

of the steric origin of all secondary isotope rate effects, it appears unlikely that the present results can be explained by change in either steric or solvent interactions on activation without the incursion of electronic interactions with the reaction center.

If the δ -effect is entirely electronic in origin, it remains to predict from this what fraction of the approximately 3-fold larger effect in the β -position is similarly electrical in origin and to estimate by difference what residual amount could be attributed to changes in nonbonded interactions. It has been found that the triple bond generally attenuates the inductive effect by a factor around three or four.²² However, the present effect is certainly mainly conjugative in nature. Kochi

paper this problem is met by a model involving charge delocalization. This is tantamount to invoking hyperconjugation but includes the novel idea that relief of nonbonded interactions assists hyperconjugative electron release.

(21) M. J. S. Dewar, "Hyperconjugation," The Ronald Press, New York, N. Y., 1962, p. 141.

(22) R. E. Dessy and J.-Y. Kim, *J. Am. Chem. Soc.*, **83**, 1167 (1961), and references there cited.

and Hammond²³ have estimated that the carbon-carbon triple bond is a four- or fivefold poorer conjugative electron releaser than the double bond. Thus we can infer that the part of the β -effect caused by electronic interactions would be much larger than 1.10 and *might* be large enough to account for the total observed. Nevertheless, it is not possible at the present time to conclude that there is *no* small "steric" component in the β -effect. The strong solvent dependencies of isotope effects transmitted by conjugation through the benzene ring remain to be elucidated by further experiments.

Acknowledgment.—This research was 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. The facilities of the Indiana University Computing Center were used for the machine computations.

(23) J. K. Kochi and G. S. Hammond, *ibid.*, **75**, 3452 (1953).

[CONTRIBUTION No. 3051 FROM THE GATES AND CRELLIN LABORATORIES OF CHEMISTRY, CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIF., AND THE DEPARTMENT OF CHEMISTRY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASS.]

Small-Ring Compounds. XLII. Synthesis and Reactions of 3-Phenyl-2-cyclobutenone and Some Related Compounds^{1,2}

BY STANLEY L. MANATT,³ MARTIN VOGEL, DAVID KNUTSON, AND JOHN D. ROBERTS

RECEIVED JANUARY 20, 1964

Hydrogenation of either 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane (VII) or 1,1-difluoro-2,2-dichloro-2-phenylcyclobutene (VI) over a palladium-on-charcoal catalyst gave 1,1-difluoro-3-phenylcyclobutane (V). Bromination of V by N-bromosuccinimide produced 1,1-difluoro-3-bromo-3-phenylcyclobutane (IX) which on dehydrobromination by potassium hydroxide in ethanol afforded 1,1-difluoro-3-phenyl-2-cyclobutene (IV). Hydrolysis of IV by concentrated sulfuric acid gave 3-phenyl-2-cyclobutenone (I). Treatment of I with hot dilute aqueous base produced mixtures of benzoic acid, acetophenone, and benzoylacetone. The ring opening of I in boiling acetic acid gave β -methyl-*trans*-cinnamic acid. Catalytic hydrogenation of I produced 3-phenylcyclobutanone (XI). Sodium borohydride reduction of I afforded 3-phenyl-2-cyclobutenol (XII) which on catalytic hydrogenation gave *cis*-3-phenylcyclobutanol (XIII); XIII was also obtained by catalytic hydrogenation of 2-chloro-3-phenyl-2-cyclobutenol (XVI) from the sodium borohydride reduction of 2-chloro-3-phenyl-2-cyclobutenone (XV).

Introduction

The cycloaddition reactions of styrene and phenylacetylene with either 1,1-difluoro-2,2-dichloroethylene, 1,1,2-trifluoro-2-chloroethylene, or tetrafluoroethylene give adducts whose conversion to substituted (either halogen- or alkoxy-substituted) 3-phenyl-2-cyclobutenones has been described in earlier papers.⁴ The ring-opening reactions of a number of substituted 3-phenyl-2-cyclobutenones have also been discussed previously.^{4a,4c,5}

(1) Presented in part at the Fourteenth National Organic Chemistry Symposium of the American Chemical Society, Lafayette, Ind., June, 1955, and at the 138th National Meeting of the American Chemical Society, New York, N. Y., Sept. 15, 1960, Abstracts of Papers, p. 72P.

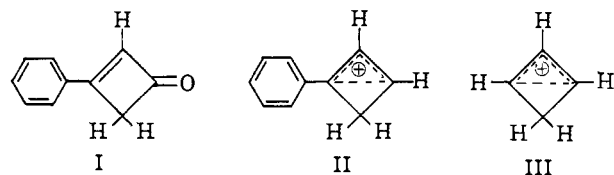
(2) Supported in part by the National Science Foundation.

(3) Monsanto Chemical Co. Predoctoral Fellow, 1957-1958.

(4) (a) J. D. Roberts, G. B. Kline, and H. E. Simmons, Jr., *J. Am. Chem. Soc.*, **75**, 4765 (1953); (b) E. F. Silversmith and J. D. Roberts, *ibid.*, **80**, 4083 (1958); (c) E. F. Silversmith, Y. Kitahara, M. C. Caserio, and J. D. Roberts, *ibid.*, **80**, 5840 (1958); (d) E. J. Smutny, M. C. Caserio, and J. D. Roberts, *ibid.*, **82**, 1793 (1960); (e) M. C. Caserio, H. E. Simmons, Jr., A. E. Johnson, and J. D. Roberts, *ibid.*, **82**, 3102 (1960); (f) Y. Kitahara, M. C. Caserio, F. Scardiglia, and J. D. Roberts, *ibid.*, **82**, 3106 (1960).

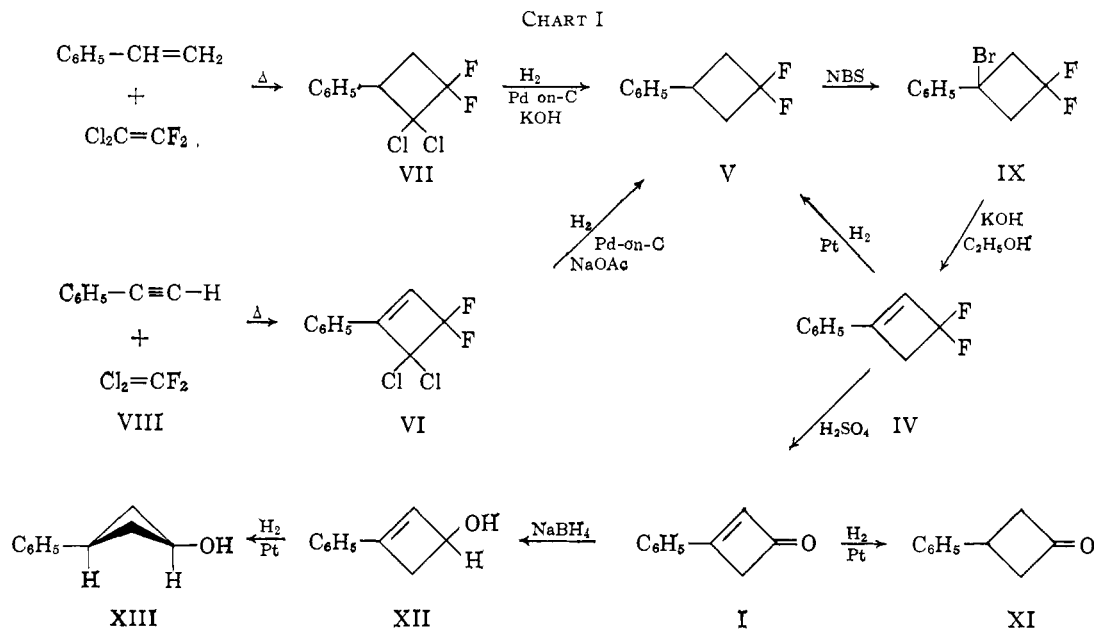
(5) (a) E. F. Jenny and J. D. Roberts, *ibid.*, **78**, 2005 (1956); (b) E. F. Silversmith and J. D. Roberts, *ibid.*, **78**, 4023 (1956); (c) L. Skattebøl and J. D. Roberts, *ibid.*, **80**, 4085 (1958); (d) E. F. Silversmith, Y. Kitahara, and J. D. Roberts, *ibid.*, **80**, 4088 (1958).

The present research was concerned with the synthesis and ring-opening reactions of 3-phenyl-2-cyclobutenone itself (I) as well as the chemistry of some of its derivatives. A synthesis of I was desired as a precursor to derivatives from which a 3-phenyl-2-cyclobutenyl cation (II) might be generated by suitable solvolyses or deamination reactions. Simple LCAO-molecular orbital calculations suggest that delocaliza-



tion of electrons as the result of π -overlap between the p-orbitals on the 1- and 3-positions in the cations II and III could well result in significant enhancement of the S_N1 solvolysis rates of substances which could yield II and III over those for suitable model compounds.

