The Stereochemistry of the Decarboxylative Dehydration of β-Hydroxy Acids[1]

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Abstract: The stereochemistry of decarboxylative dehydration of a known pair of diastereoisomeric β-hydroxypropionic acids has been determined. Both *threo*- and *erythro*-β-hydroxy-α-methyl-β-(*p*-tolyl)propionic acids have been prepared and their configurations established. Both epimeric acids were found to give the same *cis*-/*trans*-*p*-propenyltoluene product mixture (2% *cis*, 98% *trans*) upon decarboxylative dehydration at 98° in citrate buffers in the pH range 1–6. Epimerization of the hydroxy acids is strongly acid dependent while decarboxylation is not. At high pH values, decarboxylation is faster than the epimerization of either diastereoisomer. A mechanistic scheme has been proposed for decarboxylative dehydration involving preliminary equilibration of the hydroxy acid and its zwitterion, $ArC^{+}(OH_2)HC(CH_3)HCOO^{-}$. Rate-determining loss of water from the zwitterion results in a dipolar ion, $Ar^{+}CHC(CH_3)HCOO^{-}$, which loses any configurational memory by rotation prior to rapid decarboxylation.

It has been known for some time that β-hydroxy acids lose the elements of water and carbon dioxide to yield unsaturated hydrocarbons. This decarboxylative dehydration reaction occurs under widely varying conditions and is of general utility in synthetic procedures. Little work, however, has been done on elucidating the mechanism of this reaction.

Heating generally promotes decarboxylative dehydration of β-hydroxy acids. Such behavior was first observed by Fittig[2] and his coworkers; thermal decomposition of α,α-dimethyl-β-hydroxy-β-phenylpropionic acid resulted in carbon dioxide and β,β-dimethylstyrene. Schroeter[3] established that β-alkyl-β-hydroxy-β-phenylpropionic acids also decarboxylate upon heating above their melting points. Similar treatment of a number of α- and ring-alkyl-substituted cyclohexanolacetic acids[4] produced unsaturated hydrocarbons.

Recently, Vilkas and Abraham[5] prepared a number of exocyclic olefins in high yield by heating the corresponding β-hydroxy acids in quinoline in the presence of a small amount of copper powder. They propose the decarboxylative dehydration does not involve a "free" β-carbonium ion since thermal decomposition of nopinolacetic acid, in quinoline with a catalytic quantity of toluenesulfonic acid, produces none of the expected Wagner–Meerwein rearrangement products. However, compounds capable of stabilizing a positive charge at the β-carbon atom were found to decompose at considerably lower temperatures.

Other examples include the observation of Strzhalkovski[6] that *p*-propenyltoluene is formed upon boiling a solution of β-hydroxy-α-methyl-β-(*p*-tolyl)propionic acid in aqueous sulfuric acid, and the careful study of Pressman and Lucas[7] of the decarboxylation of β-hydroxyisovaleric acid to give *t*-butyl alcohol *via* isobutylene. Similarly Reformatsky and Plesconosgoff[8] observed the formation of dimethylisopropylcarbinol from α,α-dimethyl-β-hydroxyisovaleric acid.

We have previously reported several observations serving to delineate many of the mechanistic features of the decarboxylative dehydration reaction. In our previous studies[9–11] it was observed that the decarboxylative dehydration of β-hydroxy acids exhibits several unusual characteristics. First the reaction rate is relatively insensitive to the mineral acid content of the medium, with slopes of log k_{CO_2} *vs.* $-H_0$ being about 0.3–0.5; no reaction occurs in strongly basic solution. The reaction is strongly inhibited in nonpolar solvents suggesting a very polar transition state for the decarboxylation process.

In the present study we wish to examine the stereochemistry of the decarboxylative dehydration. For meaningful results, such studies must be carried out under conditions such that racemization or epimerization of the hydroxylic center is not a rapid prior reaction. Aqueous acidic solutions of relatively high pH meet this requirement. In the present study it was found that β-hydroxy-α-methyl-β-(*p*-tolyl)propionic acid (**1**) fulfilled the structural requirements and had a sufficient degree of reactivity.

