

## Electrophilic Attack on the Furan Ring

### Acid-Catalysed Protododeuteration, Protodetrutiation, Deuteriodeprotonation, and Deuteriodetrutiation at the $\alpha$ -Position. Hydrolytic Cleavage of the Ring

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Rates of acid-catalysed  $\alpha$ -hydrogen exchange reactions in 2-methylfuran have been measured. Both the observed isotope effects and the activation parameters display all the characteristics of the  $A-S_E2$  mechanism of aromatic hydrogen exchange. The subsequent acid-catalysed decomposition reactions were nearly two powers of ten slower than the  $\alpha$ -hydrogen exchange reactions.

The possible mechanisms of the ring cleavage are discussed. Experiments conducted with furan, 2-methylfuran, and 2,5-dimethylfuran revealed that, with the exception of 2,5-dimethylfuran, polymeric products are formed in subsequent reactions almost exclusively. Evidence was also collected which showed that these polymer-forming reactions occurred predominantly prior to hydrolytic cleavage of the ring. The latter reaction, which is significant in the case of 2,5-dimethylfuran only, could be best explained in terms of a rate-determining protonation at the  $\beta$ -position.

Acid-catalysed exchange of the isotopes of hydrogen in aromatic systems provides the most elementary model of electrophilic aromatic substitution.<sup>1-5</sup> In all cases studied hitherto, the aromatic systems have not undergone further reactions. This has been a great advantage for the study of the isotope effects themselves and for drawing general conclusions about the nature of electrophilic aromatic substitution. Similar detailed studies of less stable  $\pi$ -electron systems have not been reported. Apart from their interest for permitting comparisons with systems of high stability, they may be expected to give some mechanistic information about the subsequent decomposition of the ring systems.

Our particular system of interest is the furan ring. Furan and its derivatives, although stabilized by their aromaticity, undergo acid-catalysed decomposition reactions much more readily than their sulphur analogues, the

thiophens.<sup>3,6</sup> It was found in a preliminary study of the protodeuteriation of 2-methylfuran by dilute perchloric acid<sup>7</sup> that this compound exchanges its  $\alpha$ -hydrogen at a rate that is roughly two powers of ten higher than that of the subsequent reaction. Similar results have been reported for unsubstituted furan<sup>8</sup> in 4.6 to 7.2 M perchloric acid solutions, although under these conditions the protodeuteriation rate was only 7 times higher.

The above results<sup>6-8</sup> demonstrate that the rate-determining stage in the hydrolytic cleavage of the furan ring cannot be proton transfer from the catalyst acid to the  $\alpha$ -carbon atom of the ring as originally proposed by Stamhuis *et al.*<sup>9</sup> In contrast to the conclusions drawn by Unverferth and Schwetlick,<sup>8</sup> we do not see any argument by which the above results excluded the possibility of a mechanism involving a rate-determining  $\beta$ -protonation in the cleavage of the ring. The only relevant observation (agreeing with ours) was that no  $\beta$ -hydrogen exchange was detected *prior* to further reactions. The nature of the further reactions had not been studied in detail. The only kinetic quantity thus far measured for these reactions has been the rate of decrease of the concentration of the initial reactant, the furan. Possible side reactions competing with the hydrolytic cleavage of the ring have not been discussed.

2-Methylfuran was chosen as the model compound for the isotope exchange studies because this compound has only one exchangeable  $\alpha$ -hydrogen atom, that present at the 5-position. Furthermore, a comparison of our earlier results<sup>7</sup> and those obtained for unsubstituted furan<sup>8</sup> revealed that 2-methylfuran is more suitable for these studies, as the subsequent reactions are relatively much slower for this compound and do not thus interfere with the isotope exchange measurements. In addition, the decomposition reactions of furan, 2-methylfuran, and 2,5-dimethylfuran were studied under various conditions by performing kinetic measurements and analysing the reaction products.

