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ON THE ACTIVATION ENERGY FOR THE HYDROLYSIS OF BIS-(2-CHLOROETHYL) SULFIDE

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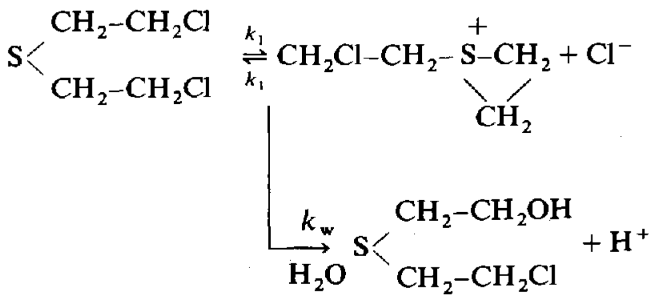
ABSTRACT

Mustard, bis-(2-chloroethyl) sulfide, hydrolyzes to form the mustard chlorohydrin with concomitant loss of chloride; the chlorohydrin subsequently hydrolyzes to form the mustard diglycol with loss of another chloride ion. The kinetics of these reactions constitutes two consecutive, irreversible reactions. Past investigators approximated the hydrolysis as a single, first-order reaction from which an activation energy was determined. Bartlett and Swain measured the rate of mustard chlorohydrin hydrolysis after which they could determine the rate of mustard hydrolysis with a graphical method. Bartlett and Swain performed their experiments at 25 °C, so no activation parameters were measured.

A non-linear least-squares program was modified to fit consecutive, irreversible first-order kinetics and refit original data for mustard hydrolysis in order to find activation parameters for each step. The data failed to conform to consecutive, first-order kinetics suggesting that either sampling error or failure to dissolve rapidly interfered with the kinetics. Thus, the activation parameters for mustard hydrolysis are incorrect not only for the single-step approximation, but also because systematic experimental errors must be present. Rate coefficients computed with Bartlett and Swain's data were statistically equivalent to their reported value of 0.155 min^{-1}.

INTRODUCTION

Mustard, bis-(2-chloroethyl) sulfides, hydrolyzes to produce mustard chlorohydrin and HCl after which the mustard chlorohydrin loses another chloride to form thiodiglycol and HCl. The mechanism of the hydrolysis involves the formation of ethylenesulfonium ions [1] as shown below.



$$\mathrm{S}\begin{matrix}\mathrm{CH_2{-}CH_2Cl}\\ \mathrm{CH_2{-}CH_2Cl}\end{matrix} \underset{k_1}{\overset{k_1}{\rightleftharpoons}} \mathrm{CH_2Cl{-}CH_2{-}\overset{+}{S}{-}CH_2 + Cl^-}\ (\text{ring } \mathrm{CH_2}) \xrightarrow[\mathrm{H_2O}]{k_w} \mathrm{S}\begin{matrix}\mathrm{CH_2{-}CH_2OH}\\ \mathrm{CH_2{-}CH_2Cl}\end{matrix} + \mathrm{H^+} \qquad (1)$$

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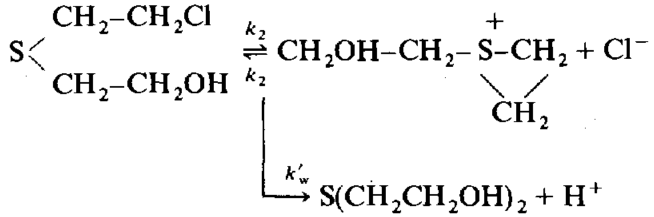

(2)

Since $k_w \gg k_{-1}$ and $k_w \ll k_{-2}$, each step appears as a first-order reaction with rate coefficients k_1 and k_2, respectively.

The rate of mustard hydrolysis was measured by monitoring the change in pH or conductance and the overall process was approximated as a single reaction with k determined from the initial part of the reaction [2–5]. Bartlett and Swain [6] attempted a direct measurement of k_1 by first measuring the hydrolysis of mustard chlorohydrin and then using the value of k_2 thus obtained with a graphical technique [7] to obtain k_1. They claimed that k_1 could be determined within one percent of the actual k_1 value with their graphical method. Bartlett and Swain did their measurements at one temperature, 25 °C, so that the activation parameters quoted for mustard hydrolysis [2–5] are based on the rate coefficients assuming a single reaction.