It is first necessary to establish the configuration of the two diastereoisomers of **1**. This was done by careful examination of the nmr spectra of the separated diastereoisomers. Canciell, Basselier, and Jacques[12] have shown that the configuration of the epimers of methyl β-hydroxy-α-methyl-β-phenylpropionate may be established by nmr, with the *threo* isomer exhibiting a larger $J_{\alpha\beta}$ and a larger τ value for the β hydrogen. By extension of this method to **1** we find that the isomer of mp 118.5–119.5° is the *erythro* isomer. The generalizations of Canciell hold not only for the methyl ester, but

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(2) (a) R. Fittig and H. W. Jayne, *Ann.*, **216**, 115 (1883); (b) R. Fittig and P. Ott, *ibid.*, **227**, 61 (1885).
(3) G. Schroeter, *Ber.*, **41**, 5 (1908).
(4) O. Wallach, *Ann.*, **365**, 255 (1909).
(5) (a) M. Vilkas and N. A. Abraham, *Bull. Soc. Chim. Fr.*, 1196 (1960); (b) N. A. Abraham and M. Vilkas, *C. R. Acad. Sci., Paris*, **248**, 2880 (1959).
(6) M. Strzhalkovski, *J. Russ. Phys. Chem. Soc.*, **41**, 18 (1909); *Chem. Abstr.*, **3**, 1761 (1909).
(7) D. Pressman and H. J. Lucas, *J. Amer. Chem. Soc.*, **62**, 2069 (1940).
(8) S. Reformatsky and B. Plesconosgoff, *Ber.*, **28**, 2839 (1895).
(9) D. S. Noyce, L. Gortler, M. J. Jorgenson, F. B. Kirby, and E. C. McGoran, *J. Amer. Chem. Soc.*, **87**, 4329 (1965).
(10) D. S. Noyce, S. K. Brauman, and F. B. Kirby, *ibid.*, **87**, 4335 (1965).
(11) D. S. Noyce, P. A. King, and G. L. Woo, *J. Org. Chem.*, **26**, 632 (1961).
(12) J. Canciell, J. Basselier, and J. Jacques, *Bull. Soc. Chim. Fr.*, 1906 (1963).

also for the acid and the ethyl ester, in chloroform, acetonitrile, and pyridine. Pyridine is a particularly useful solvent for studies of the free acid; there is less overlap of the peaks in this solvent.

Experimental Section

trans-p-**Propenyltoluene.** A solution of 36.5 g of 1-(*p*-tolyl)-1-propanol in 250 ml of benzene was refluxed for 5 hr with 10 g of phosphorus pentoxide.[13] On working up in the usual manner and fractionation with a spinning-band column [bp 74–75° (9 mm) (lit.[14] bp 83–85° (10 mm)] a pure sample of *trans-p*-propenyltoluene was obtained, homogeneous on gc and giving appropriate nmr and uv spectra.

cis-p-**Propenyltoluene.** Irradiation of *trans-p*-propenyltoluene in pentane with a 450-W Hanovia mercury lamp with quartz probe for 4 hr produced about an 80% conversion. The *cis* isomer was separated by preparative gc (20% SF 96 on 60–80 mesh Firebrick, 15 ft × $^3/_8$ in.).

*erythro- and threo-*β-**Hydroxy-**α**-methyl-**β**-(*p*-tolyl)propionic Acid.** The preparation and separation of the two isomers of **1** have been reported previously.[15] The nmr spectral data (60 MHz) are recorded in Tables I and II.

Table I. Nmr Spectral Data[a] for β-Hydroxy-α-methyl-β-(*p*-tolyl)propionic Acid in Various Solvents; Internal TMS Standard

	τ				
	Ar-H	β-H	α-H	α-CH_3	*p*-CH_3
threo (mp 119°)					
In acetonitrile		5.35 d $J_{\alpha\beta}$ = 8.5			
In $CDCl_3$	2.83 s	5.28 d $J_{\alpha\beta}$ = 8.5		8.98 d $J_{\alpha-CH_3}$ = 7.0	7.66 s
In pyridine		4.67 d $J_{\alpha\beta}$ = 8.5	6.67 q 6.82 q	8.78 d $J_{\alpha-CH_3}$ = 7.0	7.74 s
erythro (mp 108°)					
In acetonitrile		5.13 d $J_{\alpha\beta}$ = 5.5			
In $CDCl_3$	2.84 s	4.92 d $J_{\alpha\beta}$ = 4.0		8.87 d $J_{\alpha-CH_3}$ = 7.0	7.67 s
In pyridine		4.34 d $J_{\alpha\beta}$ = 5.0	6.76 q 6.85 q	8.46 d $J_{\alpha-CH_3}$ = 7.0	7.77 s

[a] *J* values in hertz; ambient temperature.