## EXPERIMENTAL

*Materials.* Furan, 2-methylfuran, and 2,5-dimethylfuran were purified as described earlier.<sup>6,7</sup>

The  $\alpha$ -deuteriated form of 2-methylfuran, 2-methylfuran-5-*d*, was prepared by two methods, both of which yielded identical products. In the first method, 32 g of nondeuteriated 2-methylfuran was dissolved in 200 ml of deuterium oxide – dimethyl sulphoxide solvent in which the mol fraction of each component was 0.5 and which contained 0.04 mol of perchloric acid as catalyst and a small amount of hydroquinone to prevent polymerization. The mixture was kept at 100°C and the progress of the  $\alpha$ -deuteriation reaction was followed by PMR spectroscopy. Equilibrium was attained in about 2 h, when about 85 % of the  $\alpha$ -protons had been replaced by deuterons. No deuteriation at the  $\beta$ -position was detected. The crude product, which still contained a substantial proportion of the  $\alpha$ -protium compound, was then extracted with five 30 ml portions of pentane. The combined extract, to which a small amount of hydroquinone had been added to prevent polymerization, was dried with anhydrous potassium carbonate. After the solution had been separated from the drying agent by filtration, the solvent was distilled off through an efficient column.

The above procedure was then repeated, but using the crude 2-methylfuran-5-*d* as starting material. This treatment yielded a product in which 95 % of the  $\alpha$ -protons had been replaced by deuterons. Further deuteriation was not considered to be justified economically, for the initial hydrogen isotope composition in the  $\alpha$ -position was actually immaterial in kinetic studies of the dedeuteriation reaction, except that the deuterium content had to be sufficiently high in order that significant changes in the  $\alpha$ -D/ $\alpha$ -H ratio

could be measured during the course of the reaction. The 95 % deuteriated product was fractionally distilled. The physical constants recorded for the purified product were b.p. 62.0°/760 torr,  $n_D^{20}$  1.4324,  $d_4^{20}$  0.9277. The PMR spectrum of a 10 % solution of the product in carbon tetrachloride containing tetramethylsilane as internal standard showed: 1 H at  $\delta$  5.85 ppm (3-hydrogen), 1 H at  $\delta$  6.13 ppm (4-hydrogen), and 3 H at  $\delta$  2.27 ppm (2-methyl protons). A trace of a peak of 5-protons was observed at  $\delta$  7.18 ppm, and it was calculated from the area of this peak that the ratio of the 5-protons to the total number of 5-hydrogens was about 0.05. The IR spectrum of the purified product was also recorded using carbon tetrachloride again as solvent. When this spectrum was compared with that of the corresponding protocompound, 2-methylfuran-5-*h*, strong peaks were observed at 730, 920, and 1150  $\text{cm}^{-1}$  in the spectrum of the latter compound, but only traces of these peaks could be seen in the spectrum of 2-methylfuran-5-*d*. In the spectrum of the deuteriocompound, the corresponding peaks had been shifted at frequencies that were lower by factors of about 1.4.

The second method by which 2-methylfuran-5-*d* was prepared was to use a two-phase system consisting of 2-methylfuran and heavy water. The volume of the aqueous phase, which was about 1 M in deuteriochloric acid, was approximately ten times that of the organic phase. Hydroquinone was added as before. The reaction vessel was placed in a bath at 50°C and agitated vigorously by means of a mechanical arrangement. At suitable intervals, the agitation was discontinued and the phases were allowed to separate. A sample of the furan phase was then analysed by PMR spectroscopy. It was found that under the chosen conditions, the  $\alpha$ -hydrogen exchange had reached equilibrium in 2 to 3 h. The crude product was then separated, and the procedure was repeated as in the first method. The product thus obtained was dried and purified by fractional distillation. The physical constants of the purified compound were almost equal to those obtained for the product prepared by the first method. Furthermore, no significant differences were found in kinetic quantities for the two preparations.

2-Methylfuran which was tritium-labelled at the  $\alpha$ -position was prepared by the second method described above as this was found to be somewhat more convenient. The water phase consisted of 200 ml of 1 M hydrochloric acid in ordinary water to which about 20 mCi of tritiated water had been added. The product, after purification by repeated fractional distillation, had the same physical constants (and gave the same PMR and IR spectra) as the unlabelled 2-methylfuran.