The cations in question are of the homocyclopropenyl type and are expected to possess at least some of the stabilization predicted by the simple LCAO-MO



method^{6,7} for cyclopropenyl cations and verified by Breslow and co-workers.⁸ Some evidence for homocyclopropenyl-type stabilization of cyclobutenylcarbonium ions has already been deduced from the solvolysis rate of 1-methyl-2-cyclobutenyl bromide which is about 10^3 – 10^5 times larger than expected unless account is taken of stabilization of the solvolytic transition state by 1,3- π -electron delocalization.⁹ As part of the present research, solvolyses of the 4-nitrobenzoates of 3-phenyl-2-cyclobutenol (XII) and 2-chloro-3-phenyl-2-cyclobutenol (XVI) were investigated in hope of throwing more light on the factors governing 1,3- π -type stabilization of cyclic carbonium ions.

Synthetic Methods.—Simmons¹⁰ attempted the synthesis of 3-phenyl-2-cyclobutenone (I) by a thermal cycloaddition reaction between phenylacetylene and ketene at 100° , but only red tarry products were obtained. However, it is now known that any I formed would probably have been destroyed under these conditions. The possibility of obtaining I from this reaction under milder conditions with longer reaction times has not been investigated. The fact that a *gem*-difluoro group in the 1-position of 3-phenyl-2-cyclobutenes can be hydrolyzed by concentrated sulfuric acid to give the corresponding ketones⁴ suggested a synthesis of I from 1,1-difluoro-3-phenyl-2-cyclobutene (IV) (see Chart I). Preparation of IV by way of cycloaddition of phenylacetylene and 1,1-difluoroethylene was unsuccessful because 1,1-difluoroethylene is not very active in cycloaddition¹¹ and, furthermore, because the product is not very stable to heat. A successful route to IV was achieved by bromination of 1,1-difluoro-3-phenylcyclobutane (V)¹² with N-bromosuccinimide at the 3-position and then elimination of hydrogen bromide with ethanolic potassium hydroxide.

(6) J. D. Roberts, A. Streitwieser, Jr., and C. M. Regan, *J. Am. Chem. Soc.*, **74**, 4579 (1952).

(7) S. L. Manatt and J. D. Roberts, *J. Org. Chem.*, **24**, 1336 (1959).

(8) R. Breslow, *J. Am. Chem. Soc.*, **79**, 5318 (1957); R. Breslow and C. Yuan, *ibid.*, **80**, 5991 (1958).

(9) E. F. Kiefer and J. D. Roberts, *ibid.*, **84**, 784 (1962).

(10) H. E. Simmons, Jr., B.S. Thesis, Massachusetts Institute of Technology, 1951.

(11) J. D. Roberts and C. M. Sharts in "Organic Reactions," Vol. 12, A. C. Cope, Ed., John Wiley and Sons, Inc., New York, N. Y., 1962, p. 1.

It was found that the yields in the previously reported catalytic hydrogenation of 1,1-difluoro-2,2-dichloro-3-phenylcyclobutene (VI) to V could be improved to 78–85% by using sodium acetate as a buffer in place of sodium carbonate.^{4a} Comparable yields could also be achieved by simultaneous dehydrogenation and hydrogenation of 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane (VII),^{4c} and this is the method of choice since VII is easily prepared by addition of 1,1-dichloro-2,2-difluoroethylene (VIII) to styrene.

Bromination of the cyclobutane V was achieved with N-bromosuccinimide in carbon tetrachloride. The product decomposes readily and is best distilled below 60° . The yield of 1,1-difluoro-3-bromo-3-phenylcyclobutane (IX) was 91–99%. The presence of 1,1-difluoro-2-bromo-3-phenylcyclobutane (X) in the product could be ruled out by the ^1H and ^{19}F n.m.r. spectra.

Attempted dehydrobromination of IX by either pyridine or quinoline proved unsatisfactory and led to highly colored products. Addition of IX at room temperature to an ethanolic or methanolic solution of potassium hydroxide resulted in smooth elimination of hydrogen bromide. Careful isolation and distillation of the product gave 89–95% yields of colorless 1,1-difluoro-3-phenyl-2-cyclobutene (IV). This substance is sensitive to air and decomposes rapidly to a deep purple colored mass with the liberation of hydrogen fluoride. Similar decomposition may take place if IV is heated much above 60° .

Compound IV reacts readily with bromine in carbon tetrachloride and potassium permanganate in acetone. On catalytic hydrogenation, 96% of the theoretical amount of hydrogen for one double bond is taken up and 1,1-difluoro-3-phenylcyclobutane (V) is formed. The ^1H and ^{19}F n.m.r. spectra of V are those of an AM_2X_2 ¹² nuclear spin system and are consistent with the proposed structure. The infrared spectrum of V showed absorption bands at 6.16 ($\text{C}=\text{C}$ stretch) and 6.97 μ (methylene deformation).

Sulfuric acid hydrolysis of V was carried out many times and it soon became apparent that the yield of 3-

(12) The notation is that used in "High-resolution Nuclear Magnetic Resonance," J. A. Pople, W. G. Schneider, and H. J. Bernstein, McGraw-Hill Book Co., Inc., New York, N. Y., 1959, p. 98.

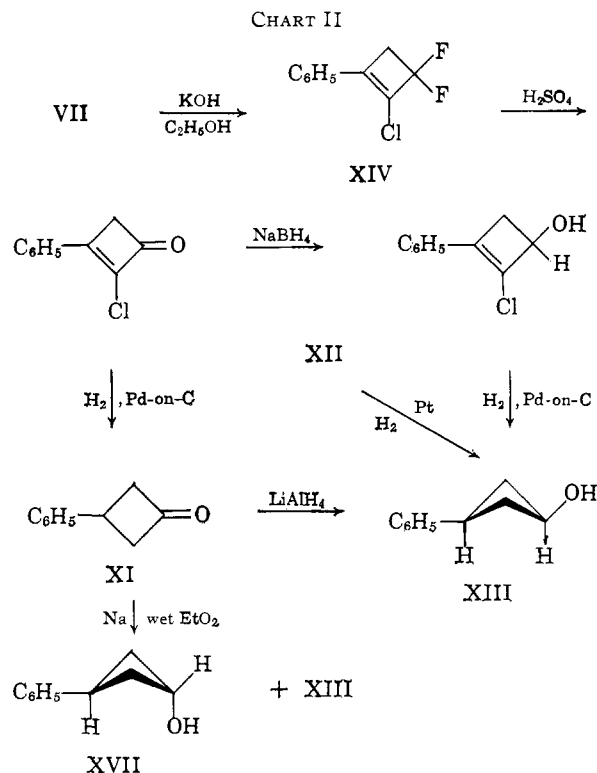
phenyl-2-cyclobutenone (I) was very dependent on the temperature and duration of the reaction. Similar difficulties have not been observed in the analogous preparations of the halogen-substituted 3-phenyl-2-cyclobutenones previously reported.⁴ A procedure was finally developed which gave 66–89% yields of crude product. The thermal instability of ketone V precluded its purification by recrystallization in a manner similar to that used for its halogen derivatives.⁴ However, high-vacuum sublimation at temperatures below 40° gave large colorless needles which had the correct elemental analysis for I. The product gave an immediate reaction with potassium permanganate in acetone and produced benzoic acid. It decolorized bromine in carbon tetrachloride only slowly. Catalytic hydrogenation produced the previously described^{1a} 3-phenylcyclobutanone (XI) which demonstrates the presence of the four-membered ring. 3-Phenyl-2-cyclobutenone was found to be very irritating to the skin. It decomposes readily in air and darkens when exposed to strong light. From samples of decomposed I, substantial yields of β -methyl-*trans*-cinnamic acid were obtained.

The infrared spectrum of I showed absorption bands at 5.65 (C=O stretch), 6.39 (C=C stretch), and 7.05 μ (methylene deformation). The ultraviolet spectrum of I appears to be nearly normal for an α,β -unsaturated- γ -phenyl ketone (λ_{\max} 286.0 m μ and ϵ 23,000). The proton n.m.r. spectrum of the vinyl and methylene protons is that of an A₂X system ($J = 0.44$ c.p.s.). The small coupling constant is the order of magnitude of that expected for this long-range coupling.¹³

Reduction of ketone I by sodium borohydride gave 3-phenyl-2-cyclobutenol (XII) which proved to be very sensitive to air and could only be preserved under nitrogen *in vacuo*. The proton n.m.r. spectrum of alcohol XII was consistent with the assigned structure. Catalytic hydrogenation of XII gave an alcohol believed to be *cis*-3-phenylcyclobutanol (XIII). For comparison purposes, syntheses of authentic XIII were sought by reduction of 3-phenylcyclobutanone (XI) with reducing agents which would produce the *cis* isomer.

It was reported previously^{5d} that catalytic hydrogenation of 2-chloro-3-phenyl-2-cyclobutenone (XV) gave XI in 75% yield. Because rather large quantities of XI were required for other work in progress in our laboratories, some attention was given to improvement of the four-step synthesis of the ketone previously described^{5d} (see Chart II) and as a result the over-all yield from styrene was raised to 41–62%. The only step which could not be improved significantly was the cycloaddition reaction giving 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane (VII). The yields in the dehydrohalogenation of VII were raised to 91–95%. The sulfuric acid hydrolysis of XIV gave yields of 90–95%. It was found that hydrogenation of XV with 20–30% palladium-on-charcoal catalyst gave 85–91% yields of ketone XI.

