and then from water to yield (+)-β-phenyl-β-hydroxypropionic acid-α-d_1, m.p. 115–118°.[10] A less completely resolved sample of the (−)-acid was also obtained, m.p. 113–118°.

Kinetic Procedures.—The kinetic procedures have been described in a previous paper.[10]

Product isolation studies were carried out as described previously.[10]

A. **Racemization.**—From a sample of (+)-β-phenyl-β-hydroxypropionic acid, there was isolated *rac*-β-phenyl-β-hydroxypropionic-α-*d* acid, m.p. 90–92°.

Anal.[22] Found: 10.05 ± 0.3 atom % excess D.

B. **Dehydration.**—Samples of cinnamic-α-*d* acid were isolated under the conditions described previously.[10] The cinnamic acid was purified by crystallization from heptane and sublimation.

Anal. Calcd. for $C_9H_7DO_2$: 12.5 atom % excess D. Found: 9.14, 9.46 from two separate preparations.

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[22] Deuterium analysis by Dr. C. W. Koch, Department of Chemistry, University of California, Berkeley.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIF.]

The Effect of Substituents upon the Rate of Isomerization of Substituted *cis*-Cinnamic Acids[1-3]

BY DONALD S. NOYCE AND HARVEY S. AVARBOCK

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The rates of isomerization of *cis*-*p*-methoxycinnamic acid and of *cis*-*p*-chlorocinnamic acid as catalyzed by sulfuric acid have been studied. Each of the isomerizations parallels the acidity function H_0 with unit slope. The corresponding β-aryl-β-hydroxypropionic acid is an intermediate. The rate of isomerization is sensitive to the electronic nature of the substituent. Correlation with σ^+ gives a ρ of -4.3. These data support a mechanism in which there is a large electron deficiency at the benzylic carbon in the transition state.

Introduction

The isomerization of *cis*-cinnamic acid as catalyzed by sulfuric acid[4] has been shown to be closely involved with the behavior of the related hydroxy acid, β-phenyl-β-hydroxypropionic acid.[1,4,5] It was also shown that the series of β-aryl-β-hydroxypropionic acid gave a very steep ρ–σ^+ correlation for the dehydration reaction, indicating the high degree of carbonium ion character at the benzylic carbon.[6]

In the present report we wish to present results on the kinetics of the acid-catalyzed isomerization of two substituted *cis*-cinnamic acids. These results show that in this reaction also there is a high degree of positive charge at the β (benzylic) carbon.

Experimental[7]

Materials.—*trans*-*p*-**Methoxycinnamic** acid was crystallized to constant m.p. and ultraviolet spectrum from methanol; m.p. 173.4–174.8°; neut. equiv.: calcd. 178.2, found 177.

cis-*p*-**Methoxycinnamic acid** was prepared by ultraviolet irradiation of a sodium carbonate solution of the *trans* isomer in a quartz flask. Separation of the *cis* and *trans* isomers was easily effected by fractional crystallization from benzene, the *cis* isomer being more soluble than the *trans* isomer by a factor of at least 300 at 25°. The product obtained in 20% yield was recrystallized to constant m.p. from a mixture of benzene and petroleum ether; m.p. 69.2–69.4° (lit.[8] 66°).

Anal. Calcd. for $C_{10}H_{10}O_3$: C, 67.41; H, 5.66; neut. equiv., 178.2. Found: C, 67.51; H, 5.78; neut. equiv., 179.

trans-*p*-**Chlorocinnamic acid** was prepared from *p*-chlorobenzaldehyde and malonic acid following the procedure of Pandya and Pandya.[9] A sample was crystallized to constant m.p. and spectrum from ethanol; m.p. 251.2–251.6° (lit. 247°,[9] 250°[10]); neut. equiv. calcd. 182.6, found 183.

cis-*p*-**Chlorocinnamic Acid.**—Ultraviolet irradiation of the *trans* isomer and separation of isomers in the manner described in the preparation of *cis*-*p*-methoxycinnamic acid produced *cis*-*p*-chlorocinnamic acid in 25% yield. It was recrystallized to constant m.p. from distilled water; m.p. 112.0–112.3° (lit.[11] 113.8–116.2°).

Anal. Calcd. for $C_9H_7O_2Cl$: C, 59.19; H, 3.86; Cl, 19.42; neut. equiv., 182.6. Found: C, 58.93; H, 3.68; Cl, 19.56; neut. equiv., 184.