The deuterium oxide used was supplied by Norsk Hydro-Elektrisk Kvaelstofaktieselskab, Norway. It was of the same batch as that used in a study of the solubilities of some salts in heavy water.<sup>10</sup> The deuterium atom fraction determined by a method described earlier<sup>11</sup> was 0.9982. Tritium-labelled water was supplied by The Radiochemical Centre, Amersham, England. Dimethyl sulphoxide was a product of E. Merck AG, Darmstadt, West Germany, which was purified by boiling under reflux over calcium hydride for 12 h, by fractional distillation under reduced pressure and by repeated recrystallization.

*Kinetic measurements.* Depending on the isotopes of hydrogen which participated in the  $\alpha$ -hydrogen exchange reaction of 2-methylfuran, different methods were used to follow the progress of the reactions. The rates of the protodeuteration and deuterioprotonation reactions were in most cases followed by a PMR method based on measuring the rate of appearance or disappearance of the 5-proton signals. The PMR spectra were recorded on a Perkin-Elmer R10 60 MHz spectrometer at 33.5°C. In some control experiments, which gave consistent results, an IR method was employed to study the protium-deuterium exchange at the 5-position. The IR spectra were measured with a Perkin-Elmer Grating Infrared Spectrometer. In the study of the detritiation reactions a Wallac Decem-NTL-314 liquid scintillation counter was used.

When the PMR method was used, the intensity of the signal of the 5-protium atom was measured at suitable intervals. To eliminate the effect of possible fluctuations in the recorded intensities, the intensities were always compared with the intensity of a standard signal. In the present case, it was found that the signal of the 4-proton was an excellent standard, because this proton remained unaffected during the isotope exchange. The signal of the 4-proton is also in the same region of the magnetic field (see above) as that of the 5-proton whose appearance or disappearance was being followed. Thus the ratio of the peak areas for the 5- and 4-protons was proportional to the progress of the dedeuteriation or deprotonation reaction. A further advantage was that, even if some decom-

position of the furan occurred during the isotope exchange measurements (which decomposition was very slow indeed, as shown below), the kinetic quantities measured in this way were independent of whether subsequent reactions took place or not.

Owing to the low solubilities of the furans, the kinetic experiments were run in mixtures of dimethyl sulphoxide and protium or deuterium oxide in which the mol fraction of each component was always 0.500. The concentration of the catalyst perchloric acid varied from 0.180 to 0.190 M in different experiments. After the 2-methylfuran had dissolved in the solvent, aliquots of the reaction mixture were sealed in 10 to 15 PMR sample tubes. The tubes were immersed simultaneously in an oil bath which was held at the desired temperature (70 to 100°C). The first sample was taken after about 15 min, and subsequent samples at intervals during the period when 10 to 80 % change occurred. The final samples were taken after about 8 to 10 times the half-lives of the reactions. All sample tubes were stored in an ice-water bath until the last sample had been taken and were then analysed in close succession. The reactions followed simple first-order kinetics.

When the reactions were followed by the IR method, 5 ml samples of the initial reaction mixture were sealed into glass vials, which were then kept at a constant temperature in a thermostat. The samples were analysed as follows. After a vial had been opened, its contents were carefully rinsed into a separatory funnel using always the same volume (0.6 ml) of water. Ten ml of hexane was added, whereupon the 2-methylfuran present distributed itself between the hexane and water-dimethyl sulphoxide phases. The hexane layer was dried with anhydrous magnesium sulphate and analysed. The IR spectra were recorded in sodium chloride cells. The reference cell was filled with hexane. The progress of the reaction was followed by measuring peak heights at 730, 920, and 1150  $\text{cm}^{-1}$  (see above) using reference standard solutions prepared by dissolving weighed quantities of 2-methylfuran-5-*h* in known volumes of hexane.