Reduction of the ketone XI with lithium aluminum hydride gave only one product which was identical



with that obtained from the catalytic hydrogenation of 3-phenyl-2-cyclobutenol (XII) and believed to be the *cis*-alcohol XIII. The clear-cut stereochemical result in this reduction suggests that the 3-phenyl group in XI provides a considerable steric hindrance to approach of the reducing agent which then attacks the carbonyl group on just one side in what has been termed "steric approach control."¹⁴ Of the two possible 3-phenylcyclobutanols, *cis* and *trans*, it would seem that if the cyclobutane ring were planar the *trans* isomer should be the most thermodynamically stable. However, reduction of XI with sodium in wet ether, a reaction expected to give the thermodynamically most stable isomer, gave besides considerable polymer a mixture of starting material and two alcohols. The starting material was removed by extraction with bisulfite. Treatment of the resulting mixture of alcohols with 4-nitrobenzoyl chloride in pyridine gave a mixture of esters from which the ester of the *cis*-alcohol was isolated by fractional crystallization. The mother liquors gave a second crystalline ester which is assumed to be the 4-nitrobenzoate of *trans*-3-phenylcyclobutanol (XVII). That mixtures of the *cis*- and *trans*-alcohols appeared to be obtained in this reduction suggests that the two alcohols are of comparable thermodynamic stability as might be expected if the four-membered ring were puckered so as to reduce the 1,3-steric interaction of the hydroxy and the phenyl groups in the *cis* isomer.^{15,16}

Ring-Opening Reactions.—Treatment of 3-phenyl-2-cyclobutenone (I) with hot dilute aqueous base produces benzoic acid, acetophenone, and benzoylacetone (XVIII). Benzoylacetone is known to give aceto-

(13) F. S. Mortimer, *J. Mol. Spectry*, **3**, 335 (1959); A. D. Cohen and N. Sheppard, *Proc. Roy. Soc. (London)*, **A252**, 488 (1959); A. A. Bothner-By and C. Naar-Colin, *J. Am. Chem. Soc.*, **83**, 231 (1961); R. W. Fessenden and J. S. Waugh, *J. Chem. Phys.*, **30**, 944 (1959); S. Alexander, *ibid.*, **28**, 358 (1958); **32**, 1700 (1960).

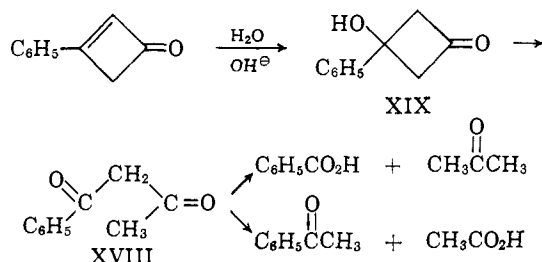
(14) W. G. Dauben, G. J. Fonken, and D. S. Noyce, *J. Am. Chem. Soc.*, **78**, 2579 (1956); W. G. Dauben, E. J. Blany, Jr., J. Liu, and R. A. Micheli, *ibid.*, **78**, 3752 (1956).

(15) M. Takahashi, D. R. Davis, and J. D. Roberts, *ibid.*, **84**, 2935 (1962).

(16) J. B. Lambert and J. D. Roberts, *ibid.*, **85**, 3710 (1963).

phenone when treated with base,¹⁷ presumably by a retrograde Claisen condensation involving initial attack of hydroxide ion on the carbonyl carbon γ to the aromatic ring. Benzoic acid could arise from benzoylacetone in a similar manner by attack of hydroxide on the carbonyl carbon α to the aromatic ring. We have observed that the treatment of benzoylacetone with hot dilute aqueous base leads to both benzoic acid and acetophenone along with acetone and acetic acid. Thus, the initially isolable product from the ring opening is likely to be benzoylacetone and the extent of its degradation to benzoic acid and acetophenone depends on the rate of the subsequent base-catalyzed cleavage.

The mechanism of the ring opening of ketone I probably involves an addition of water to the double bond induced by hydroxide ion, followed by a retrograde aldol condensation of the resulting ketol XIX.



This mechanism is in accord with the finding that cyclobutan-3-ol-1-one readily undergoes a retrograde aldol condensation with base to give acetoacetaldehyde.¹⁸

The ring opening of 3-phenyl-2-cyclobutenone (I) with alkali thus appears to follow a different course from either of the other two mechanisms which operate in base-induced ring-opening reactions of halogen-substituted 3-phenylcyclobutenones.^{4a,4c,5a,5b} With halogen-substituted derivatives of I, the products result from initial attack of hydroxide ion on the carbonyl carbon.

When 3-phenylcyclobutenone (I) is heated in acetic acid, it gives a good yield of β -methyl-*trans*-cinnamic acid. This reaction is in accord with similar ring-opening reactions of the halogen-substituted 3-phenyl-2-cyclobutenones which have been demonstrated previously to proceed by way of vinylketene intermediates. The character of the product is determined by whether the vinylketene undergoes 1,2- or 1,4-addition in formation of a carboxylic acid derivative.^{4c,5a,5b} In those cases where the bulkiness of the attached groups is such that the ketene and vinyl groups cannot achieve coplanarity, the ketene adds acetic acid in a 1,2-manner as if it were an isolated group. When the groups present are not so bulky to prevent the ketene and vinyl groups from achieving coplanarity, 1,4-addition to the vinylketene is observed. Both 3-phenyl-2-cyclobutenone and 2-fluoro-3-phenyl-2-cyclobutenone^{5b} fall into this latter category.

Hydrolysis Rate Studies.—The rates of the acid-catalyzed hydrolysis in "80%" acetone-water of the 4-nitrobenzoates of 3-phenyl-2-cyclobutenol, 2-chloro-3-phenyl-2-cyclobutenol, cinnamyl alcohol, and methylstyrylcarbinol were determined. The results are given

(17) (a) E. Fisher and C. Bülow, *Ber.*, **18**, 2131 (1885); (b) L. Claisen and O. Lowman, *ibid.*, **21**, 1149 (1888).

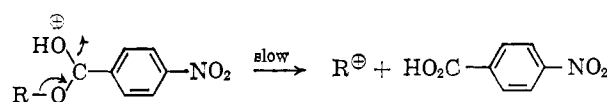
(18) E. Vogel and K. Haase, *Ann.*, **615**, 22 (1958).

TABLE I
KINETIC DATA FOR 4-NITROBENZOATES IN "80%" ACETONE-WATER AT $100.20 \pm 0.02^\circ$

4-Nitrobenzoate	k_1 , hr. ^{-1a}	k_1 , hr. ⁻¹ $\times 10$
Cinnamyl	0.083 ± 0.005	
Methylstyrylcarbinyl	$7.81 \pm .22$	
2-Chloro-3-phenyl-2-cyclobutenyl	$0.0376 \pm .0025$	
3-Phenyl-2-cyclobutenyl	$1.006 \pm .019$	2.63 ± 0.13
<i>cis</i> -5-Methyl-2-cyclohexenyl	0.799^b	1.24^b
<i>trans</i> -5-Methyl-2-cyclohexenyl	4.51^b	1.33^b

^a Perchloric acid concentration at 100° of 0.0862 N. ^b From Goering and Silversmith.¹⁹

in Table I along with the rates for *cis*- and *trans*-5-methyl-2-cyclohexenol esters previously reported by Goering and Silversmith.¹⁹ In this reaction, the rate-determining step is assumed to be a formation of a carbonium ion.



Introduction of a γ -phenyl group into an α,γ -alkyl-substituted allyl system is estimated from available data^{20,21} on the corresponding chlorides in aqueous ethanol to increase the solvolysis rate by about 10^2 . Introduction of an α -methyl group is expected to contribute an acceleration of about this same magnitude, again in the case of the chlorides in aqueous ethanol.²¹ The introduction of an α -methyl group into the γ -phenylallyl system on going from cinnamyl alcohol to methylstyrylcarbinol results in a 94-fold increase in the rate for the acid-catalyzed hydrolysis of the 4-nitrobenzoates which is about the same as that predicted for the chlorides.

Methylstyrylcarbinyl 4-nitrobenzoate has been found to be 7.8 times more reactive than 3-phenylcyclobutenyl 4-nitrobenzoate which corresponds to a difference in free energy of activation of about 1.1 kcal./mole. Because the increase in strain energy on going to a carbonium ion-type transition state in a four-membered ring compound should result in an increase of the energy of activation of at least 5 kcal. over that for an open-chain compound,⁹ it would appear that 1,3- π -interaction does contribute considerably to the stabilization of the 3-phenyl-2-cyclobutenyl carbonium ion. The 27-fold rate difference between the 3-phenyl-2-cyclobutenyl and 2-chloro-3-phenyl-2-cyclobutenyl esters can be attributed to the strong inductive effect of the vinyl chlorine atom in the latter compound.

Experimental

Microanalyses were performed by Dr. Adalbert Elek Microanalytical Laboratories, Los Angeles, Calif. Proton n.m.r. spectra were taken at 40 and 60 Mc./sec. and fluorine n.m.r. spectra at 40 and 56.4 Mc./sec. Melting points and boiling points are uncorrected. Infrared absorption spectra were determined using a Perkin-Elmer Model 21 spectrometer. Ultraviolet absorption spectra were obtained with a Cary Model 11M spectrometer. Vapor-phase chromatograms were obtained with a Perkin-Elmer Model 154-B vapor fractometer.