Product Isolation under Conditions of the Kinetic Experiments. A. *p*-**Methoxycinnamic Acid.**—A solution of 104 mg. of *cis*-*p*-methoxycinnamic acid in 1000 ml. of 43.57% sulfuric acid was maintained at 25.0° for a period corresponding to eight half-lives; during the course of reaction, 75 mg. of material precipitated from solution. After being worked up in the usual manner, it was recrystallized to constant m.p. from methanol; m.p. 173.1–173.6°; neut. equiv. calcd. 178.2, found 177.0. A mixed melting point with known *trans*-*p*-methoxycinnamic acid showed no depression. Dilution of the reaction solution with water followed by extraction with ether on a continuous extractor yielded 15 mg. of material, m.p. 171–173°. The infrared spectra of both portions was identical with that of pure *trans*-*p*-methoxycinnamic acid. The combined yield was 90 mg., 87%.

B. *p*-**Chlorocinnamic Acid.**—A solution of 109 mg. of *cis*-*p*-chlorocinnamic acid in 160 ml. of 53.18% sulfuric acid was maintained at 90° for a period corresponding to 6 half-lives. During the course of reaction, 96 mg. of material precipitated from solution. After isolation in the usual manner, it was recrystallized from ethanol; m.p. 251.1–251.7°. The infrared spectrum was identical with that of pure *trans*-*p*-chlorocinnamic acid. Extraction of the reaction solution with ether yielded no further product. The yield of 96 mg. was 88% of theoretical.

cis–trans **Isomerization in Sulfuric Acid-d_2.**—A solution of 400 mg. of *cis*-*p*-chlorocinnamic acid in 216 g. of 51% sulfuric acid-d_2 was maintained at 90° for a period corresponding to 1 half-life. The solution was then immediately chilled at −10° and filtered through a sintered glass funnel. The precipitate was dissolved in 25 ml. of 1 *M* sodium hydroxide

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[1] Paper XVII in the Series Carbonyl Reactions; previous paper, D. S. Noyce and C. A. Lane, *J. Am. Chem. Soc.*, **84**, 1641 (1962).

[2] Supported in part by a grant from the Petroleum Research Fund administered by the American Chemical Society. Grateful acknowledgment is hereby made to the donors of this fund.

[3] Presented in part at the Eighth Conference on Organic Reaction Mechanisms, Princeton, N. J., September, 1960.

[4] D. S. Noyce, P. A. King, F. B. Kirby and W. L. Reed, *J. Am. Chem. Soc.*, **84**, 1632 (1962).

[5] D. S. Noyce and C. A. Lane, *ibid.*, **84**, 1635 (1962).

[6] D. S. Noyce, P. A. King, C. A. Lane and W. L. Reed, *ibid.*, **84**, 1638 (1962).

[7] Analyses are by the Microanalytical Laboratory of the University of California. Melting points are corrected.

[8] W. A. Roth and R. Stoermer, *Ber.*, **46**, 260 (1913).

[9] K. C. Pandya and R. B. Pandya, *Proc. Indian Acad. Sci.*, **14A**, 112 (1941).

[10] J. K. Kochi, *J. Am. Chem. Soc.*, **78**, 1228 (1956).

[11] S. Lindenfors, *Arkiv. Kemi*, **10**, 561 (1957).

solution, reprecipitated with dilute hydrochloric acid solution, filtered, and dried *in vacuo* at 60°. The total precipitate including 14 mg. recovered from filtrates and wash liquids weighed 350 mg.

The great solubility difference between the *cis*- and *trans*-acids comprising this material allowed facile separation of the two substances. The filtrates from two extractions of the mixture with 40-ml. portions of boiling water yielded 150 mg. of material. After recrystallization to constant m.p. (m.p. 112.0–112.4°) from distilled water, it gave an infrared spectrum identical with that of pure *cis*-*p*-chlorocinnamic acid. The insoluble material recovered from extraction of the mixture of cinnamic acids weighed 135 mg. and was combined with 80 mg. of material produced in an earlier experiment under the same conditions of temperature and acidity. The 80-mg. portion, however, resulted from isomerization for a period corresponding to 3 half-lives but had an infrared spectrum identical with that of the 135-mg. material. The combined material was dissolved in dilute sodium hydroxide solution, reprecipitated with dilute hydrochloric acid solution, filtered, washed, and recrystallized to constant m.p. from 50% ethanol; m.p. 251.0–251.8°.