In the detritiation studies, the procedure was similar to that described above except for the analyses, for which 2 ml samples of the hexane layers were pipetted into the vials of the liquid scintillation counter. The scintillation liquid comprised 4 g of diphenyloxazole and 100 mg of *p*-bis-(*o*-methylstyryl)-benzene dissolved in 1 l of toluene. The volume of the scintillation liquid added to each sample was 8 ml. First-order rate coefficients were calculated from the measured activities of the samples. A small empirical correction (about 3 % of the overall activity change measured during the reaction) was applied to the final samples taken after ten half-lives. Unlike the samples taken in the earlier stages of the reaction, the final samples and also their hexane extracts were light yellow. This caused a slight quenching, which had to be corrected for in the liquid scintillation analysis in order to obtain as accurate values as possible. The empirical correction for this colour quenching was determined by running a reaction with nontritiated 2-methylfuran under the same conditions. Equal amounts of tritiated 2-methylfuran were added to the hexane extracts and the counts per minute were recorded.

*Decomposition of the furan ring and product analyses.* The rates of subsequent reactions that followed the relatively fast  $\alpha$ -hydrogen exchange reactions were also measured under identical conditions. Similar kinetic experiments were also run with 2,5-dimethylfuran. Regardless of the particular nature of the reaction, the rate of decrease of the concentration of the furan in question could be easily measured by the PMR techniques described above, by following the disappearance of the signal of the 5-proton (in case of 2-methylfuran) or of the signals of 3- and 4-protons (in case of 2,5-dimethylfuran). In most experiments, a protium oxide-dimethyl sulphoxide (mol fraction 0.500) mixture was used as solvent. The concentration of the catalyst perchloric acid was the same, about 0.2 M, as in the isotope exchange studies. Samples taken at suitable intervals were analysed as follows. The unchanged furan and the soluble reaction products were extracted into carbon tetrachloride, to which 0.4 vol. % of tetramethylsilane had been added as an internal standard for the PMR analyses. In separate experiments, it was established by gas chromatography that at least 98 % of the unchanged furan was extracted from the sample solution. The peak areas in the PMR spectra were then compared with those of the internal standard and the first-order rate coefficients were calculated.

In the case of 2-methylfuran, no hydrolysis products were detected by PMR or by gas chromatographic analyses. The only product of the reaction was a polymeric compound which was insoluble in the solvents employed. In contrast, acetylacetone was formed almost quantitatively from 2,5-dimethylfuran under the experimental con-

ditions. Thus the rate of formation of acetylacetone could be measured (from the PMR spectrum) simultaneously with the rate of decomposition of 2,5-dimethylfuran; both rates were almost equal.

Similar product analyses were also made using other solvents. For example, the reactions of furan and 2-methylfuran in water containing 0.2 mol of perchloric acid per litre as catalyst were studied. No traces of nonpolymeric reaction products were detected in either case.

For the applications to be discussed below, it was of interest to carry out some experiments that would indicate at what stage of the acid-catalysed solvolytic decomposition of the furan ring the polymerization actually takes place. If the polymerization occurred only *after* the cleavage of the ring, the overall rate of disappearance could be set equal to the rate of the ring cleavage. In contrast, if the polymerization (or, at least, a significant part of it) were a side reaction competing with the cleavage reaction, then the rate of the latter reaction would be but a small fraction of the overall rate. A solvent in which this distinction could be made was ethanol. The products of ring cleavage in this solvent are  $\alpha,\delta$ -diacetals, which, unlike the  $\alpha,\delta$ -dicarbonyl compounds formed in water, cannot undergo further reactions in this solvent. In these experiments, furan, 2-methylfuran, and 2,5-dimethylfuran were dissolved in ethanol which contained 0.2 mol of perchloric acid per litre. The reaction mixtures were sealed in glass vials and held at 100°C. The samples were analysed by gas chromatography. It was found that, while 2,5-dimethylfuran yielded the respective diacetal at the same rate at which its concentration decreased with time, only traces of diacetals (less than 2% of the amounts of substrate that had reacted) were detected among the reaction products formed from furan and 2-methylfuran. Thus it could be concluded that the main route to polymeric products in the ethanolysis was *via* side reactions *prior* to ring cleavage and that the polymerization was much more marked with unsubstituted furan and 2-methylfuran than with 2,5-dimethylfuran. Similar conclusions can be drawn about the reactions in aqueous solvents, for, as shown above, the tendencies of different furans to polymerize under acidic conditions in various solvents are very similar. Quite naturally, the (probably very small amounts of) dicarbonyl compounds first formed by the cleavage of furan or 2-methylfuran in the latter solvents may polymerize later.