1,1-Difluoro-2,2-dichloro-3-phenylcyclobutene (VI) was obtained in 88% yield by heating phenylacetylene (45 g., 0.44 mole) and 1,1-difluoro-2,2-dichloroethylene (63 g., 0.46 mole) for 12

(19) H. L. Goering and E. F. Silversmith, *J. Am. Chem. Soc.*, **77**, 6249 (1955).

(20) A. Streitwieser, Jr., *Chem. Rev.*, **56**, 571 (1956).

(21) See R. H. DeWolfe and W. G. Young, *ibid.*, **56**, 753 (1956).

hr. at 130° without hydroquinone; b.p. 66–69° (0.5–0.6 mm.) and n_D^{25} 1.5423 (lit.^{1a} b.p. 109–111° at 5 mm., n_D^{25} 1.5435).

1,1-Difluoro-2,2-dichloro-3-phenylcyclobutene (VII) was obtained in 61–72% yield by heating styrene (52 g., 0.50 mole) and 1,1-difluoro-2,2-dichloroethylene (74 g., 0.55 mole) for 24 hr. at 130° without addition of hydroquinone; b.p. 78–82° (1 mm.) and n_D^{25} 1.5105 (lit.^{4b} b.p. 73.8–74.2 at 1 mm., n_D^{25} 1.5103). Considerable light brown polymeric side product is formed in this reaction.

1,1-Difluoro-3-phenylcyclobutane (V). A. From 1,1-Difluoro-2,2-dichloro-3-phenylcyclobutene (VI).—A mixture of 111 g. (0.47 mole) of 1,1-difluoro-2,2-dichloro-3-phenylcyclobutene, 75.0 g. (0.91 mole) of anhydrous sodium acetate, 3 g. of 10% palladium-on-charcoal catalyst, and 150 ml. of reagent methanol was shaken with hydrogen in a citrate bottle at about 60 p.s.i. until the calculated amount of hydrogen had been taken up; usually about a week was required except with very active catalyst. The catalyst and solids were removed by filtration and washed several times with methanol. The methanol solution was poured into 500 ml. of water, and the mixture extracted six times with a total of 1 l. of ether. The ethereal solution was dried in four stages with anhydrous magnesium sulfate and distilled. The yield of 1,1-difluoro-3-phenylcyclobutane was 61–66 g. (80–83%), b.p. 32–40° (0.8–1.0 mm.), n_D^{25} 1.4840 (lit.^{4a} b.p. 88.1–88.3° at 20 mm., n_D^{25} 1.4828), and 12 g., b.p. 52–65° (0.8–1.0 mm.), n_D^{25} 1.5050, which is a mixture of chlorofluoro-phenylcyclobutanes. The latter material can be rehydrogenated to give more of the desired product.

B. From 1,1-Difluoro-2,2-dichloro-3-phenylcyclobutane (VII).—To a cooled solution of 30.0 g. (0.447 mole) of potassium hydroxide (assay 86%) in 100 ml. of reagent methanol in a citrate bottle, 100 g. (0.420 mole) of 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane was added with swirling at such a rate that the vigorous exothermic reaction did not get out of control; sometimes cooling with an ice bath was necessary. The bottle was flushed with nitrogen, 3 g. of 10% palladium-on-charcoal catalyst was added, and the mixture shaken with hydrogen at 60 p.s.i., until approximately 1 equivalent of hydrogen had been taken up; at this point 28 g. (0.41 mole) more of potassium hydroxide was added. The mixture was then shaken with hydrogen until a second equivalent was taken up. Usually about 6 hr. was required for the uptake of 2 equivalents of hydrogen. The product was isolated as described in the previous preparation. Distillation through a 10-cm. Vigreux column gave 55–62 g. (79–88%) of 1,1-difluoro-3-phenylcyclobutane, b.p. 69–71° (7.5 mm.), n_D^{25} 1.4840 (lit.^{4a} n_D^{25} 1.4828), and 3–9 g. of material of b.p. 78–100° (7.5 mm.), n_D^{25} 1.5170.

1,1-Difluoro-3-bromo-3-phenylcyclobutane (IX).—In a dry 500-ml. round-bottomed flask fitted with a reflux condenser were placed 50 g. (0.30 mole) of 1,1-difluoro-3-phenylcyclobutane (V), 53 g. (0.30 mole) of N-bromosuccinimide (Arapahoe Chemical, Inc.), 250 ml. of reagent grade carbon tetrachloride, and 0.5 g. of benzoyl peroxide. The mixture was heated until the vigorous exothermic reaction started, and then the heating mantle was removed until the reaction no longer refluxed from its own heat. The reaction mixture was heated under reflux for 2 hr., cooled, the succinimide removed, and the carbon tetrachloride distilled under reduced pressure at a temperature below 40°. A series of Dry Ice-cooled traps in the system facilitated the latter operation. The residue was distilled through a 10-cm. Vigreux column using a magnetic stirrer and an oil bath. A heating mantle should not be used as decomposition may result from overheating; a pressure of about 1 mm. or less should be used. Glass apparatus with etched walls can cause the product to decompose. On distillation, 66–73 g. (91–99%) of 1,1-difluoro-3-bromo-3-phenylcyclobutane, b.p. 49–53° (less than 1 mm.), n_D^{25} 1.6276, was obtained. This material can be kept for several months in the refrigerator under nitrogen without apparent decomposition.

Anal. Calcd. for $C_{10}H_8BrF_2$: C, 48.61; H, 3.67; Br, 32.34. Found: C, 48.51; H, 3.60; Br, 32.26.

Compound IX gave an immediate precipitate with alcoholic silver nitrate solution and did not react with bromine or permanganate. The infrared spectrum of IX had four very strong bands at 7.69, 8.02, 8.65, 9.10, 10.31, and 10.92 μ which are assigned to C–F vibrations.²² One anomalous feature in the infrared spectrum of IX is the weakness of the band at about 6.2 μ , which is very sharp in 1,1-difluoro-3-phenylcyclobutane and

phenylcyclobutane, and which can be assigned to C=C skeletal in-plane vibration of the aromatic ring.²² The 6.2- μ band is present in 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane, but much lower in intensity than the other bands from 6.6–7.2 μ . The ultraviolet spectrum of IX in cyclohexane showed λ_{max} 238.5 (ϵ 5,800) and 202.0 $m\mu$ (ϵ 17,300).

The 1H n.m.r. spectrum of IX showed peaks characteristic of phenyl (7.22 δ), and cyclobutyl methylene (four-line multiplet centered at 3.38 δ). The ^{19}F spectrum showed a quartet structure characteristic for the two nonequivalent fluorines of the CF_2 group ($J_{FF} = 199.2$ c.p.s.). Each member of the quartet was further split by 1H – ^{19}F coupling. The two high-field members of the quartet were each split into five sharp lines in the intensity ratios of 1:4:6:4:1. This pattern is characteristic of coupling with four 1H nuclei ($J_{HF} = 12.8$ c.p.s.). The low-field members of the quartet of ^{19}F spectrum also show a gross five-line pattern, $J_{HF} = 10.1$ c.p.s., but the three center lines were doublets.

1,1-Difluoro-3-phenyl-2-cyclobutene (IV).—To a solution of 12.8 g. (0.191 mole) of potassium hydroxide (assay 86%) in 125 ml. of 95% ethanol was added slowly with swirling 41 g. (0.19 mole) of 1,1-difluoro-3-bromo-3-phenylcyclobutane. After the initial exothermic reaction was complete, the mixture was refluxed for 1 hr. and then poured into 500 ml. of water. The resulting mixture was extracted five times with a total of about 700 ml. of ether. The ether was dried in four stages with anhydrous magnesium sulfate and distilled until the head temperature reached 45°. The residue was transferred to a distilling flask fitted with a 10-cm. Vigreux column and stirred magnetically while the last traces of solvent were removed under reduced pressure. The product was distilled with the aid of mineral oil as a still base. One fraction of 1,1-difluoro-3-phenyl-2-cyclobutene, 24.5–26.2 g. (89–95%), was obtained, b.p. 43–46° (0.7–0.8 mm.), n_D^{25} 1.5130, m.p. 5–6°.

Anal. Calcd. for $C_{10}H_8F_2$: C, 72.28; H, 4.85. Found: C, 72.26; H, 5.01.

The infrared spectrum of IV showed bands at 3.28, 3.40, 6.16, 6.97, 6.27, 6.34, 6.70, 6.89, 7.70, 7.90, 8.67, and 9.05 μ . The strong band at 6.16 μ was assigned to C=C stretch and the band at 6.97 μ to C–H methylene deformation. The ultraviolet spectrum in cyclohexane showed λ_{max} 253.0 (16,000), 215.5 (14,300), 209.0 (19,200), and 204.0 $m\mu$ (ϵ 17,600). Compound IV reacts readily with bromine in carbon tetrachloride and potassium permanganate in acetone, but is inert to alcoholic silver nitrate. The proton n.m.r. spectrum showed peaks characteristic of phenyl-ring protons (7.22 δ), one vinyl proton (6.03 δ ; triplet of triplets, $J_{HF} = 1.45$ c.p.s. and $J_{HH} = 0.3$ c.p.s.), and two methylene protons (3.04 δ ; triplet of doublets, $J_{HF} = 3.03$ and $J_{HH} = 0.3$ c.p.s.), and the ^{19}F spectrum was a triplet of doublets. The 1H and ^{19}F n.m.r. spectra of IV make up an AM_2X_2 ¹² nuclear spin system and are consistent with the 1,1-difluoro-3-phenylcyclobutene structure.