Table II. Nmr Spectral Data[a] for Ethyl β-Hydroxy-α-methyl-β-(*p*-tolyl)propionate in $CDCl_3$; External TMS Standard

	τ			
	Ar-H	β-H	α-CH_3	*p*-CH_3
threo	2.88 t	5.37 d $J_{\alpha\beta}$ = 9.0	9.10 d $J_{\alpha-CH_3}$ = 7.5	7.70 s
erythro	2.88 t	5.12 d $J_{\alpha\beta}$ = 5.5	8.87 d $J_{\alpha-CH_3}$ = 7.5	7.70 s

[a] *J* values in hertz; ambient temperature.

Decarboxylation Product Studies. A solution of the appropriate buffer (225 ml) was placed in a 1-l., three-necked, round-bottomed flask equipped with an addition funnel, distillation head with receiver, and a nitrogen inlet tube extending below the liquid surface. An additional side arm was fitted with a serum cap for injection of **1** in a small amount of ethanol. The buffer solution was heated to boiling and flushed with nitrogen. Then a solution of 0.8 g of **1** in 15 ml of absolute ethanol was injected. Heating was continued and the distillate collected slowly in the receiver which contained a small amount of 1% sodium carbonate solution. Addition of water from the dropping funnel maintained the total volume of 225 ml. As the *p*-propenyltoluene steam-distilled over, the distillate became cloudy and a film formed on the surface. The reaction mixture, however, always remained clear. After a reaction period of 5 hr measured from the time of injection of substrate, the reaction was quenched by pouring the reaction mixture over ice. The mixture was extracted with 150 ml of mixed hexanes to remove any hydrocarbons.

The remaining aqueous phase of the reaction mixture was extracted with three 300-ml portions of diethyl ether. If the pH of the buffer solution used in the experiment was 3 or greater (less acidic), the aqueous phase was acidified to a pH of **1** with 10% hydrochloric acid prior to extraction with ether. The combined ether extracts were dried over magnesium sulfate and then concentrated on the rotary evaporator. The recovered acid was weighed and the entire sample was dissolved in pyridine for analysis by nmr for per cent epimerization.

The distillate was diluted with water and shaken with a known volume of *n*-pentane (25–40 ml). Both phases were washed into a graduated cylinder with water, and the top meniscus of the pentane phase was recorded. When the separation of the two phases became sharp, the lower meniscus of the organic layer was recorded, giving the volume of this phase. The *cis–trans* ratio of *p*-propenyltoluene was obtained by injecting samples of known volume of the *n*-pentane phase directly into the vpc. From 50 to 100 μl of solution was required to give full-scale peaks and, in general, the ratio determination was repeated two or three times, the results being averaged. The isomer distribution always was determined immediately after extraction with *n*-pentane and always without concentration of the pentane phase. The vpc column had been calibrated for *p*-propenyltoluene and, consequently, the yield of the styrene, in pentane solution, could be estimated.

From the percentage of recovered starting material and the percentage of epimerization assuming an equilibrium ratio of 40:60 *erythro*:*threo*, integrated rate constants for decarboxylation and epimerization were calculated.

Buffer Solutions. Citrate buffers were used in order to have a single buffer over a fairly wide pH range. They were prepared as described by Sorensen.[16] Walbaum[17] has found that the pH of citrate buffers in the range of pH of 1–5 are constant from 10 to 70° and Cohen and Jones[18] have found that the change in pH between 25 and 100° is less than 0.1 for citrate buffers containing added potassium chloride. Hence, though the exact pH of the buffers used here is not known exactly at 100°, it appears probable that the value at 70° is within 0.1 unit of the correct value. This is of sufficient accuracy for comparison of extent of reaction at different pH's.

Olefin Analysis. The *cis–trans* ratio of *p*-propenyltoluenes was determined by vpc analysis using an Aerograph gas chromatograph and a recorder equipped with a disk integrator. The column was 20% Carbowax 20M on 60–80 mesh Chromosorb W, 5 ft × 0.25 in. At a column temperature of 135° the retention time for *cis-p*-propenyltoluene was 7.5 min, for *trans-p*-propenyltoluene 10.25 min.

Duplicate analyses were carried out; results were ±0.5%. Careful calibration with known samples and with standard solutions of the olefins allowed determination of yields as well as ratios of the two olefins.