## RESULTS AND DISCUSSION

*Acid-catalysed exchange of the isotopes of hydrogen.* The isotopically different systems studied were similar to those Kresge and Chiang<sup>12</sup> employed in their investigation of hydrogen exchange in 1,3,5-trimethoxybenzene. The initial compositions were: *A*,  $\text{FuD} + \text{HClO}_4$  in  $\text{H}_2\text{O}$ ; *B*,  $\text{FuT} + \text{HClO}_4$  in  $\text{H}_2\text{O}$ ; *C*,  $\text{FuH} + \text{DClO}_4$  in  $\text{D}_2\text{O}$ ; *D*,  $\text{FuT} + \text{DClO}_4$  in  $\text{D}_2\text{O}$ ; here Fu denotes the radical derived from 2-methylfuran by removal of the  $\alpha$ -hydrogen atom. Owing to the low solubility of 2-methylfuran in water, the kinetic experiments were run in water-dimethyl sulphoxide mixtures in which the mol fractions of water were 0.500. The concentration of the catalyst perchloric acid was about 0.2 M throughout. The first-order rate law yielding rate coefficients proportional to the molar concentration of the catalyst acid was accurately obeyed at the concentrations used.

The average values of the rate coefficients are collected in Table 1. As described in the experimental section, the slow subsequent reactions did not interfere with the measurement of the rate coefficients for the  $\alpha$ -hydrogen exchange reactions. Most of the values in the table are average values from several replicate runs. The values for the detritiation reactions derived by the liquid scintillation counting method were the most accurate. The relative standard errors of these values usually did not exceed 1%, whereas those for

Table 1. Second-order rate coefficients for the acid-catalysed exchange of the isotopes of hydrogen at the  $\alpha$ -position in 2-methylfuran.

Substrate	Reaction	$t$ °C	$10^3 \times k(\text{M}^{-1} \text{s}^{-1})$
2-Methylfuran-5- <i>d</i>	Protododeuteriation	70	0.196
		80	0.423
		90	0.950
		100	2.86
2-Methylfuran-5- <i>t</i>	Protodetrition	70	0.117
		80	0.290
		90	0.817
		100	1.95
2-Methylfuran-5- <i>h</i>	Deuteriodeprotonation	70	0.483
		80	1.18
		90	2.68
		100	6.27
2-Methylfuran-5- <i>t</i>	Deuteriodetrition	70	0.171
		80	0.445
		90	1.092
		100	2.55

the deprotonation and dedeuteriation reactions that were followed by PMR or IR techniques were in the worst cases as large as 4 %.

The plots of the logarithms of the rate coefficients against reciprocal temperature are shown in Fig. 1. Except for the protododeuteriation of 2-methylfuran-5-*d*, the Arrhenius equation seems to be satisfactorily obeyed. However, owing to the similar nature of the reactions studied, there is no reason to believe that the apparent deviation from the Arrhenius equation is real—it is more likely due to experimental errors. In fact, the experimental data for

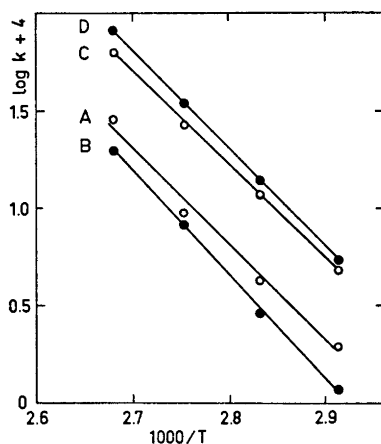


Fig. 1. Arrhenius plots for the acid-catalysed exchange of isotopes of hydrogen in 2-methylfuran. (A) Protododeuteriation, (B) protodetrition, (C) deuteriodeprotonation, (D) deuteriodetrition ( $\log k + 4.5$ ).