A 0.328-g. (0.00197 mole) sample of IV dissolved in methanol was treated with hydrogen over a platinum catalyst. The uptake of hydrogen was 96% of that calculated for one double bond. Removal of the catalyst by filtration and distillation of the solvent under reduced pressure left a residue which had an infrared spectrum identical in all respects with that of 1,1-difluoro-3-phenylcyclobutane (V).

3-Phenyl-2-cyclobutenone (I).—1,1-Difluoro-3-phenyl-2-cyclobutene (20 g., 0.12 mole) contained in a 200-ml. conical flask was cooled in an ice bath until it solidified, and 100 ml. of concentrated sulfuric acid (assay 98%) was added slowly with vigorous swirling. This reaction must be carried out in a hood because a large amount of hydrogen fluoride is evolved. When the addition was complete, the deep purple-colored mixture was swirled and heated on a steam bath for 4 min. and then poured with vigorous stirring onto ice. The mixture was immediately filtered by suction, and the solid, which contained pieces of ice, was washed twice with water, three times with dilute sodium bicarbonate solution to remove the last traces of acid, and once more with water. The cream-colored product was sucked dry and then pumped under vacuum. The yield of crude cinnamou-smelling product, m.p. 44–50°, was 11.5–15.4 g. (66–89%). Recrystallization of the crude unstable ketone from a number of different solvents was attempted without success. The only satisfactory method of purification was high-vacuum sublimation at a temperature below 40° which gave 7.6–10.2 g. (44–59%) of large, colorless crystals of 3-phenyl-2-cyclobutenone, m.p. 51.4–

(22) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," John Wiley and Sons, Inc., New York, N. Y., 1954.

52.7°. The ketone was found to be very irritating to the skin and should be handled with care.

Anal. Calcd. for $C_{10}H_8O$: C, 83.31; H, 5.59. Found: C, 83.33; H, 5.47.

The black sublimation residue when extracted with boiling water afforded β -methyl-*trans*-cinnamic acid, m.p. 96–97° (lit.²³ m.p. 98.5°). Ketone I becomes dark when exposed to strong light and decomposes slowly in the presence of moist air to give a colorless oil. From decomposed samples, good yields of β -methyl-*trans*-cinnamic acid were isolated. Compound I can be stored under reduced pressure at Dry Ice temperature for long periods of time without apparent decomposition.

The 2,4-dinitrophenylhydrazone of I was very insoluble in most common solvents, but was obtained from ethyl acetate as very fine red crystals, m.p. 240.9–241.5°.

Anal. Calcd. for $C_{16}H_{12}O_4N_4$: C, 59.26; H, 3.73. Found: C, 59.21; H, 3.79.

The infrared spectrum of I had bands at 3.26, 3.39, 3.42, 5.65 ($C=O$ stretch), 6.21, 6.30, 6.39 ($C=C$ stretch), 6.72, 6.88, and 7.05 μ (methylene deformation). The ultraviolet spectrum in 95% ethanol has λ_{max} 286.0 (23,000), 222.5 (11,600), and 217.0 $m\mu$ (ϵ 13,000). Cinnamaldehyde and benzalacetone have conjugated systems similar to that of I; the former has λ_{max} 287.5 (ϵ 25,000), 222.5, and 220.5 $m\mu$ and the latter has λ_{max} 287.5 (ϵ 25,000), 226.5, and 221.5 $m\mu$.

The proton n.m.r. spectrum of I showed peaks characteristic for phenyl protons (complex multiplet structure centered at 7.54 δ), one vinyl proton (broad triplet centered at 6.35 δ , $J = 0.4$ c.p.s.), and two methylene protons (doublet centered at 3.49 δ , $J = 0.44$ c.p.s.).

With potassium permanganate in acetone, compound I gave an immediate reaction and produced benzoic acid. It decolorized bromine in carbon tetrachloride only slowly.

A mixture of 3.0 g. (0.021 mole) of 3-phenyl-2-cyclobutenone, 10 ml. of methanol, and 0.1 g. of Adams catalyst was shaken with hydrogen for 2 hr. and then poured into 50 ml. of water. The resulting cream-colored emulsion was extracted three times with ether and the ether extracts were dried over anhydrous magnesium sulfate in four stages. The ether was removed, and the crude 3-phenylcyclobutanone was distilled twice under reduced pressure. The identity of the material was established by its infrared spectrum and 2,4-dinitrophenylhydrazone, m.p. 150–151° (lit.⁴⁶ m.p. 148.5–150°).

3-Phenyl-2-cyclobutenone with Aqueous Sodium Hydroxide. A.—A mixture of 30 ml. of 1.5 *N* sodium hydroxide and 3.0 g. (0.021 mole) of 3-phenyl-2-cyclobutenone (m.p. 47.0–49.5) was heated on a steam bath. After 7 min. only one phase was present, but after 10 min. there were two phases again. At this point, 0.5 g. of solid sodium hydroxide was added, and the mixture was heated for 10 min., cooled, and acidified with 6 *N* hydrochloric acid. A reddish oil was separated from the aqueous layer by decantation and extracted with aqueous sodium bicarbonate solution. Acidification of the bicarbonate extracts gave an oil which crystallized on standing in the refrigerator overnight. Several recrystallizations of this material from 30–60° petroleum ether gave benzoic acid, m.p. 120.7–122.1°.

The bicarbonate-insoluble oil was taken up in ether the ethereal solution was dried with anhydrous magnesium sulfate and then evaporated in a stream of air. The infrared and ultraviolet spectra of the residue suggested that it was a mixture of acetophenone and benzoic acid. The residue gave a 2,4-dinitrophenylhydrazone, m.p. 248.5–249.1°, which gave a melting point of 248.6–249.3° when admixed with a sample of acetophenone 2,4-dinitrophenylhydrazone of m.p. 248.6–249.3° (lit.²³ m.p. 250°) and a 4-nitrophenylhydrazone, m.p. 183.4–185.0° (lit.²³ m.p. 184–185° for acetophenone 4-nitrophenylhydrazone).

B.—A mixture of 3.0 g. (0.021 mole) of 3-phenyl-2-cyclobutenone and 20 ml. of 1.5 *N* (0.045 mole) sodium hydroxide was heated on a steam bath with swirling for a period of 10 min. An excess of 6 *N* hydrochloric acid was then added and the resulting emulsion was placed in the refrigerator for several hours. The mixture was made basic and extracted with ether several times. Removal of the ether gave 0.8 g. of oily brown crystals, which gave a positive ferric chloride test (enol test). After the other extractions, the basic solution was made acidic and extracted with ether. Removal of the ether gave 1.5 g. of cream-colored solid, m.p. 56–60°, which gave a positive ferric chloride test.

The infrared and ultraviolet spectra of the fractions showed them to be, respectively, benzoylacetone containing a little acetophenone and benzoylacetone containing a little benzoic acid.

Vacuum distillation of the oily brown crystals and the cream-colored solid each gave white crystalline solids whose identity as benzoylacetone was confirmed from infrared spectra and from the fact that they gave no melting point depression with a sample of authentic benzoylacetone.

Reaction of Benzoylacetone (XVIII) with Aqueous Base.—A solution of 4.0 g. (0.09 mole) of sodium hydroxide in 50 ml. of water was added to 5.0 g. (0.031 mole) of benzoylacetone (Eastman). The mixture was heated and swirled on a hot plate. Complete solution occurred in about 2 min. After 7 min., concentrated hydrochloric acid was added to the cooled solution to bring it to pH 2. An organic layer separated and this was removed with ether. The aqueous layer was extracted twice more with ether. The ether extracts were dried over magnesium sulfate and evaporated in a stream of nitrogen to give 4.5 g. of oily crystalline residue. The n.m.r. spectrum of a portion of the residue in deuteriochloroform indicated the presence of benzoic acid, acetophenone, acetone, and acetic acid. The ratio of benzoic acid to acetophenone was determined to be 1:1 by electronic integration. The n.m.r. of the original aqueous phase showed the presence of acetone and acetic acid.

Acetolysis of 3-Phenyl-2-cyclobutenone (I).—Glacial acetic acid (55 ml.) and 2.5 g. (0.017 mole) of 3-phenyl-2-cyclobutenone were heated under reflux for 48 hr.; 10 ml. of water was then added and heating continued for 3 hr. The mixture was poured into 300 ml. of water. The cream-colored solid was collected by suction filtration and washed several times with water. Recrystallization from water gave needles, m.p. 97.0–97.9° (lit.²³ m.p. 98.5° for β -methyl-*trans*-cinnamic acid). The ultraviolet spectrum in 95% ethanol showed λ_{max} 265.5 $m\mu$; the ultraviolet spectrum of cinnamic acid has λ_{max} 274.0 $m\mu$. The infrared spectrum was also consistent with the β -methyl-*trans*-cinnamic acid structure as was the neutralization equivalent (calcd. 162.2, found 162).