Anal.[12] Found: *trans*-acid: 9.59 atom % excess deuterium; *cis*-acid: 0.30 atom % excess deuterium.

Kinetic Procedures.—The rate of isomerization was followed by the increase in ultraviolet absorption at an appropriate wave length as described previously.[4] At 25° and 45° optical density readings were made on a single sample maintained in a thermostated cell block. At 90°, the conventional sealed ampule technique was used.

Reactions were, in general, followed to completion. Rate constants were determined graphically by plotting the kinetic data in the form of apparent percentage of remaining *cis*-acid, *i.e.*, $(\text{O.D.}_\infty - \text{O.D.}_t)/(\text{O.D.}_\infty - \text{O.D.}_0) \times 100$, and analytically by the method of least squares. The precision of the data was generally between 1 and 3% under optimum conditions. The absorbances at infinite time were reasonably stable and, in all cases, corresponded closely to those expected for complete conversion to *trans*-acids in accordance with the results of the product isolation experiments described above.

Results of a typical kinetic run are given in Table I.

TABLE I

Typical kinetic run: temp. = 25.00°, H_2SO_4 = 46.22%, init. concn. *cis*-*p*-methoxycinnamic acid = 3.52×10^{-5} *M*

Time, sec. $\times 10^{-2}$	Optical density	Rx,[a] %	$k \times 10^4$, sec.$^{-1}$
0	0.475	0	..
4.65	.518	15.19	3.54
7.20	.538	22.26	3.50
9.60	.557	28.98	3.57
12.30	.574	34.98	3.50
15.30	.595	42.40	3.60
19.35	.615	49.47	3.53
19.63	.635	56.54	3.53
27.15	.650	61.84	3.54
32.40	.668	68.20	3.53
38.10	.683	73.50	3.50
44.10	.700	79.51	3.60
51.60	.712	83.75	3.52
192.60 (∞)	.758	...	..[b]

[a] $\text{Rx} = (\text{O.D.}_t - \text{O.D.}_0)/(\text{O.D.}_\infty - \text{O.D.}_0) \times 100$. [b] Av. = $3.54 \pm 0.03 \times 10^{-4}$ sec.$^{-1}$.

Results

Isomerization of *cis*-*p*-Methoxycinnamic Acid.—The results of kinetic measurements at both 25° and 45° are given in Table II. The range of acidity encompassed by these results is sufficient to establish that the isomerization of *cis*-*p*-methoxycinnamic acid parallels the acidity function H_0 with very nearly unit slope. Difficulties are apparent if one wishes to extend the range of acidities over which measurements are made. At low acidities the behavior of β-(*p*-methoxyphenyl)-β-hydroxypropionic acid becomes complex.[13] As we anticipated that β-(*p*-methoxyphenyl)-β-hydroxypropionic acid would be an unstable intermediate in the isomerization (a premise which is fully validated by the evidence below), this precluded simple, straightforward studies at lower acidities.

TABLE II

RATE OF ISOMERIZATION OF *cis*-*p*-METHOXYCINNAMIC ACID IN SULFURIC ACID AT 25.00°

Initial concentration of *cis*-acid 3.52×10^{-5} *M*

H_2SO_4, %	H_0[a]	$k \times 10^4$, sec.$^{-1}$	$\log k + H_0$
37.66	−2.25	0.653	−6.44
40.50	−2.45	1.00	−6.45
42.00	−2.59	1.47	−6.42
46.22	−2.98	3.54	−6.43
51.66	−3.56	11.9	−6.48[c]
	At 45.00°		
31.44	−1.82[b]	1.68	−5.59
39.67	−2.39[b]	6.90	−5.55[d]

[a] H_0 values are from Paul and Long.[14] [b] There is no temperature correction to H_0 in this acidity region.[15] [c] Av. −6.44 ± 0.02. [d] Av. −5.57 ± 0.02.

Role of β-(*p*-Methoxyphenyl)-β-hydroxypropionic Acid as an Intermediate.—In the investigation[4] of the kinetics of the isomerization of *cis*-cinnamic acid, direct evidence that β-phenyl-β-hydroxypropionic acid was an intermediate in the isomerization was obtained. The dehydration of the hydroxy acid was observed to be faster than the *cis–trans* isomerization; an induction period was observed when the isomerization was studied at low acidity.