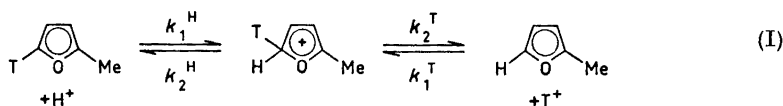
the dedeuteriation reaction were the least accurate of the data for the four reactions investigated.

The parameters of activation calculated by the method of least squares on the assumption that the Arrhenius equation is valid are given in Table 2. The last column of the table gives the values and standard errors of the rate coefficients at 70°C as calculated by the least squares method.

Table 2. Activation parameters and rate coefficients at 70°C for  $\alpha$ -hydrogen exchange in 2-methylfuran.

Reaction	$E(\text{kcal/mol})$	$\Delta S^\ddagger(\text{cal K}^{-1} \text{mol}^{-1})$	$10^3 \times k^{70}(\text{M}^{-1} \text{s}^{-1})$
Protodedeuteriation	$22.5 \pm 1.8$	$-12.5 \pm 5.1$	$0.179 \pm 0.024$
Protodetrition	$24.1 \pm 0.6$	$-8.6 \pm 1.7$	$0.1134 \pm 0.0030$
Deuteriodeprotonation	$21.7 \pm 0.2$	$-12.9 \pm 0.7$	$0.479 \pm 0.009$
Deuteriodetrition	$22.9 \pm 0.0$	$-11.3 \pm 0.1$	$0.1713 \pm 0.0004$

Extensive studies of the acid-catalysed exchange of hydrogen atoms attached to aromatic nuclei indicate that the exchange mechanism is a simple two-step  $A-S_E2$  mechanism.<sup>12,13</sup> As exemplified by the protodetrition, this mechanism may be written for the furan system as follows:



As the solvent hydrogens (protons or deuterons) are always present in great excess, the reversal of the second step need not be considered. As the reaction intermediate is an unstable species that is present in very low concentration, the steady state principle is applicable. This gives

$$(k_{\text{obs}})^{\text{HT}} = k_1^{\text{H}} / (1 + k_2^{\text{H}}/k_2^{\text{T}}) \quad (1)$$

for the protodetrition reaction. Similar equations can be written for the other three exchange systems studied. The four equations thus obtained contain four unknown quantities,  $k_1^{\text{H}}$ ,  $k_1^{\text{D}}$ ,  $k_2^{\text{H}}/k_2^{\text{D}}$ , and  $k_2^{\text{H}}/k_2^{\text{T}}$ . An exact solution is therefore possible.

The above analysis does not take into account secondary isotope effects.<sup>12,14</sup> Several methods, all of which give only approximate results, have been proposed. In their study of 1,3,5-trimethoxybenzene, Kresge and Chiang<sup>12</sup> made use of the Swain relations<sup>15</sup> to reduce the number of unknown quantities in the equations that resulted when the secondary effects were taken into account. Owing to the low precision of our values for the dedeuteriation reaction, a

similar method would give but very crude approximations. Gold<sup>16</sup> and Streitwieser and Van Sickle<sup>17</sup> proposed values from 1.15 to 1.17 as appropriate multipliers to calculate values of  $k_2^H/k_2^D$  from experimental ones, and Bell<sup>18</sup> proposed a factor of 1.25 for the corresponding secondary effect in  $k_2^H/k_2^T$ .

As an explicit consideration of the secondary isotope effects would require experimental values of a very high level of accuracy, no attempt is made here to determine their absolute magnitudes. Instead, uncorrected values for the isotope effects are calculated from eqn. (1) and similar equations for the other systems studied and compared then with similar uncorrected values determined for other aromatic systems. Such a comparison is possible in Table 3.

Table 3. Kinetic isotope effects in aromatic hydrogen exchange reactions.