3-Phenyl-2-cyclobutenol (XII).—Sublimed 3-phenyl-2-cyclobutenone (2.00 g., 0.0134 mole) was dissolved in 5 ml. of reagent methanol. The solution was cooled to about 0° in an ice bath, and 0.50 g. (0.0132 mole) of sodium borohydride (Metal Hydrides Inc.) was added with swirling and cooling over 5 min. After 5 min. longer, the mixture was heated for 2 min. at 70° and poured into a 125-ml. flask filled with crushed ice, at which point white microscopic platelets precipitated. The slurry was swirled, and, as the ice melted, more was added until the volume of liquid was about 100 ml. The solid was collected by filtration and washed twice with ice-water. The crude product was pumped under high vacuum overnight in the dark to remove the last trace of water, and 1.7 g. (75%) of white material was obtained. One recrystallization of 0.5 g. of the latter from pentane gave 0.4 g. of 3-phenyl-2-cyclobutenol as long white needles, m.p. 66.4–68.6°.

Anal. Calcd. for $C_{10}H_{10}O$: C, 82.16; H, 6.90. Found: C, 81.89; H, 6.99.

Good yields of alcohol XII were obtained only when the 3-phenyl-2-cyclobutenone used was very pure. The alcohol was quite unstable to light, heat, and air. The crude material could only be stored in the dark under high vacuum at Dry Ice temperature. The recrystallized material can be stored satisfactorily in an evacuated ampoule in a refrigerator. Compound XII reacted immediately with bromine in carbon tetrachloride and potassium permanganate in acetone. The infrared spectrum of alcohol XII showed a strong band at 3.02 μ assigned to O-H stretch, a strong band at 3.27 μ assigned to vinyl C-H stretch, and a strong band at 3.38 μ assigned to C-H stretch of the methylene group. There were four bands at 6.27, 6.36, 6.72, and 6.91 μ which were assigned to aromatic C=C stretching. A band at 6.99 μ was assigned to methylene deformation. There does not seem to be any band in the region 5.5–6.5 μ which can be assigned to C=C stretch in the four-membered ring. The infrared spectra of cinnamyl alcohol and methylstyrylcarbinol show only a very weak band at about 6.0 μ which can be attributed to C=C stretch. The ultraviolet spectrum of XII had λ_{max} 255.0 (ϵ 19,000), 217.5, and 211.0 $m\mu$ and was quite similar in form to the ultraviolet spectra of cinnamyl alcohol which has λ_{max} 251.5, 219.5, and 213.5 $m\mu$. The proton n.m.r. spectrum of alcohol XII was strongly indicative of its structure. There were peaks assignable to phenyl protons (7.33 δ), a vinyl proton (doublet of triplets of 6.34 δ), one proton bonded to carbon substituted

(23) I. Heilbron, "Dictionary of Organic Compounds," Oxford University Press, Oxford, 1953.

with a hydroxyl group (centered at 4.84 δ and broad), two methylene protons having different chemical shifts (one centered at 3.15 δ , doublet of quartets with $J_{\text{CH}_2} = 12.95$ c.p.s. and the other $J = 3.81$ and 0.81 c.p.s.; second group centered at 2.55 δ , doublet of triplets with $J_{\text{CH}_2} = 12.95$ c.p.s. and the other $J = 1.2$ c.p.s.) and a hydroxyl proton (doublet at 2.66 δ , $J_{\text{HH}} = 7.6$ c.p.s.). This five-spin system is rather easily analyzed and confirms the presence of every type of proton expected for the structure of XII.

3-Phenyl-2-cyclobutenyl 4-nitrobenzoate was prepared from the alcohol and the acid chloride in a benzene solution with the calculated amount of pyridine added. The customary pyridine method for preparation of esters from an alcohol and an acid chloride failed.²⁴ To an ice-cooled solution of 0.30 g. (0.0021 mole) of 3-phenyl-2-cyclobutenol and 0.20 g. of pyridine, a solution of 0.40 g. (0.0023 mole) of recrystallized 4-nitrobenzoyl chloride in dry benzene was added at once. The mixture was stirred for 30 min. at 0°. The solvent was evaporated in a stream of nitrogen with gentle warming, and the residual solids were extracted twice with hot ethyl acetate. The residue, which was water soluble, was discarded. The ethyl acetate solution was evaporated to a volume of 3–5 ml., and on cooling, cream-colored platelets were obtained, m.p. 145–146°. Recrystallization from hexane–ethyl acetate gave material, m.p. 146.2–148.4°.

Anal. Calcd. for $\text{C}_{17}\text{H}_{14}\text{O}_4\text{N}$: C, 69.14; H, 4.44. Found: C, 69.05; H, 4.60.

Catalytic Hydrogenation of 3-Phenyl-2-cyclobutenol (XII).—A methanol solution of 0.65 g. of crude 3-phenyl-2-cyclobutenol was shaken with hydrogen over 10% palladium-on-charcoal catalyst. The vapor-phase chromatogram of the product indicated three components to be present, the major one making 89% of the total. The infrared spectrum of the product mixture was closely similar to that of *cis*-3-phenylcyclobutanol (XIII) to be described below.

1,1-Difluoro-2-chloro-3-phenyl-2-cyclobutene (XIV).—In a 2-l. round-bottomed flask, 133 g. (2.01 moles) of potassium hydroxide (assay 86%) was dissolved in 1 l. of 95% ethanol. The solution was cooled, the flask equipped with an Allihn condenser, and 462.5 g. (1.95 moles) of 1,1-difluoro-2,2-dichloro-3-phenylcyclobutane was poured slowly, with vigorous swirling, through the condenser into the alcoholic base solution at such a rate that the exothermic reaction did not get out of control. External cooling was occasionally necessary. After the addition was complete (about 5 min.), the mixture was swirled intermittently and allowed to stand 12 hr. The mixture was poured into about 2 l. of water, and the resulting two-phase mixture was allowed to stand in the refrigerator for an hour. The lower organic layer was separated and the water layer extracted four times with ether (total volume 1.5 l.). The extracts were combined with the organic layer, and the resulting ether solution was dried in four stages with anhydrous magnesium sulfate. After the ether had been distilled through a straight distilling head, the residue was fractionated through a 20-cm. Vigreux column to give 356–372 g. (91–95%) of 1,1-difluoro-2-chloro-3-phenyl-2-cyclobutene as a colorless product, b.p. 44–48° (0.6 mm.), n_D^{25} 1.5388; lit.^{4b} b.p. 66–67° (1 mm.), n_D^{25} 1.5390.

2-Chloro-3-phenyl-2-cyclobutenone (XVI).—A mixture of 10 g. (0.0494 mole) of 1,1-difluoro-2-chloro-3-phenyl-2-cyclobutene and 5 ml. of concentrated sulfuric acid (assay 98%) was heated in a 200-ml. conical flask on a steam bath. After about 2 min., 55 ml. more of acid was added, and the deep red mixture was heated and swirled until it was homogeneous (5–15 min.). Considerable gas evolution took place. The solution was then poured slowly onto ice with vigorous stirring. The white solid was collected by filtration, washed twice with water and three times with dilute sodium bicarbonate solution, and dried under vacuum overnight to give 7.7–8.7 g. (87–99%) of crude product, m.p. 63–67°. Recrystallization from 30–60° petroleum ether, after treatment with Norit, gave 6.9–7.9 g. (78–90%) of 2-chloro-3-phenyl-2-cyclobutenone as long white needles, m.p. 67.8–69.2° (lit.^{4b} m.p. 67.2–68.2°). This reaction was run several times on a 2-mole scale with yields of crude product of about 90–95%.

2-Chloro-3-phenyl-2-cyclobutenol (XVI).—To a solution of 50.5 g. (0.283 mole) of 2-chloro-3-phenyl-2-cyclobutenone dissolved in 150 ml. of reagent methanol was added 11.6 g. (0.283 mole) of sodium borohydride with vigorous swirling at such a rate as

to keep the mixture from foaming over. The temperature was kept below 5°. After the addition of the sodium borohydride was complete, the solution was allowed to stand 20 min. at room temperature and then poured onto crushed ice. The resulting mixture was placed in the refrigerator for 2 hr. The crude 2-chloro-3-phenyl-2-cyclobutenol was removed by suction filtration, the filter cake was washed several times with water, and dried under reduced pressure. The yield was 35.8–44.7 g. (70–86%) of white material, m.p. 76–78°. Three recrystallizations from pentane gave white cottony material, m.p. 79.0–79.8°. An analytical sample was prepared by precipitating a sample three times from a methanol solution by addition of ice.

Anal. Calcd. for $\text{C}_{16}\text{H}_{13}\text{OCl}$: C, 66.86; H, 4.49; Cl, 19.74. Found: C, 66.71; H, 4.64; Cl, 19.65.