In the present instance, completely parallel observations have been made. The rate of dehydration of β-(*p*-methoxyphenyl)-β-hydroxypropionic acid is faster than the rate of isomerization of *cis*-*p*-methoxycinnamic acid. Comparison of the rates at various acidities is given in Table III.

TABLE III

COMPARISON OF RATE OF DEHYDRATION OF β-(*p*-METHOXYPHENYL)-β-HYDROXYPROPIONIC ACID WITH RATE OF ISOMERIZATION OF *cis*-*p*-METHOXYCINNAMIC ACID AT 25.00°

H_2SO_4, %	H_0	$k_{\text{dehydr.}}$,[a] sec.$^{-1}$	$k_{\text{isom.}}$, sec.$^{-1}$	$k_{\text{dehyd}}/k_{\text{isom.}}$	Induction period obsd.
26.35	−1.46	1.20×10^{-4}	9.77×10^{-6}	12	Yes
37.66	−2.25	1.44×10^{-3}	6.53×10^{-5}	22	Slight
40.50	−2.45	2.62×10^{-3}	1.00×10^{-4}	26	Quest.
42.00	−2.59	4.17×10^{-3}	1.47×10^{-4}	28	No
46.22	−2.98	1.38×10^{-2}	3.54×10^{-4}	39	No
51.66	−3.56	8.70×10^{-2}	1.19×10^{-3}	73	No

[a] Interpolated from the data of Noyce, King, Lane and Reed.[6]

At the lowest acid concentration where measurements were made, 26% sulfuric acid, the induction period is clearly evident. The apparent rate constant for the formation of *trans*-*p*-methoxycinnamic acid shows a gradually rising value during the

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(12) Deuterium analyses by Mr. Joseph Nemeth, Urbana, Ill.

(13) D. S. Noyce, P. A. King and G. L. Woo. *J. Org. Chem.*, **26**, 632 (1961).

(14) M. A. Paul and F. A. Long, *Chem. Revs.*, **57**, 1 (1957).

(15) A. I. Gelbstein, G. G. Shcheglova and M. I. Temkin, *Zhur. neorg. Khim.*, **1**, 506 (1956).

first 20% of the reaction. The data are given in Table IV. These data clearly support the role of β-(*p*-methoxyphenyl)-β-hydroxypropionic acid as an intermediate in the isomerization of *cis*-*p*-methoxycinnamic acid.

TABLE IV

RATE OF ISOMERIZATION OF *cis*-*p*-METHOXYCINNAMIC ACID, SHOWING INDUCTION PERIOD AT 25.00° IN 26.35% SULFURIC ACID

Time, sec. × 10^{-3}	Optical density 310 mμ	Rx,[a] %	$k \times 10^6$,[b] sec.$^{-1}$	$k \times 10^6$,[c] sec.$^{-1}$
0	0.333	...		
8.34	.337	1.12	1.31	
16.26	.353	5.60	3.53	
23.70	.368	9.80	4.37	
33.42	.395	17.37	5.71	
77.94	.488	43.42	7.30	...
93.48	.515	50.98	7.63	9.22
111.5	.545	59.38	8.08	9.88
124.3	.560	63.59	8.13	9.51
174.1	.612	78.15	8.74	9.90
184.6	.623	81.23	9.06	10.35
590.4 (∞)	.690			
			Av.	9.77 ± 0.29

[a] $(\text{O.D.}_t - \text{O.D.}_0)/(\text{O.D.}_\infty - \text{O.D.}_0) \times 100$. [b] $k = \ln [(\text{O.D.}_\infty - \text{O.D.}t)/(\text{O.D.}_\infty - \text{O.D.}_0)]_t^{-1}$, starting at zero time. [c] $k = \ln [(\text{O.D.}_\infty - \text{O.D.}t)/(\text{O.D.}_\infty - \text{O.D.}_0)]_t^{-1}$, zero time taken at 77.94 × 10^3 sec.

Isomerization of *cis*-*p*-Chlorocinnamic Acid.—Rate data for the isomerization of *cis*-*p*-chlorocinnamic acid were obtained over a range of acidity sufficient to show that the reaction rate parallels the acidity function with unit slope. Rate measurements were made at both 45 and 90°. The data are summarized in Table V.