Substrate	$k_1^H/k_1^D$	$k_2^H/k_2^D$	$k_2^H/k_2^T$	Ref.
1,3,5-Trimethoxybenzene	2.9	6.7		19
Azulene	4.3	9.2		13
Guaiazulene		6.0	14	14
4,6,8-Trimethylazulene		9.6	26	14
Guaiazulene-2-sulphonate		7.4	18	14
2-Methylfuran	3.1	6.2	14	This work

The calculations indicated that much more accurate values could be derived for the isotope effects if only three of the equations of type (1) were used, namely one for deuteriodeprotonation, one for deuteriodetrutiation, and one for protodetrutiation, for which the most accurate experimental values were available. This method of calculation necessitated the use of the Swain relations<sup>15</sup>

$$k^H/k^T = (k^H k^D)^{1.442}; \quad k^D/k^T = (k^H/k^D)^{0.442} \quad (2)$$

The justification of this procedure could be studied by calculating a value for the rate coefficient of the protodeuteriation reaction and comparing this calculated value with the experimentally measured value. Values at 70°C obtained in this way are:

$$k_1^H = (1.71 \pm 0.10) \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}; \quad k_1^D = (0.556 \pm 0.011) \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$$

$$k_2^H/k_2^D = 6.25 \pm 0.25; \quad k_2^H/k_2^T = 14.1 \pm 0.8$$

When these values were used to calculate the rate coefficient for the protodeuteriation reaction,

$$k^{\text{HD}} = k_1^H / (1 + k_2^H/k_2^D)$$

the result was  $k^{\text{HD}} = (0.236 \pm 0.016) \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$ . In view of the low accuracy of the dedeuteriation data, this value agrees satisfactorily with the value in Table 2. The agreement would have been excellent, as shown by calculations, if the rate coefficient for the dedeuteriation at 70°C had been omitted when making the least squares analysis. However, there was no justification for



doing this, for the rate coefficients at the different temperatures had similar standard errors.

It can be seen from Table 3 that the kinetic isotope effects calculated for the furan system resemble closely those derived for other aromatic systems. It should be noted that the present values refer to a temperature of 70°C, whereas the other values given in the table were measured at 25°C. Calculations based on furan data at temperatures below 70°C indicated slightly greater isotope effects, although the extrapolation to temperatures outside the range where the actual measurements were performed made the calculated standard errors of the rate coefficients much larger than those in Table 2.

Table 4 contains values of the parameters of activation for various aromatic hydrogen exchange reactions. It will be seen that the lower reactivity of furan

Table 4. Parameters of activation for various aromatic protodetrutiation reactions.

Substrate	$\Delta H^\ddagger$ (kcal/mol)	$\Delta S^\ddagger$ (cal K <sup>-1</sup> mol <sup>-1</sup> )	Ref.
Azulene-1,3- <i>t</i>	15.4	-10.1	20
1,3,5-Trimethoxybenzene-2- <i>t</i>	15.6	-16.3	21
1,3-Dimethoxybenzene-4- <i>t</i>	21.5	-9.7	21
Thiophene-2- <i>t</i>	17.0	-14.6	3
2-Methylfuran-5- <i>t</i>	23.4	-8.6	This work

as compared with its sulphur analogue, thiophen, is primarily due to the relatively high enthalpy of activation. Thiophen also exchanges its  $\beta$ -hydrogens<sup>3</sup> at rates that are lower than the  $\alpha$ -hydrogen exchange by factors from 440 to 1200, depending on temperature and the acidity of the reaction solution. As described in the experimental section, similar  $\beta$ -hydrogen exchange without the occurrence of other reactions was not observed in the furans.

*Subsequent decomposition reactions of the furan ring.* The overall rates of disappearance of 2-methylfuran and 2,5-dimethylfuran in 50 mol % water-dimethyl sulphoxide solvent are given in Table 5.

Table 5. Rate coefficients for the decomposition of furans in water-dimethyl sulphoxide solvent (mol fraction of water = 0.500).