The infrared spectrum of 2-chloro-3-phenyl-2-cyclobutenol showed a sharp band at 2.79 μ assigned to free O–H stretching, a strong band at 3.01 μ assigned to associated O–H, a band at 3.27 μ assigned to vinyl C–H stretching, and a band at 3.43 μ characteristic of methylene C–H stretching. A sharp band at 6.08 μ is assigned to C=C stretch. There are four bands at 6.25, 6.35 (weak), 6.71, and 6.90 μ which are characteristic of the aromatic ring and due to C=C stretching. A sharp band at 6.98 μ is assigned to methylene C–H deformation.²²

The n.m.r. spectrum showed peaks assignable to phenyl protons (7.2–7.8 δ) and one proton bonded to carbon substituted with a hydroxyl group (4.78 δ), broadened by an intermediate rate of exchange and becoming a quartet on addition of a small amount of hydrogen chloride gas. The J -values for this proton were 1.40 and 4.10 c.p.s. There was also a hydroxyl proton (doublet, $J \approx 8$ c.p.s. at 2.30 δ) and two nonequivalent methylene protons, one centered at 3.10 δ , doublet of doublets with $J = 4.12$ and 11.39 c.p.s.; and the other second centered at 2.52 δ doublet of doublets with $J = 1.60$ and 11.29 c.p.s.

2-Chloro-3-phenyl-2-cyclobutenol decomposes slowly to give a yellow oil if exposed to air, moisture, heat, or light, but can be stored quite satisfactorily *in vacuo* in the dark.

The 4-nitrobenzoate of 2-chloro-3-phenyl-2-cyclobutenol was prepared from the alcohol, pyridine, and the acid chloride in benzene in a manner similar to that described above for the 4-nitrobenzoate of 3-phenyl-2-cyclobutenol. Recrystallization of the ester from ethyl acetate gave cream-colored platelets, m.p. 172–173°.

Anal. Calcd. for $\text{C}_{17}\text{H}_{12}\text{O}_4\text{NCl}$: C, 61.92; H, 3.67; Cl, 10.75. Found: C, 62.10; H, 3.80; Cl, 10.71.

***cis*-3-Phenylcyclobutanol (XIII).**—In a citrate bottle were placed 40.0 g. (0.222 mole) of crude 2-chloro-3-phenyl-2-cyclobutenol, 18.2 g. of sodium acetate, 3 g. of 10% palladium-on-charcoal catalyst, and 150 ml. of reagent methanol. The mixture was hydrogenated at 60 p.s.i. and after 20 hr. the pressure drop corresponded to 0.52 mole of hydrogen. The solids were removed by filtration and washed first with methanol and then with water. To the resulting cloudy mixture, 11 g. of sodium hydroxide was added with vigorous swirling to saponify any acetate ester present and to neutralize the acetic acid formed in the hydrogenolysis. After the mixture had stood at room temperature for 3 hr., it was poured into 600 ml. of water, and the resulting emulsion was extracted six times with a total volume of 600 ml. of ether. The ether was dried in three stages with anhydrous magnesium sulfate and evaporated in an air stream on a steam bath. Distillation of the material remaining gave 30 g. (92%) of *cis*-3-phenylcyclobutanol, b.p. 80–84° (less than 1 mm.), n_D^{25} 1.5453. A sample for analysis was distilled through a 30-cm. Holzman column²⁵; b.p. 62–64° (less than 1 mm.).

Anal. Calcd. for $\text{C}_{10}\text{H}_{12}\text{O}$: C, 81.04; H, 8.16. Found: C, 80.83; H, 8.18.

The α -naphthylurethan of *cis*-3-phenylcyclobutanol had m.p. 125.2–127.4° after recrystallization from 60–70° petroleum ether.

Anal. Calcd. for $\text{C}_{21}\text{H}_{19}\text{O}_2\text{N}$: C, 79.46; H, 6.03. Found: C, 79.50; H, 6.00.

The 4-nitrobenzoate of *cis*-3-phenylcyclobutanol was prepared from the alcohol and acid chloride in pyridine,²⁴ long white needles, m.p. 131.1–131.6°, after recrystallization from ethyl acetate–hexane.

Anal. Calcd. for $\text{C}_{17}\text{H}_{15}\text{O}_4\text{N}$: C, 68.67; H, 5.09. Found: C, 68.80; H, 5.23.

The infrared spectrum of *cis*-3-phenylcyclobutanol showed a sharp band at 2.78 μ characteristic to free O–H stretch and a

(24) (a) R. L. Shriner and R. C. Fuson, "The Systematic Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1948; (b) N. D. Cheronis and J. B. Entrikin, "Semimicro Qualitative Organic Analysis," Thomas Y. Crowell Co., 1947.

(25) C. W. Gould, G. Holzman, and C. Niemann, *Anal. Chem.*, **20**, 361 (1948).

very strong broad band at 3.03μ characteristic of associated O-H stretch. The band structure from 3.2 – 3.5μ was very similar to that of 3-phenylcyclobutanone with a pair of bands of equal intensity at 3.39 and 3.44μ and a pair at 3.24 and 3.27μ (strongest). These bands are assigned to C-H stretch. There are three bands at 6.25 , 6.71 , and 6.92μ which are characteristic of aromatic C=C in-plane stretch. A somewhat broad band at 7.03μ is attributed to methylene C-H deformation.

The proton n.m.r. spectrum showed phenyl hydrogens, a hydroxyl hydrogen, two complex patterns assigned to the tertiary hydrogens, and methylene hydrogens split into either four or five peaks.

3-Phenylcyclobutanone (XI).—In a citrate bottle were placed 50.0 g. (0.283 mole) of 2-chloro-3-phenyl-2-cyclobutanone, 24 g. (0.29 mole) of anhydrous sodium acetate, 200 ml. of reagent methanol, and 4.0 g. of freshly prepared 20–30% palladium-on-charcoal catalyst. The mixture was shaken with hydrogen at 60 p.s.i. for 10 hr. , and then 2.0 g. more of catalyst was added. The hydrogenation was allowed to proceed until the uptake of hydrogen ceased. The catalyst and solids were removed by filtration and washed with methanol and then with water. To the filtrate, 700 ml. of water was added, and the mixture was extracted six times with ether (total volume 700 ml.). The ether was dried in four stages with anhydrous magnesium sulfate and then distilled through a 30-cm. Vigreux column until the head temperature reached 45° . The residue was pumped under reduced pressure for several hours to remove the last traces of solvent and distilled through a 10-cm. Vigreux column to give 35.1 – 37.6 g. (85 – 91%) of 3-phenylcyclobutanone as a colorless liquid, b.p. 69 – 76° (1 – 2 mm.); lit.⁴ b.p. 93 – 95° (1.5 mm.), $n_D^{25} 1.5423$.

The infrared spectrum of 3-phenylcyclobutanone had four sharp bands at 3.28 , 3.32 , 3.38 , and 3.44μ . The first two bands were assigned to aromatic C-H stretch, and the latter pair were ascribed, respectively, to the in-phase and out-of-phase C-H stretching modes. There are three very sharp bands at 6.23 , 6.69 , and 6.88μ which are assigned to C=C in-plane vibration of the aromatic ring. A strong band assigned to C=O stretching came at 5.58μ . A strong band at 7.24μ was assigned to methylene C-H deformation. The infrared spectrum of freshly prepared material was identical with that of material purified through the semicarbazone.

The proton n.m.r. spectrum showed bands assigned to phenyl, methylene, and tertiary hydrogens in the ratio $5:4:1$. The ultraviolet spectrum shows a broad λ_{max} at $254.0 \text{ m}\mu$.

3-Phenylcyclobutanone slowly became yellow on standing in light for several weeks and took on a very sweet odor. The infrared spectrum showed a new strong band at 5.75μ and a band at 6.97μ . The band at 7.24μ was much weaker. The vapor-phase chromatogram showed several components. Distillation failed to effect a satisfactory separation as indicated by the infrared spectrum, although the vapor phase chromatogram showed only one major component.

Reduction of 3-Phenylcyclobutanone (XI) with Sodium in Wet Ether.—In a 200-ml. three-necked round-bottomed flask fitted with a mechanical stirrer, dropping funnel, and reflux condenser were placed 5.7 g. of freshly cut pieces of sodium and 20 ml. of ether. The stirrer was started, and a solution of 5.0 g. (0.034 mole) of freshly distilled 3-phenylcyclobutanone in 30 ml. of wet ether was added slowly. It was necessary to add several drops of water occasionally to maintain the evolution of hydrogen from the sodium. After the addition of the ketone solution was complete (1 hr.), the mixture was stirred until the remainder of the sodium had dissolved. A solution of 14 g. of ammonium chloride in 100 ml. of water was added, and the ether layer was separated. The water layer was extracted three times with ether, and the combined ether extracts were dried with anhydrous magnesium sulfate. The ether was evaporated in a stream of air, and the residue distilled through a 10-cm. Vigreux column to give 4.0 g. of colorless material, b.p. 64 – 81° (1 mm.), $n_D^{25} 1.5268$. The infrared spectrum showed that a significant amount of the starting material was present. The product was dissolved in ethanol, and an alcoholic solution of sodium bisulfite was added with cooling. After the mixture had stood for 5 min. , the solid was removed by filtration, and the filtrate was treated with another portion of bisulfite solution. After about 15 min. , the small amount of precipitate was removed by filtration, and the filtrate extracted four times with ether. The ether extracts were dried with anhydrous magnesium sulfate. The ether was evaporated in an air stream, and the

residue was distilled through a $1.2 \times 10\text{-cm.}$ glass tube packed with glass wool, and gave 2.0 g. of colorless product, b.p. 87 – 96° (1 mm.), $n_D^{25} 1.5280$. This material did not give a satisfactory analysis for a $\text{C}_{10}\text{H}_{12}\text{O}$ isomer. It did not give a precipitate with 2,4-dinitrophenylhydrazine reagent. The infrared spectrum showed a sharp band at 2.78μ characteristic of free O-H stretch and a broad band at 3.00μ characteristic of associated O-H. There were four bands at 3.28 , 3.31 (shoulder), 3.38 , and 3.41μ giving a structure similar to that found in *cis*-3-phenylcyclobutanone and due to the various C-H stretching vibrations. There were three bands at 6.23 , 6.69 , and 6.89μ assigned to aromatic C=C stretch. A band at 6.96μ was assigned to methylene C-H deformation. There was a very strong, sharp band at 5.75μ of unknown origin. There was no broad band at 10.65μ which was present in the *cis* isomer. A band at 8.60μ , missing in the *cis* isomer, was present. A strong broad band at 9.2μ may correspond to the strong broad band in the *cis* isomer at 9.1μ . The band structure from 7 – 8μ was quite different from that of *cis*-3-phenylcyclobutanone which had only one strong band at 7.58μ ; a multiplicity of bands was present in this region.