Control Experiments. Though the propenyltoluenes decompose rather quickly at room temperature, they were found to be quite stable when stored under nitrogen in the cold. Samples of the separate pure isomers showed a single peak on vpc on both silicone and Carbowax columns. Carbowax columns gave the better resolution of a mixture for analysis.

A mixture (16% *cis*, 84% *trans*) of the *p*-propenyltoluenes was recycled through the hot decarboxylation procedure and upon reanalysis showed 15.5% *cis*- and 84.5% *trans-p*-propenyltoluene; the recovery was 86%.

The *cis–trans* ratio was also found to remain constant during the course of the steam distillation. Using a sodium formate–formic acid buffer and starting with *erythro*-**1**, the distillate was collected in ten fractions over a period of 43 hr and each was analyzed separately. The results are given in Table III. At the end of this period the aqueous buffer solution afforded a 5% recovery of **1**, which analyzed by nmr for 76% *erythro*-**1** and 24% *threo*-**1**.

(13) J. H. Brown and C. S. Marvel, *J. Amer. Chem. Soc.*, **59**, 1176 (1937).
(14) F. Kunckell, *Ber. Pharm. Ges.*, **22**, 180 (1912); *Chem. Abstr.*, **6**, 2410 (1912).
(15) D. S. Noyce and S. K. Brauman, *J. Org. Chem.*, **33**, 843 (1968).
(16) S. P. L. Sorensen, *Ergeb. Physiol. Biol. Chem. Exptl. Pharmakol*, **12**, 393 (1912).
(17) L. W. Walbaum, *Biochem. Z.*, **107**, 219 (1920).
(18) L. A. Cohen and W. M. Jones, *J. Amer. Chem. Soc.*, 82, 1907 (1960).

Table III. Isomer Distribution in the *p*-Propenyltoluene Formed as a Function of Time in Formic Acid–Sodium Formate Buffer at 98°

Fraction no.	Time, hr	*cis*, %
1	3.5	1.7
2	7.5	2.1
3	12.3	1.5
4	14.8	2.1
5	18.3	2.1
6	21.3	2.0
7	24.3	2.1
8	26.3	1.5
9	36.5	1.1
10	43.0	2.2
		Av 1.8 ± 0.3

The citrate buffers were stable under the conditions of the decarboxylative dehydration as shown by measurement of the pH of samples before heating and after boiling for 12–18 hr.

Results

The decarboxylative dehydration of both stereoisomers of **1** proceeds at a modest rate at 98°; at a pH of 1.2 the half-life for decarboxylation is just about 5 hr. The reaction is slower at higher pH's; at a pH of 5 only 15% decarboxylation occurs in 5 hr. Concomitantly, substantial epimerization occurs at a pH of 1.2, but no epimerization is observed in 5 hr at a pH of 5 or 6. The contrast is to be noted; epimerization is strongly acid catalyzed whereas decarboxylation is not. Thus, at high pH's the stereochemistry of the decarboxylative dehydration may be studied without interference from prior epimerization.

Data for the extent of decarboxylation and the extent of epimerization are given in Tables IV and V. Also given in Tables IV and V are the approximate rate constants. Though the rates of decarboxylation of the two isomers are similar, evidence from other studies[19] indicate that they are not identical.

The *p*-propenyltoluene which was isolated from each of these runs was analyzed by vpc for the isomer content. Though difficulty was encountered in several experiments due to partial polymerization of the olefin, it was shown that the isomer composition was not substantially affected by partial loss due to polymerization.

These results (Table VI) clearly show that at high pH's the decarboxylative dehydration is not stereospecific, but results in the more stable isomer. As the same *cis–trans* ratio (2:98) is found under all conditions studied, we conclude that this represents the fundamental stereochemical characteristic of the decarboxylative dehydration.

Table IV. Decarboxylation of *threo*-**1** in Citrate Bufiers at 98°

pH	Total acid recovered,[a] %	$k_{-CO_2} \times 10^5$, sec^{-1}	*erythro* acid, %	$k_{epim} \times 10^6$, sec^{-1}
1.2	46.2	4.3	40.4	...
1.9	67.6	2.2	11.7	19
3.0	71.0	1.9	2.9	4.2
3.9	87.2	0.76	2.3	3.3
4.9	84.2	0.96	0.0	...
6.4	85.7	0.86	0.0	...

[a] Amount of total β-hydroxy acid recovered after heating for 5 hr.

