

Studies on Alkylsulfinylcarboxylic Acids

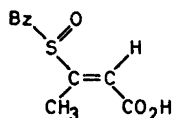
VI. The Geometric Isomers of β -Benzylsulfinylcrotonic Acid and Their Rates of Reduction in Acidic Iodide Solution

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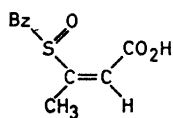
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The geometric configuration of β -alkylsulfinyl- α,β -unsaturated carboxylic acids can be readily determined by their very great difference in reactivity in acidic iodide solutions. Thus, β -benzylsulfinyl-*trans*-crotonic acid is reduced over 100 times faster than β -benzylsulfinylpropionic acid under identical conditions, while no reaction at all can be detected in the case of β -benzylsulfinyl-*cis*-crotonic acid. The reactions were studied kinetically at 25.0°C, using 50 % (v/v) acetic acid as a solvent. The reduction of β -benzylsulfinyl-*trans*-crotonic acid was carried out at various low hydrogen ion concentrations and the kinetic data obtained were found to fit a rate equation: $dx/dt = k(a - x)(b - 2x)$, where $a - x$ and $b - 2x$ are the concentrations of the sulfoxide-acid and of hydrogen ions, respectively, at the time t .

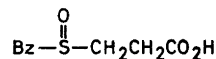
In an earlier paper the geometric isomers of β -ethylsulfinylcrotonic acid were described and a study of their reduction in acidic iodide solution revealed an enormous rate-difference.¹ In order to extend this investigation concerning *cis-trans* isomeric α,β -unsaturated sulfoxide-acids, the following compounds



II



V



VIII

were synthesized together with the sulfones corresponding to II and V. These acids, with the exception of VIII, have not been reported previously.

The reductions of II, V, and VIII by means of sodium iodide and perchloric acid were performed at 25.0°C in a 50 % (v/v) acetic acid solution in order to obtain a homogeneous phase during the reaction.

Using the following concentrations:

$$C_{\text{HClO}_4} = 0.50 \text{ M}, C_{\text{NaI}} = 0.200 \text{ M}, \text{ and } C_{\text{II}}, C_{\text{V}}, C_{\text{VIII}} \sim 0.005 \text{ M},$$

the rate can be considered as depending upon the concentration of the sulfide compound only and the following pseudo first-order rate constants were found:

$$k_{\text{II}} = 0, k_{\text{VIII}} = 0.00283 \text{ min}^{-1}, k_{\text{V}} = 0.36 \text{ min}^{-1}.$$

However, in the reduction of V a consecutive reaction, consisting in addition of the liberated iodine to the unsaturated sulfide-acid,¹ was observed. Owing to this complication and to the very fast reduction of V in 0.50 M perchloric acid, the value of k_{V} is somewhat uncertain. Therefore, the kinetic study of V was repeated using $C_{\text{HClO}_4} = 0.25 \text{ M}$, other concentrations being the same as before. This gave a value of $k_{\text{V}} = 0.177 \text{ min}^{-1}$ which seems to be reasonable, since a linear relationship between $\log k$ and $-H_0$ with unit slope has been found earlier for this type of reaction.²

A considerable decrease in the rate of iodine addition to the unsaturated sulfide-acid formed in the reaction was observed at lower perchloric acid concentrations. This addition is apparently strongly hydrogen ion-catalyzed. The total reaction can be written in the following way:

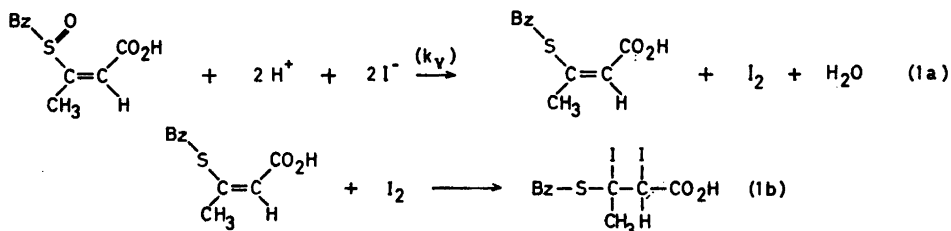


Fig. 1 represents the iodine concentration as a function of time for both kinetic series concerning the reduction of V. It can be seen that the first four