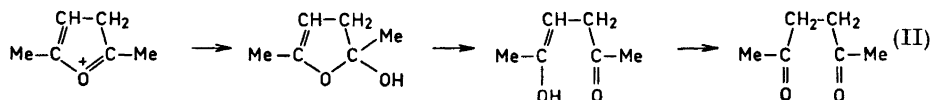
Substrate	°C	$10^5 \times k$ (M <sup>-1</sup> s <sup>-1</sup> )
2-Methylfuran	80	3.10
	90	6.12
	100	10.6
2,5-Dimethylfuran	70	4.46
	80	11.05
	90	27.6

As shown in the experimental section, polymerization reactions predominate over hydrolytic cleavage reactions with furan and 2-methylfuran, whereas only with 2,5-dimethyl furan is the overall decomposition rate approximately equal to the rate of formation of the cleavage product, acetylacetonone. Some experiments described above indicate also that these polymerization reactions are predominantly side reactions rather than reactions following cleavage of the ring. Another piece of evidence that these reactions are side reactions comes from the observation made earlier<sup>6</sup> that the rates of these reactions were enhanced when the reaction mixtures were exposed to ultraviolet light. It was found that if the reactions were carried out in the cell of an UV spectrophotometer, the decomposition rates increased by factors of 2 to 50 from the values measured when the reaction mixtures were kept in the dark. A normal type of acid-catalysed cleavage of the ring (by the *A*-1, *A*-2, or *A*-S<sub>E</sub>2 mechanism) would be hardly expected to be affected by light.

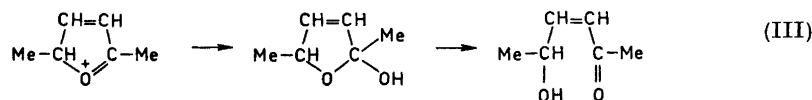
Our results are in harmony with experience in preparing  $\alpha,\delta$ -dicarbonyl compounds by the hydrolysis of furans.<sup>22,23</sup> Only 2,5-dimethylfuran, when treated under relatively mild conditions, gives good yields of the  $\alpha,\delta$ -dicarbonyl compound, whereas less substituted furans yield only polymeric products.

From the above results it can be concluded that the rate of hydrolytic cleavage of 2-methylfuran hardly exceeds 1% of the overall decomposition rate. As the latter is lower by a factor of nearly  $10^{-2}$  than the rate of the  $\alpha$ -hydrogen exchange reaction, the cleavage rate is some  $10^{-4}$  times lower than the rate of  $\alpha$ -hydrogen exchange. A rate of about this magnitude would be what one would expect for the  $\beta$ -protonation of the furan ring in view of the fact that the relative electrophilic reactivities of the  $\alpha$ - and  $\beta$ -positions differ more in the furan ring than in its sulphur analogue, the thiophen ring.<sup>24-26</sup>

Explanations based on ring cleavage following  $\alpha$ -protonation<sup>8,9</sup> have other difficulties to meet, whereas those based on  $\beta$ -protonation have not. In the latter case, irrespective of the particular mechanism of the cleavage reaction (be it *A*-1, *A*-2, or *A*-S<sub>E</sub>2), the  $\beta$ -protonated substrate is an oxonium-carbonium ion, which hydrolyses *via* a hemiacetal<sup>27</sup> to the  $\alpha,\delta$ -dicarbonyl compound. In the case of 2,5-dimethylfuran, the sequence of the reactions is



Similar reactions starting from the  $\beta$ -protonated substrate, which are assumed to be operative in the mechanisms proposed by Stamhuis *et al.*<sup>9</sup> and by Unverferth and Schwetlick,<sup>8</sup> would first lead to an unsaturated keto-alcohol,



If the ring cleavage really occurred by the last-mentioned route, one would have to postulate that the unsaturated keto-alcohol first formed rearranges

very rapidly to give the  $\alpha,\delta$ -dicarbonyl compound, acetylacetone in the case in question. However, no definite examples of such rapid rearrangements of keto-alcohols of this type are found in the literature. Furthermore, the solvolytic cleavage of 2,5-dimethylfuran in ethanol gives definitely the diacetal of acetylacetone, which is well understood to result from a reaction route similar to (II), but not if the reaction occurred *via*  $\alpha$ -protonation.

The slowness of hydrolytic decomposition reactions of alkylsubstituted furans renders the establishment of general acid catalysis experimentally difficult. However, in the case of a more reactive furan derivative, 2-methoxyfuran, involvement of general acid catalysis has been recently demonstrated.<sup>28</sup>

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