Table V. Decarboxylation of *erythro*-**1** in Citrate Buffers at 98°

pH	Total acid recovered,[a] %	$k_{-CO_2} \times 10^5$, sec^{-1}	*threo* acid, %	$k_{epim} \times 10^6$, sec^{-1}
1.2	49.6	3.9	46.7	84
1.9	65.3	2.4	22.9	27
3.0	67.2	2.2	5.3	5.1
3.0[b]	64.3	2.7	...	3.3[c]
3.9	72.3	1.8	0.1	0.1
4.9	86.2	0.83	0.0	...
6.4	90.3	0.57	0.0	...

[a] Amount of total β-hydroxy acid recovered after heating for 5 hr at 98°. [b] In formic acid–sodium formate buffer for 4.5 hr. [c] Determined from the observation of the formation of 24% of *threo*-**1** in the hydroxy acids recovered after heating for 43 hr; *cf.* Table III.

Table VI. Olefin Formation in the Decarboxylation of **1** in Citrate Buffers at 98°

	from *threo*-**1**			from *erythro*-**1**		
pH	% neutral[a]	% ene[a]	% *cis*[b]	% neutral[a]	% ene	% *cis*[b]
1.2	87	65	2.1	..	70	2.0
1.9	...	53	2.6	..	54	2.4
3.0	...	21[c]	3.3	..	24[c]	1.0[c]
3.0[d]	...	..	2.7	..	..	2.1
3.9	100+	69	3.1	..	54	1.6
4.9	60	22	4.4	61	29	1.8
5.4	66	3	2.8	83	12	1.4

[a] Yield based on amounts of acid which reacted; see Tables IV and V. [b] Percentage of isolated *p*-propenyltoluene which was *cis*. [c] Large losses due to evaporation. [d] In formic acid–sodium formate buffer.

Discussion

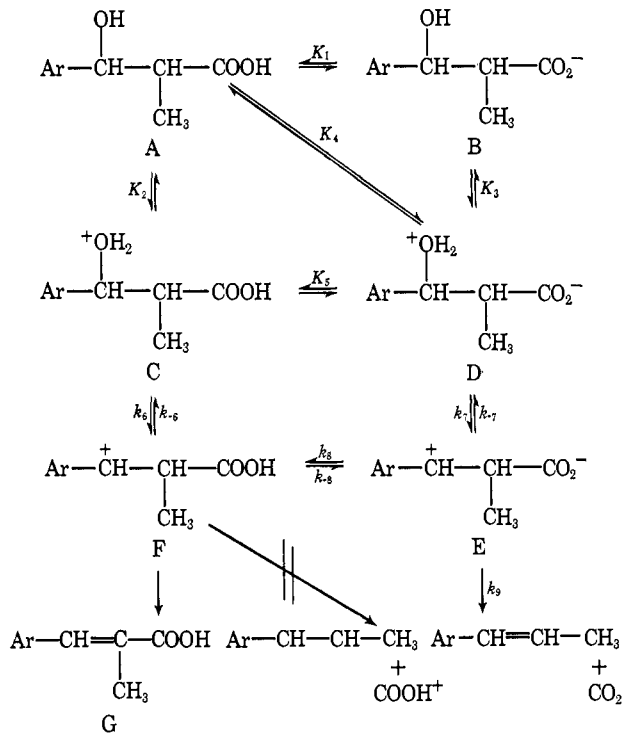
The results just summarized immediately exclude several reaction pathways. A simultaneous loss of the elements of water and carbon dioxide by way of a *trans* coplanar transition state is excluded. Also excluded is a reaction sequence in which the hydroxy acid is converted stereospecifically to the corresponding β-lactone and subsequent decarboxylation of the β-lactone,[20] as the decarboxylation of β-lactones has been shown to be a stereospecific *cis* elimination. It also appears abundantly clear that the rate-determining step cannot be loss of water from the protonated hydroxy acid, or else the acidity dependence of the decarboxylation rate would parallel the rate of epimerization (or/and the rate of dehydration).

Of the various reaction pathways which might be considered, it is most helpful to examine those outlined in Chart I.

In order to determine the reaction pathway, it is necessary to identify the decarboxylating species. As the previous discussion shows, the results exclude structures A, B, C, and D as this reactive species. In addition, structure F cannot represent the decarboxylating species, for a singular relationship would then exist among the possible modes of reaction of F. At very high concentrations of mineral acid, epimerization and

(19) D. S. Noyce and E. C. McGoran, in preparation.
(20) D. S. Noyce and E. G. Banitt, *J. Org. Chem.*, 31, 4043 (1966).