The advent of high-speed, digital computers eases the problem of treating complex kinetic schemes. We have modified a non-linear, least-squares program [8] to fit consecutive, first-order reactions and examined the literature for the original data on which the rate coefficients were calculated in order to obtain values of k_1 free of any approximation. Bartlett and Swain's data were available in an OSRD report [9]. Table 1 lists the rate coefficients and the availability of original data for the other investigators. The data of Brookfield et al. at 5, 10 and 15 °C were also available at our laboratory in a declassified World War II report.

KINETICS OF CONSECUTIVE FIRST-ORDER REACTIONS

The mechanism depicted in eqns. (1) and (2) can be represented as

$$\mathrm{M} \xrightarrow{k_1} \mathrm{CH} \xrightarrow{k_2} \mathrm{TG} \tag{3}$$

$$[\mathrm{H}^+]_t = [\mathrm{M}]_0\left[2 - \left(\frac{k_1 - 2k_2}{k_1 - k_2}\right)\mathrm{e}^{-k_1 t} - \left(\frac{k_1}{k_1 - k_2}\right)\mathrm{e}^{-k_2 t}\right] \tag{4}$$

where $[\mathrm{M}]_0$ is the initial concentration of mustard, and it is assumed that only mustard is present initially.

Equation (4) was fit with the non-linear, least-squares program with $[\mathrm{H}^+]$ as the dependent variable; time, t, as the dependent variable; and k_1, k_2 and [M] as the parameters to be fit. DeTar [10] and, more recently, Swain et al.

[11], elaborated on the need to treat the experimental value at infinite time as a parameter to be fit. Bentley and Carter [12] discussed the difficulties encountered when measuring solvolyses of *t*-butyl halides in water, such as the apparent induction period caused by dissolved carbon dioxide or the failure of the substrate to dissolve completely. Mismatched experimental and "best-fit" infinity values reflect such errors.

RESULTS AND DISCUSSION

The first set of calculations were performed with Bartlett and Swain's data for mustard chlorohydrin hydrolysis, since this rate coefficient is the basis for the graphical method used to obtain the value of mustard hydrolysis. Table 2 lists the results: the mean value of 0.260 min^{-1} agrees exactly with Bartlett and Swain's value, and it should be noted that the best-fit and experimental values of $[\mathrm{M}]_0$ agree.

Table 3 lists the results for the hydrolysis of mustard. The calculations were first made with k_1, k_2 and $[\mathrm{M}]_0$ varying after which they were repeated with k_2 fixed at 0.260 min^{-1}. The calculated values of k and k_2 are 0.163 and 0.253 min^{-1}, respectively, as compared to Bartlett and Swain's values of 0.155 and 0.260 min^{-1}. Confidence intervals constructed for the computed rate coefficients showed that there was no significant difference between these values at the 95% confidence level. The values of k and $[\mathrm{M}]_0$ do not change significantly when k_2 is fixed at 0.260 min^{-1}, all of which shows that Bartlett and Swain's data conform to eqn. (4), minus any of the difficulties that Bentley and Carter [12] enumerated. It should be noted that Bartlett

TABLE 1

Rate coefficients used to compute activation parameters for mustard hydrolysis

Temp(°C)	$k_1(\text{min}^{-1})$ [a]	Ref.	Temp(°C)	$k_1(\text{min}^{-1})$ [a]	Ref.
0.6	0.0044 [b]	2	14.5	0.028 [b]	4
10.0	0.012 [b]		24.6	0.097 [b]	
20	0.047 [b]		36.8	0.355	
30	0.21 [b]				
37.4	0.27 [b]		0.0	0.0069	5
			5.0	0.0118 [b]	
12.5	0.0215 [b]	3	10.0	0.0235 [b]	
20	0.044 [b]		15.0	0.0387 [b]	
30	0.188 [b]		20.0	0.0702	
40	0.261 [b]		25.0	0.116	
50	0.646 [b]				

[a] First-order rate coefficient determined on assumption of one reaction.

