chemical shift (δ -scale) of the protons. The relative integrated areas of the bands were in accord with the number of the corresponding protons in the measured compounds.

Compounds

2,3-Dichlorotetrahydrofuran (*IV*) was prepared by chlorination of *I* at 20°C. The crude product was distilled under reduced pressure and redistilled after several days, b.p. 59.5–60.0°C/16 Torr; n_D^{20} 1.4833; d_4^{20} 1.3271; NMR spectrum: 6.2 p.p.m. (H_α), 4.5 p.p.m. (H_β), 4.2 p.p.m. (H_{α'}), 2.1 p.p.m. (H_{β'}). 2,3,5-Trichlorotetrahydrofuran (*V*) was prepared by photochlorination of *IV* at 40°C, using 1.2 mol Cl₂ for 1 mol of *IV*, and distilled three times, b.p. 70.0°C/8 Torr; n_D^{20} 1.5061; d_4^{20} 1.5178; NMR spectrum: 6.2 p.p.m. (H_α), 6.0 p.p.m. (H_{α'}), 4.6 p.p.m. (H_β), 3.0 p.p.m.

(H_{β}). 2,3,4,5-Tetrachlorotetrahydrofuran (VI) was obtained by chlorination of IV at 140°C, using 2.5 mol of Cl_2 for 1 mol of IV, and three times distilled *in vacuo*; b.p. 80–81°C/9 Torr; n_D^{20} 1.5078; NMR spectrum: 6.6 p.p.m. ($H_{\alpha,\alpha'}$), 4.5 p.p.m. ($H_{\beta,\beta'}$). 3-Chlorotetrahydrofuran was synthesized according to ref.¹⁴; b.p. 59–61°C/30 Torr; n_D^{20} 1.4545; d_4^{20} 1.1632; NMR spectrum: 4.3 p.p.m. (H_{β}), 3.8 p.p.m. ($H_{\alpha,\alpha'}$), 2.1 p.p.m. ($H_{\beta'}$). 3,4-Dichlorotetrahydrofuran was prepared according to ref.¹⁵; b.p. 55–57°C/11 Torr; n_D^{20} 1.4873; d_4^{20} 1.3635; NMR spectrum: 4.3 p.p.m. ($H_{\alpha,\alpha'}$), 3.9 p.p.m. ($H_{\beta,\beta'}$). 2,3,3-Trichlorotetrahydrofuran was prepared by dropwise addition of IV (0.5 mol) to diethylaniline (1 mol) at 170°C. The arising 4-chloro-2,3-dihydrofuran was removed by a stream of nitrogen, trapped in a cooled receiver and then distilled under nitrogen (b.p. 71°C/200 Torr; yield about 10%). The distillate was diluted with a five-fold volume of tetrachloromethane and chlorinated at 5°C with a mixture of chlorine and nitrogen till the solution decolorized. The tetrachloromethane was removed under reduced pressure and distillation gave about 1 ml of product, boiling at 78°C/10 Torr; n_D^{20} 1.4943; d_4^{20} 1.4785. 2,3,4-Trichlorotetrahydrofuran was prepared by photochlorination of 3,4-dichlorotetrahydrofuran at –25°C; b.p. 93°C/22 Torr; n_D^{20} 1.5070; d_4^{20} 1.5433; NMR spectrum: 6.0 p.p.m. (H_{α}), 4.6 p.p.m. (H_{β}), 4.3 p.p.m. ($H_{\alpha',\beta'}$).

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