Chart I



dehydration are *faster* than decarboxylative dehydration, but in solutions of relatively high pH, epimerization and dehydration are *slower* than decarboxylative dehydration. Epimerization (or the equivalent process, racemization) is strongly acid catalyzed, and the sequence A ⇄ C ⇄ F represents this process. Acid-dependent dehydration is represented by A ⇄ C ⇄ F ⇄ G.

Thus, the dipolar ion, E, appears to be the decarboxylating species. Since E is not in equilibrium with A, k_9 is not the rate-limiting step. It is possible to predict kinetically which of the two precursors D and F is involved in the predominant pathway to E. The sequence including F

$$A \rightleftharpoons C \xrightarrow{\text{rds}} F \rightleftharpoons E$$

can be excluded for lack of appropriate acidity dependence. In addition, the other pathway through F

$$A \rightleftharpoons C \rightleftharpoons F \xrightarrow{\text{rds}} E$$

also seems unlikely. The interconversion F → E involves only proton transfer to and from oxygen and is therefore extremely rapid.[21] It is thus difficult to imagine k_8 representing the rate-limiting process. Alternatively, the reaction sequence involving precursor D

$$A \rightleftharpoons D \xrightarrow{\text{rds}} E$$

readily accommodates all the experimental evidence. Hence we favor this reaction pathway in which k_7 represents the rate-limiting step.

The reaction sequence, A ⇄ D → E, has several interesting features arising from the restrictions imposed by the results. Both stereoisomers of **1** give mostly *trans-p*-propenyltoluene. This means that as the dipolar ion E is generated from D, both stereoisomers must lose any stereochemical memory, without regenerating D as a mixture of stereoisomers. This is feasible, taking into account the following considerations. If E is symmetrically solvated this requirement is satisfied upon simple rotation about the C_α–C_β bond. As this rotational barrier is likely to be relatively small, this rotational process will be extremely rapid, and hence may occur prior to the loss of carbon dioxide from E, once species E is formed. Estimating this rate constant to be 10^{10} sec^{-1} at 100°,[22] k_9 can be no greater than 10^8 sec^{-1} to account for the product stereochemistry.

This sequence has a further consequence, which is even more interesting. This picture requires that the fragmentation of species E to give olefin and carbon dioxide must occur more rapidly than the collapse of dipolar ion E with water to regenerate zwitterion D. It is generally agreed that the rate of reaction of carbonium ions with solvent is a relatively rapid reaction, but few studies define the rates for such processes. In recent work, Taft[23] has investigated the reaction of substituted diarylmethyl cations with water and has shown that these processes have rate constants in the neighborhood of 10^6 M^{-1} sec^{-1}. His studies suggest that for less stable carbonium ions the rate constant is somewhat larger. The rate constant for fragmentation of species E (k_9) is thus placed between 10^6 and 10^8 sec^{-1}.

An additional consideration is important as well. Making use of the results of Eigen,[21] k_8 may be estimated to be nearly diffusion controlled. Thus, the failure of the dipolar ion to protonate in the pH range studied is presumably due to the low hydrogen ion concentration. Hence, we favor the higher value of k_9.

These considerations support the dipolar ion E as the active decarboxylating species. It is formed by the sequence A ⇄ D ⇄ E, and analogies make this pathway attractive. For example, the decomposition of β-bromo acids in alkaline solution has been studied by Cristol and Norris[24] and by Grovenstein and Lee.[25] Though the reaction was stereospecific in nonaqueous solvents, there was a marked tendency for both stereoisomers to give the same olefin in aqueous solution. This result is completely concordant with our observations: loss of bromide ion from the carboxylate salt is followed by very rapid rotation in the dipolar ion analogous to E and then loss of carbon dioxide to give the final olefin. A very similar intermediate was proposed by Shiner and Martin[26] in the decomposition of glycidic acids, and the similarity to the decarboxylation of azulene-1-carboxylic acid is manifest.[27]

We conclude that all of the evidence supports dipolar ion E being the active decarboxylating species in solutions of pH 2–6. This accommodates all of the results reported, including a fairly negative ρ (*vs.* σ^+), indicating

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(22) S. W. Benson, K. W. Egger, and D. M. Golden, *J. Amer. Chem. Soc.*, 87, 468 (1965).