TABLE V

RATE OF ISOMERIZATION OF *cis*-*p*-CHLOROCINNAMIC ACID IN AQUEOUS SULFURIC ACID

H_2SO_4, %	H_0[a]	ΔH_0[b]	Cor. H_0	$k \times 10^4$, sec.$^{-1}$	$-\log k + H_0$ Uncor.	$-\log k + H_0$ Cor.
			$T = 45.0°$			
65.00	−5.04	0.08	−4.96	0.571	−9.28	−9.20
69.64	−5.61	0.09	−5.52	2.12	−9.28	−9.19
			$T = 90.0°$			
50.35	−3.42	0	−3.42	1.95	−7.13	−7.13
54.73	−3.88	0.08	−3.80	4.18	−7.26	−7.18
55.33	−3.95	0.09	−3.86	5.03	−7.25	−7.16 [c]

[a] From Paul and Long.[14] [b] From data of Gelbstein, Shcheglova and Temkin.[15] [c] Av. = −7.16 ± 0.02.

In a separate experiment, *cis*-*p*-chlorocinnamic acid was reisolated after 1 half-life for the isomerization at 90° in sulfuric acid-d_2–deuterium oxide. Under these conditions, the *trans*-*p*-chlorocinnamic acid contained 9.59 atom % excess of deuterium, while the recovered *cis*-*p*-chlorocinnamic acid contained essentially no deuterium (0.3 atom % excess).

Activation Parameters.—The activation parameters for the three cinnamic acids are compared in Table VI. The extrapolation of the rate data to unit activity for the hydrogen ion ($h_0 = 1$) is, of course, severe for *cis*-*p*-chlorocinnamic acid. Nevertheless, the data reveal a nearly constant entropy of activation for all three compounds with the difference in rate being due to differences in the energy of activation.

TABLE VI

ACTIVATION PARAMETERS

Acid	$\Delta F^{\ddagger}$, kcal./mole	$\Delta H^{\ddagger}$, kcal./mole	$\Delta S^{\ddagger}$, e.u.
cis-*p*-Methoxycinnamic	26.8	18.3	−26.7
cis-Cinnamic[4]	31.5	23.4	−26 ± 3
cis-*p*-Chlorocinnamic	32.1	23.4	∼−27

Effect of Substituents on Reaction Rate.—The rate data obtained at 45° allow construction of a Hammett plot depicting substituted *cis*-cinnamic acid reactivities as a function of substituent constants. We have chosen to use the σ^+-constants of Brown and Okamoto[16] in correlating the data. The value of ρ is −4.3. Correlation of rates with σ^+ indicates important resonance interactions between the *para* substituent and the electron-deficient center (of the incipient carbonium ion) at the transition state. The high sensitivity of the reaction to substituents, with electron release stabilizing the transition state and thus facilitating reaction, leads to the conclusion that substantial positive charge is developed at the benzylic carbon in the transition state.

TABLE VII

RATE DATA FOR ISOMERIZATION OF *cis*-CINNAMIC ACIDS AT 45.0° IN SULFURIC ACID

cis-Cinnamic acids	log *k*, sec.$^{-1}$[a]	σ^+
p-Methoxy	−5.57	−0.778
Unsubstituted	−8.92	0
p-Chloro	−9.20	+0.114

[a] Extrapolated to $h_0 = 1$.

Other carbonium ion reactions give similarly large, negative values of ρ. In the study by Brown and Okamoto,[16] the solvolysis of cumyl chlorides gives a $\rho = -4.54$; the ionization of diarylcarbinols in sulfuric acid[17] correlates $\rho = -4.74$; and we obtain a ρ of −4.6 for the rates of dehydration of β-aryl-β-hydroxypropionic acids.[6]

Conclusions.—The foregoing body of information supports the conclusion that the isomerization of the three *cis*-cinnamic acids is proceeding by a common mechanism. The data also clearly show a high degree of positive charge at the transition state with strong resonance interaction with the benzene ring.

(16) H. C. Brown and Y. Okamoto, *J. Am. Chem. Soc.*, **80**, 4979 (1958).

(17) N. C. Deno and A. Schriesheim, *ibid.*, **77**, 3051 (1955); N. C. Deno and W. L. Evans, *ibid.*, **79**, 5804 (1957).