[b] Original data available in referenced article.

and Swain dissolved the mustard or mustard chlorohydrin in acetone which was then added to water to make the final solutions. Bentley and Carter also recommended this procedure for sparingly soluble substrates. A final point from Table 3 is that the precision of k_2 is much less than when k_2 was measured directly. Thus, if possible, one should directly measure the rate of the second step of a consecutive reaction.

TABLE 2

Summary of results for mustard chlorohydrin hydrolysis [a]

Run ID [b]	k(min^{-1})	$[CH]_0$ exp(ml) [c]	$[CH]_0$ fit(ml) [c]
63	0.261	1.69	1.69
64	0.256	1.73	1.72
74	0.268 [d]	1.98	1.89
76	0.259	1.70	1.71
77	0.253	1.71	1.74
101	0.261 [d]	1.91	1.96
116	0.265	1.68	1.67
122	0.259	1.68	1.69
123	0.264	1.72	1.69
127	0.254	1.73	1.75
Mean	0.260		
Sample std. dev.	0.010		

[a] All runs contain 0.00089 M mustard chlorohydrin in 5%, v/v, acetone–water solution at 25.0 °C.

[b] Ref. 9.

[c] Concentration of mustard chlorohydrin expressed as volume of titrant.

[d] Kinetics followed polarographically to determine rate of chloride ion production.

TABLE 3

Summary of rate coefficients for mustard hydrolysis using Bartlett and Swain's data

Run ID [a,b]	k_1(min^{-1})	k_2(min^{-1})	k_1(min^{-1}) [c]	$[M]_0$ exp(ml)	$[M]_0$ fit(ml) [c]	$[M]_0$ fit(ml) [c]
8	0.167	0.232	0.162	4.40	4.28	4.26
28	0.172	0.220	0.164	4.00	3.94	3.92
100 [d]	0.148	0.306	0.155	4.60	4.60	4.60
105 [d]	0.158	0.262	0.158	4.60	4.57	4.57
114	0.168	0.247	0.166	4.16	4.10	4.09
Mean [e]	0.163 ± 0.010	0.253 ± 0.03	0.161 ± 0.004			
Ref. 6,9 [f]	0.155 ± 0.010	0.260 ± 0.016				

[a] All runs contain 0.00108 M mustard and 5%, v/v, acetone–water at 25 °C.

[b] Ref. 9.

[c] k_2 fixed at 0.260 min^{-1}.

[d] Followed polarographically to monitor chloride ion production.

[e] Error is sample standard deviation.

[f] Error estimates by Bartlett and Swain.

TABLE 4

Rate coefficients for mustard and mustard chlorohydrin hydrolysis (Hopkins' data)

Temp (°C)	k(min^{-1})[a]	k_1(min^{-1})[b]	k_2(min^{-1})[b]	$[M]_0$ exp	$[M]_0$ fit
0.6	0.0044	[c]	[c]		
10	0.013	0.0325	0.0192	18.3	16.1
20.5	0.046	0.201	0.0617	34.8	33.4
20.9	—	0.164	0.0667	5.4	5.3
30	0.20	0.397	0.317	10.0	9.2
37.5	0.28	[d]	[d]		

[a] Reported in ref. 2.

[b] Computed by fitting data from ref. 2 to eqn. (4).

[c] Failed to converge.

[d] Too few points to fit data.