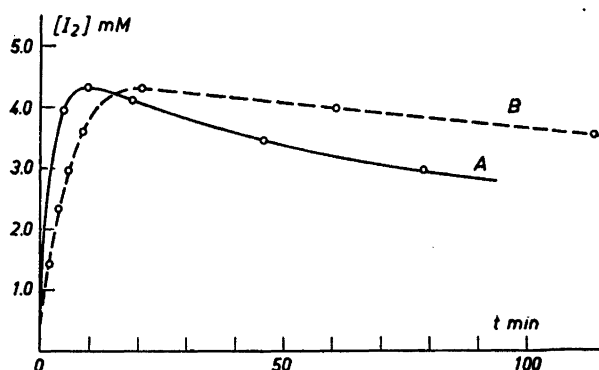


Fig. 1. Iodine concentration vs. time for the reduction of β -benzylsulfinyl-*trans*-crotonic acid with sodium iodide and perchloric acid in 50 % (v/v) acetic acid at 25°C. Curve A: $C_{\text{HClO}_4} = 0.50 \text{ M}$, curve B: $C_{\text{HClO}_4} = 0.25 \text{ M}$.

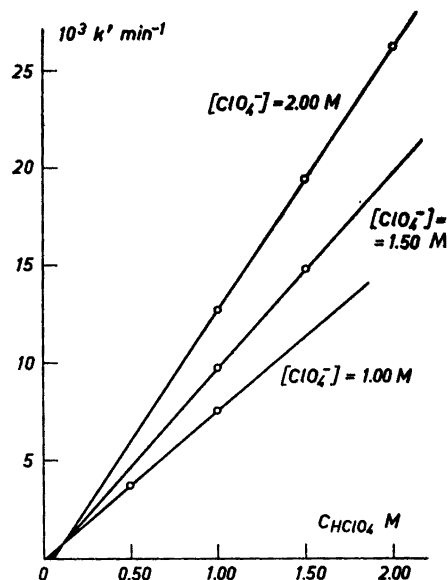


Fig. 2. Pseudo first-order rate constant k' vs. perchloric acid concentration at constant ionic strengths. The figure refers to the reduction of β -sulfinyldipropionic acid with sodium iodide and perchloric acid in water at 25°C.²

points of curve B can be used for the calculation of k_v without introducing any great error by neglecting reaction 1b.

Reaction 1a proceeds with retention of the geometric configuration. This was definitely proved by isolation of the reaction product, which was compared with the unsaturated sulfide-acid used for the preparation of V. The infrared spectra were completely identical, the melting points were the same and a mix-melting point showed no depression.

In earlier kinetic investigations on the reduction of sulfoxide-acids,^{2,3} water was used as a solvent and if the ionic strength was kept constant, linearity between the pseudo first-order rate constants and the hydrogen ion concentrations, as shown in Fig. 2, was found. Under these conditions the rate equation can therefore be written:

$$v = k \left[\text{>SO} \right] \left[\text{H}^+ \right] \quad (2)$$

Eqn. 2 was now found to hold exceedingly well even for the reduction of V in 50 % (v/v) acetic acid at low perchloric acid concentrations when the ionic strength was kept approximately constant. Eqn. 2 now represents reaction 1a only, as the influence of the consecutive reaction 1b upon the overall rate at the low perchloric acid concentrations used was very small. For the slowest kinetic runs reaction 1b could be completely neglected.