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(24) S. J. Cristol and W. P. Norris, *ibid.*, **75**, 632 (1953); **75**, 2645 (1953).

(25) E. Grovenstein, Jr., and D. E. Lee, *ibid.*, **75**, 2639 (1953); E. Grovenstein, Jr., and S. P. Theophilou, *ibid.*, 77, 3795 (1955).

(26) V. J. Shiner, Jr., and B. Martin, *ibid.*, **84**, 4824 (1962).

(27) F. A. Long, personal communication; *cf.* F. A. Long and J. L. Longridge, *ibid.*, **90**, 3092 (1968).

a high degree of positive charge at the benzyl carbon, and a positive entropy of activation,[19] consistent with a fragmentation step as the rate-determining process.

In summary, decarboxylative dehydration is a sequential process in which loss of water from zwitterion D to give the dipolar ion E is rate controlling in weakly acidic solution. Species E does not return to D; rapid rotation about the C_α–C_β bond of E occurs prior to fragmentation to give carbon dioxide and *trans*-*p*-propenyltoluene.

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Cyclopropanes. XXIV. Sodium–Liquid Ammonia Reduction of Optically Active Cyclopropyl Halides[1]

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Abstract: The reduction of (−)-(*R*)-1-halo-1-methyl-2,2-diphenylcyclopropane (**1**) leads to the formation of optically active (+)-(*S*)-1-methyl-2,2-diphenylcyclopropane (**2**) with over-all retention of configuration, as well as two ring-opened products, 1,1-diphenyl-2-methylpropane (**3**) and 1,1-diphenylbutane (**4**). The amount of optical activity observed in **2** is dependent on the nature of the starting halogen (Cl > Br > I), the concentration of the sodium in liquid ammonia solution, and a heterogeneity factor.

Sodium in liquid ammonia solutions have been used for some time as a means of reducing organic halides to hydrocarbons; indeed, this reaction is the basis for a quantitative determination of halogen in such compounds.[2] The mechanism of such reactions has, however, been speculative. Two mechanisms have generally been considered: the displacement of halogen as an anion in a two-electron process leading to the formation of a carbanion (eq 1), and a one-electron displacement of halogen as an anion leading to a carbon radical (eq 2) which can then react with solvent or add another electron to give a carbanion intermediate. It has been fairly well established that

$$\text{R–X} + 2e^- \longrightarrow \text{R}^- + \text{X}^- \quad (1)$$

$$\text{R–X} + e^- \longrightarrow \text{R}\cdot + \text{X}^- \quad (2)$$

radical intermediates generally lead to products which reflect loss of configurational stability whereas carbanionic intermediates often give products whose configuration is maintained. Several workers have used these observations in trying to decide between the two possible mechanisms shown above for reduction of organic halides by solutions of sodium in liquid ammonia. Thus Verkade and coworkers[3] have reduced optically active (−)-6-chloro-2,6-dimethyloctane and obtained optically active (+)-2,6-dimethyloctane with over-all retention of configuration and an optical purity of at least 20%. They have interpreted their results as favoring eq 1 as the mechanism for such reductions. The low optical purity of the product presumably reflects the fact that carbanions derived from tetrahedrally substituted halides are not very optically stable. Hoff, Greenlee, and Boord[4] have carried out the reduction of 3-chloro-*cis*-3-hexene and 3-chloro-*trans*-3-hexene and obtained *cis*-3-hexene and *trans*-3-hexene, respectively. Again these results have been interpreted to favor a carbanionic mechanism rather than one of radical nature and support the existing acceptance of configurational stability of trigonally hybridized carbanions.

It has been well established that the cyclopropyl carbanion derived from optically active 1-bromo-1-methyl-2,2-diphenylcyclopropane (**1**) is capable of retaining its optical activity and configuration.[5] It has also been demonstrated that when the corresponding radical is generated, the bulk of the products isolated are racemic.[6] For these reasons it was believed that one could use the reduction of this optically active halide with sodium in liquid ammonia as a tool to shed further light on the mechanism of such reductions.

The chemical composition and physical properties of solutions of sodium in liquid ammonia have been known for some time to depend upon the concentration of these solutions. In particular, physical measurements have generally shown that such solutions pass from conditions where they contain essentially free solvated electrons at very high dilution (0.003 *M*), through solutions having saltlike characteristics

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