TABLE 5

Results of fitting Hopkins' data at 20.9°C to eqn. (4) ($k_1 = 0.164 \pm 0.006$ min^{-1}; $k_2 = 0.0067 \pm 0.005$ min^{-1})

Time(min)	Exp(ml)	Fit(ml)	Time(min)	Exp(ml)	Fit(ml)
2.0	0.80	0.79	16.0	3.71	3.70
3.75	1.31	1.37	21.0	4.21	4.16
5.50	1.79	1.86	26.0	4.52	4.49
6.75	2.25	2.17	41.0	1.98	5.00
8.00	2.50	2.45	56.0	5.00	5.18
9.75	2.75	2.80	121	5.25	5.29
11.0	3.01	3.01	139	5.35	5.29
				5.40	5.29

TABLE 6

Rate coefficients for mustard and mustard chlorohydrin hydrolysis by exact treatment of consecutive, first-order kinetics

T(°C)	k_1(min^{-1})[a]	k_1(min^{-1})[b]	k_2(min^{-1})[b]	Ref.
12.5	0.0215	[c]	[c]	3
20	0.044	0.118	0.101	3
30	0.188	0.307	0.279	3
40	0.261	[c]	[c]	3
50	0.646	[c]	[c]	3
24.6	0.097	0.199	0.096	4
5.0	0.0118	0.011	0.024	5
10.0	0.235	0.016	0.112	5
15.0	0.0387	[c]	[c]	5

[a] Rate coefficient for k_1 listed in appropriate reference.

[b] Rate coefficients obtained with fit to eqn. (4).

[c] Failed to converge.

In contrast to Bartlett and Swain's data, poor fits were obtained with data from all investigators who measured mustard hydrolysis at various temperatures [2–5]. Table 4 summarizes our results with Hopkin's data [2]. At the lowest temperature, 0.6 °C, the program did no converge. At the higher end of the temperature scale, too few points were available to try a fit. At 20 °C, the fit to eqn. (4) yielded values of k_1 exceeding k_2 (Table 5). One explanation may be that Hopkins was measuring the rate of dissolution of the mustard rather than the hydrolysis. The dissolution would be a first-order process, and the small value of k_2 suggests that Hopkins' data nearly fit a first-order scheme.

Similar results were obtained with other data, in particular Mohler and Hartnagel's results [3] which failed to converge at three temperatures as shown in Table 6. Thus, the activation parameters computed from the rate coefficients from these data do not represent the temperature dependence of the rate coefficient, k_1, as defined in eqn. (1).

CONCLUSIONS

One must question the accuracy of the activation energies derived from the rate coefficients in Table 2 not only because the mustard hydrolysis was approximated as a single reaction, but also because the data fail to conform to eqn. (4). The rate coefficient Bartlett and Swain measured at 25.0 °C is not significantly different from that obtained from an exact fit to eqn. (4).

REFERENCES

1 B. Cohen, Kinetics of Reactions of Sulfur and Nitrogen Mustard, Chap. 20, Parts III–IV, Chemical Warfare Agents, and Related Chemical Problems, Summary Tech. Rep. Div. 9, NDRC, 1946.
2 E.F. Hopkins, J. Pharmacol., 12 (1919) 393.
3 H. Mohler and J. Hartnagel, Helv. Chim. Acta, 24 (1941) 564.
4 H.A. Peters and E. Walker, Biochem. J., 17 (1923) 260.
5 K.J. Brookfield, F.N. Woodward and R. Owens, The Kinetics of the Hydrolysis of Vesicants, Part II, 2,2-Dichlorodiethylsulfide (H), Sutton Oak Rep. 576, 1942.
6 P.D. Bartlett and C.G. Swain, J. Am. Chem. Soc., 71 (1949) 1406.
7 C.G. Swain, J. Am. Chem Soc., 66 (1944) 1696.
8 R.H. Moore and R.K. Ziegler, The Solution of the General Least-Squares Problem with Special Reference to High Speed Computers, LASL Rep. LA-2367, 1960.
9 P.D. Bartlett and C.G. Swain, The Mechanism of Hydrolysis and Displacement of Mustard Chlorohydrin and Mustard in Aqueous Solutions, OSRD Rep. 4683, 1945.
10 D.F. DeTar, J. Chem. Educ., 44 (1967) 759.
11 C.G. Swain, M.S. Swain and L.F. Berg, J. Chem. Inf. Comput. Sci., 20 (1980) 47.
12 T.W. Bentley and G.E. Carter, J. Chem. Soc., Faraday Trans. 1, 78 (1982) 1633.