The following symbols are introduced:

- a = sulfoxide concentration at $t = 0$
- $a - x$ = " " " " time t
- b = hydrogen ion concentration at $t = 0$
- $b - 2x$ = " " " " time t

Eqn. 2 then becomes:

$$\frac{dx}{dt} = k(a-x)(b-2x)$$

Integration and determination of the integration constant yields the second-order expression:

$$\frac{k(b-2a)}{2.303} = \frac{1}{t} \log \frac{a(b-2x)}{(a-x)b} \quad (3)$$

For the calculation of $b = [\text{H}^+]$ the following expressions must be considered:

$$\frac{[\text{H}^+][\text{Ac}^-]}{[\text{HAc}]} = 1.76 \times 10^{-5} \quad (4)$$

$$[\text{H}^+] = [\text{Ac}^-] + [\text{ClO}_4^-]^* + [\text{OH}^-] \quad (5)$$

$$[\text{HAc}] + [\text{Ac}^-] = C_{\text{HAc}} \quad (6)$$

$[\text{ClO}_4^-]^* = C_{\text{HClO}_4}$, if the perchloric acid is assumed to be completely dissociated.^{4,5}

Omitting $[\text{OH}^-]$ in eqn. 5, the combination of these equations will give:

$$[\text{H}^+] = \frac{1}{2}(C_{\text{HClO}_4} - 1.76 \times 10^{-5})$$

$$\frac{+}{(-)} \sqrt{0.25(C_{\text{HClO}_4})^2 + 0.88 \times 10^{-5} C_{\text{HClO}_4} + 1.76 \times 10^{-5} C_{\text{HAc}}} \quad (7)$$

Now 50 % (v/v) acetic acid corresponds to $C_{\text{HAc}} = 8.74 \text{ M}$ so eqn. 7 can easily be solved for the various perchloric acid concentrations used. The values of b thus obtained have been put into eqn. 3 for the calculation of the rate constants represented in Tables 1–4. In Fig. 3 the second-order

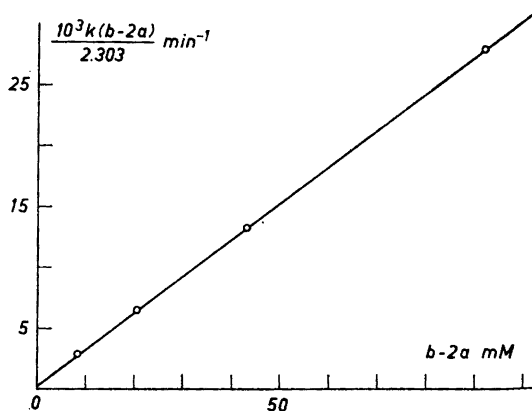


Fig. 3. Graphic determination of the second-order rate constant k in eqn. 3.

* As the sodium perchlorate concentration has no influence upon the calculations it is neglected here.

Tables 1-4. Kinetic data for the reduction of β -benzylsulfinyl-*trans*-crotonic acid with sodium iodide and perchloric acid in 50 % (v/v) acetic acid at 25 °C. $C_{\text{NaI}} = 0.200 \text{ M}$. $[\text{ClO}_4^-] = 0.250 \text{ M}$.

1. $C_{\text{HClO}_4} = 100.0 \text{ mM}$, eqn. 7 gives: $b = [\text{H}^+] = 101.5 \text{ mM}$, $a = 4.655 \text{ mM}$.

$x \text{ mM}$	$\left(\frac{b}{2} - x\right) \text{ mM}$	$(a - x) \text{ mM}$	$t \text{ min}$	$\frac{k(b - 2a)}{2.303} \text{ min}^{-1}$
1.143	49.62	3.512	4	0.0281
1.592	49.17	3.063	6	0.0280
2.302	48.46	2.353	10	0.0276
3.136	47.62	1.519	17	(0.0270)
3.821	46.94	0.834	28	(0.0255)
			mean value:	0.0279

2. $C_{\text{HClO}_4} = 50.0 \text{ mM}$, eqn. 7 gives: $b = [\text{H}^+] = 52.9 \text{ mM}$, $a = 4.785 \text{ mM}$

0.970	25.49	3.185	6	0.0137
1.337	25.12	3.448	9	0.0133
2.012	24.44	2.773	15	0.0135
2.499	23.96	2.286	21	0.0132
3.251	23.20	1.534	34	0.0129
3.522	22.93	1.263	40	0.0129
3.830	22.63	0.955	49	0.0129
			mean value:	0.0132

3. $C_{\text{HClO}_4} = 25.0 \text{ mM}$, eqn. 7 gives: $b = [\text{H}^+] = 30.1 \text{ mM}$, $a = 4.655 \text{ mM}$

$x \text{ mM}$	$\left(\frac{b}{2} - x\right) \text{ mM}$	$(a - x) \text{ mM}$	$t \text{ min}$	$\frac{k(b - 2a)}{2.303} \text{ min}^{-1}$
0.951	14.10	3.704	11	0.00645
1.569	13.49	3.086	20	0.00654
2.059	13.00	2.596	29	0.00654
2.821	12.23	1.834	48	0.00655
3.282	11.77	1.373	66	0.00642
3.834	11.22	0.821	101	(0.00620)
			mean value:	0.00650

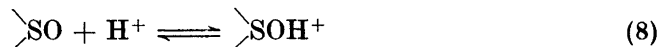
4. $C_{\text{HClO}_4} = 10.00 \text{ mM}$, eqn. 7 gives: $b = [\text{H}^+] = 18.37 \text{ mM}$, $a = 4.990 \text{ mM}$

0.820	8.365	4.170	13	0.00287
1.315	7.870	3.675	24	0.00274
2.016	7.169	2.974	42	0.00279
2.444	6.741	2.546	56	0.00282
3.008	6.177	1.982	80	0.00286
3.563	5.622	1.427	115	0.00287
3.872	5.313	1.118	142	0.00290
			mean value:	0.00284

rate constant k is obtained from the slope of the line. Thus, for the reduction of V with 0.200 M sodium iodide in 50 % (v/v) acetic acid at a constant perchlorate ion concentration of 0.250 M, the value of k is 0.69 l mole⁻¹ min⁻¹.

DISCUSSION

The results make clear that even for the reduction of α,β -unsaturated β -alkylsulfinylcarboxylic acids in acidic iodide solution, the only step preceding the rate-determining one is a rapid proton-sulfoxide equilibrium:²



The rate-difference between V and VIII for the reduction under identical conditions ($k_V/k_{VIII} \sim 1.3 \times 10^2$) and the failure of II to react at any measurable rate can be understood only if the formation of a five-membered ring intermediate is assumed to be a rate-determining step.⁶

The lowering of the free energy of activation for this reaction by the structural change in the sulfoxide compound is likely to be due to the favoured steric arrangement in V as compared to VIII. In other words, the effect should be almost exclusively a steric and not a polar one.

EXPERIMENTAL

Preparation of the sulfur-containing carboxylic acids

β -Benzylthio-cis-crotonic acid (I) was prepared from the sodium salt of β -chloro-cis-crotonic acid and sodium benzyl mercaptide according to Autenrieth.⁷ M.p. 129.0–130.5° (Ref. 7: 130–131°).

β -Benzylsulfinyl-cis-crotonic acid (II). An attempt to oxidize I with hydrogen peroxide in acetone only resulted in the recovery of I. The use of a peracetic acid solution (containing ~13 % peracetic acid in acetic acid⁸) as an oxidizing agent was, however, successful. To 4.16 g (0.020 mole) of I dissolved in a mixture of acetone and ether, this peracetic acid solution was added in a 25 % excess of the calculated amount. After one day at 0°C and another day at room temperature, the solvent was evaporated, the residue dried over sulfuric acid and washed with dry ether, yielding a product of m.p. 136.0–137.5°. After a recrystallization from ethyl acetate + light petroleum, 3.95 g (88 %) of pure material with m.p. 139.2–139.7° was obtained. (Found: C 58.4; H 5.35; S 14.2. Calc. for C₁₁H₁₂O₃S: C 58.9; H 5.39; S 14.3).

β -Benzylsulfonyl-cis-crotonic acid (III) was easily prepared by dissolving I in an excess of peracetic acid solution. This process was accompanied by a considerable evolution of heat. As the solvent was allowed to evaporate a crystalline mass precipitated. This was dried over sulfuric acid and gave a m.p. of 176–180°. A recrystallization from water yielded glossy leaves of m.p. 182.0–182.5°. (Found: C 55.15; H 5.04; S 13.45. Calc. for C₁₁H₁₂O₄S: C 55.0; H 5.03; S 13.35).

β -Benzylthio-trans-crotonic acid (IV) was obtained by the method of Autenrieth⁷ using the sodium salt of β -chloro-trans-crotonic acid and sodium benzyl mercaptide without warming the reaction mixture. Starting with 12.05 g (0.10 mole) of chloro-acid, 9.45 g (45 %) of IV was obtained. A recrystallization from ethanol gave a m.p. of 194.0–195.0° (Ref. 7: 192–194°).

β -Benzylsulfinyl-trans-crotonic acid (V). The same method as described for the preparation of II was used. Starting with 4.16 g (0.020 mole) of IV, the yield was 3.6 g (80 %) of a product with m.p. 117–119° (decomp.). Recrystallizations from toluene

raised the m.p. to 124.5–125.0° (decomp.). (Found: C 58.95; H 5.44; S 13.9. Calc. for $C_{11}H_{12}O_2S$: C 58.9; H 5.39; S 14.3).

β -Benzylsulfonyl-trans-crotonic acid (VI). This acid was obtained as described for the synthesis of III. A recrystallization from chloroform + light petroleum yielded a product of m.p. 121.5–122.0°. (Found: C 55.15; H 5.07; S 13.4. Calc. for $C_{11}H_{12}O_4S$: C 55.0; H 5.03; S 13.35).

β -Benzylthiopropionic acid (VII) was prepared according to Adell⁸ by benzylation of β -mercaptopropionic acid. From 10.6 g (0.10 mole) mercapto-acid, 19.5 g (99 %) of VII with m.p. 80–81° was obtained. A recrystallization from acetone + benzene raised the m.p. to 81.5–82.5° (Ref. 9: 83°).

β -Benzylsulfinylpropionic acid (VIII). This acid has been described by Holmberg,¹⁰ who oxidized VII with hydrogen peroxide in an alkaline water-solution. The present author found acetone to be an equally suitable solvent. From 3.9 g (0.020 mole) of VII, the yield was 4.0 g (94 %) of VIII. A recrystallization from ethanol gave a m.p. of 153.0–154.0° (Ref. 10: 149–150°).

General kinetic procedure

All reactions were studied at $25.00 \pm 0.02^\circ\text{C}$. In 50 % (v/v) acetic acid, used as the solvent in all the kinetic experiments, the system investigated was completely homogeneous. For each run 700–760 mg of the sulfoxide compound were dissolved in 25 ml of glacial acetic acid. Then 2.00 ml portions of this stock solution were added to a series of reaction flasks, each one containing 48 ml of a thermostated, oxygen-free solution of sodium iodide, perchloric acid and sodium perchlorate in acetic acid + water, so that at $t = 0$ all concentrations were those given in Tables 1–4. The reactions took place under nitrogen and were followed by titration with sodium thiosulfate as described earlier.^{3,6} Even the fastest reactions studied could be effectively stopped at the time t by rapid immersion of the reaction flask in a cooling bath and addition of crushed ice.

Identification of the reaction products and determination of the initial concentrations

To show that the reduction of V exclusively yielded IV, *i.e.* that no inversion of the geometric configuration occurs during the reaction, the following simple method was used: a certain amount of V, dissolved in acetic acid, was mixed with a solution of potassium iodide in 3 M hydrochloric acid. The rapidly formed iodine was continuously removed by titration with sodium thiosulfate. The sulfide-acid precipitated from the water solution during this procedure and could finally be filtered, washed with a little water and dried. This product had a m.p. of 191.5–192.5°. A mixture with IV gave m.p. 193.5–194.5°. Infrared spectra of this product and of IV (in KBr) were completely identical. The method was also found to be useful for the determination of the initial concentrations of V in the various kinetic runs, as the reduction under the above conditions was complete after only a fairly short time.

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