A 4-nitrobenzoate ester prepared by the pyridine method²⁵ had m.p. 60.7 – 63.0° after recrystallization from absolute alcohol. This material is apparently the ester of the *trans*-alcohol.

Anal. Calcd. for $\text{C}_{17}\text{H}_{15}\text{O}_4\text{N}$: C, 68.67 ; H, 5.09 . Found: C, 68.62 ; H, 5.05 .

Several of the product mixtures from other sodium and wet ether reductions (in some cases a small amount of ethanol being added) were treated directly with 4-nitrobenzoyl chloride in pyridine. Oily mixtures of 4-nitrobenzoate esters were obtained, and by fractional crystallization poor yields of an ester, m.p. 131 – 132° , were obtained. This material gave no melting point depression on admixture with an authentic sample of *cis*-3-phenylcyclobutyl 4-nitrobenzoate. The mother liquors were evaporated to give yellowish oils from which long needle-like crystals were deposited after about 3 months. These crystals were washed with a small amount of pentane and had m.p. 61 – 63° . They gave no melting point depression with the analytical sample above having m.p. 60.7 – 63.0° .

The ultraviolet spectrum in cyclohexane of the ester of m.p. 60.7 – 63.0° showed λ_{max} 259.0 , $\lambda_{\text{infl.}}$ 219.0 , and $\lambda_{\text{infl.}}$ $209.5 \text{ m}\mu$. This spectrum was identical with the corresponding one of the 4-nitrobenzoate of *cis*-3-phenylcyclobutanone, m.p. 131 – 132° . The ultraviolet spectrum of the 4-nitrobenzoate of 3-phenyl-2-cyclobutanone had λ_{max} 258.0 , 217.5 , 211.5 , and $205.0 \text{ m}\mu$. The latter three bands were very sharp and typical of many of the 3-phenyl-2-cyclobutene systems studied in the present research. On the basis of this evidence the ester of m.p. 60.7 – 63.0° is assumed to be *trans*-3-phenylcyclobutyl 4-nitrobenzoate.

Reduction of 3-Phenylcyclobutanone (XI) with Lithium Aluminum Hydride.—Freshly ground lithium aluminum hydride (Metal Hydrides Inc.) was mixed with 100 ml. of anhydrous ether in a 300-ml. three-necked round-bottomed flask fitted with a reflux condenser, mechanical stirrer, and dropping funnel. A solution of 10 g. (0.069 mole) of 3-phenylcyclobutanone in 30 ml. of anhydrous ether was added with stirring at such a rate as to maintain gentle reflux. After the addition was complete, the mixture was refluxed for 45 min. The excess lithium aluminum hydride was decomposed with a concentrated solution of ammonium chloride, and when the hydrogen evolution ceased, 6 N hydrochloric acid was added until the solid hydroxides just dissolved. The ether layer was separated, and the aqueous layer was extracted three times with ether. The combined ether phases were dried in two stages with anhydrous magnesium sulfate and evaporated in a stream of air. The residue was pumped several hours under high vacuum to remove the last traces of solvent and then distilled to give 8.0 g. (80%) of colorless product, b.p. 82 – 94° (1 mm.), $n_D^{25} 1.5385$. The infrared spectrum was identical with that of *cis*-3-phenylcyclobutanone prepared above. The product gave a 4-nitrobenzoate, m.p. 131 – 132° , which was not depressed when the sample was admixed with the authentic 4-nitrobenzoate of *cis*-3-phenylcyclobutanone.

Methylstyrylcarbinol.—To a solution of 34.8 g. (0.238 mole) of benzalacetone (Eastman White Label) dissolved in 100 ml. of absolute ethanol was added sodium borohydride (9.05 g. , 0.238 mole) over a period of 10 min. with vigorous swirling at 0° . After the addition of the borohydride was complete, the solution was heated and swirled on a steam bath for 1 min. and then allowed to stand for 15 min. The solution was poured onto an ice-water slurry. When the ice had melted, the organic layer was extracted three times with ether and the ether extracts were dried

in four stages over anhydrous magnesium sulfate. The ether was distilled until the temperature rose to 50°, and then the residue was pumped under reduced pressure to remove the last traces of solvent. Distillation through a 10-cm. Vigreux column gave 29.6 g. (82%) of methylstyrylcarbinol as a colorless liquid, b.p. 73–81° (less than 1 mm.), n_D^{25} 1.5594; lit.²⁶ b.p. 106° (18 mm.). The infrared spectrum showed no carbonyl absorption. There was a broad band at 3.0 μ characteristic of O–H stretch. There were three bands at 3.30, 3.39, and 3.51 μ assigned to the various C–H stretching vibrations. The bands at 6.25, 6.34, 6.69, and 6.90 μ were assigned to aromatic C=C stretch, and the weak band at 6.03 μ was assigned to C=C stretch. A broad band at 7.1 μ could be due to C–H deformation.

The 4-nitrobenzoate was prepared by the pyridine method. Recrystallization of this ester from a number of solvent systems gave only oils which crystallized after standing in the refrigerator for several days to several weeks. Five "recrystallizations" (the material oiled out) from pentane gave a white powder, m.p. 61–65°; lit.²⁷ m.p. 60°.

Anal. Calcd. for C₁₇H₁₆O₄N: C, 68.67; H, 5.09. Found: C, 68.84; H, 5.15.

4-Nitrobenzoate of Cinnamyl Alcohol.—The ester was prepared from the alcohol and acid chloride in pyridine²⁴ and after three

recrystallizations from pentane had m.p. 76.5–77.0°; lit.²⁴ m.p. 78°.

Anal. Calcd. for C₁₆H₁₄O₄N: C, 67.84; H, 4.63. Found: C, 67.62; H, 4.72.

Hydrolysis Rate Measurements.—The rates were measured by a procedure similar to that described by Goering and Silver-smith.¹⁹ In all but one case, stock solutions of the esters were made up and aliquots sealed in ampoules. The 4-nitrobenzoate of 2-chloro-3-phenyl-2-cyclobutenol was so insoluble at room temperature that individual samples (20–30 mg.) were weighed out and transferred to ampoules to which the measured volumes of the purified solvent was added. The solvent was prepared by mixing 80% by volume of acetone²⁸ with 20% by volume of boiled, distilled water. The acidic solvent was made similarly, except that a solution of reagent grade perchloric acid in boiled, distilled water was mixed with the acetone. Titrations were carried out under nitrogen with 0.01 *N* carbonate-free sodium hydroxide solution to an end point of pH 7.50. A Leeds and Northrup direct-reading pH meter was employed. Preliminary titrations using indicators gave poor results. The rate data are summarized in Table I. Most of the kinetic runs were 50% complete after 20 hr. Initial rate constants were obtained graphically from plots $[(\chi_0 - \chi)/\chi_0]$ vs. time where χ_0 is the initial concentration of ester present and χ is the concentration of acid produced at time t .

(26) A. Klages, *Ber.*, **35**, 2649 (1902).

(27) H. Burton, *J. Chem. Soc.*, 455 (1929).

(28) J. K. Kochi and G. S. Hammond, *J. Am. Chem. Soc.*, **75**, 3452 (1953).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, IOWA STATE UNIVERSITY, AMES, IOWA]

The Chemistry of Cyclopropanols. I. The Hydrolysis of Cyclopropyl Acetate and the Synthesis of Cyclopropanol

BY C. H. DEPUY^{1a} AND L. R. MAHONEY^{1b}

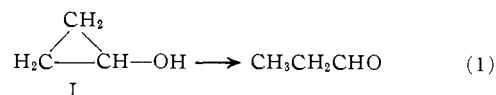
RECEIVED DECEMBER 19, 1963

A kinetic study of the alkaline hydrolysis in pure water of cyclopropyl acetate, *n*-butyl acetate, and cyclopentyl acetate as well as several enol acetates has been carried out. Examination of the activation parameters indicated no abnormality for any of these esters, and suggested that there was no ring opening of cyclopropyl acetate in the transition state for the hydrolysis. The ultimate product from the treatment of cyclopropyl acetate with base is the aldol condensation product of propionaldehyde, 2-methyl-2-pentenal. Under conditions where cyclopropyl acetate is rapidly and completely hydrolyzed, the rate of appearance of this aldol product is 100–200 times more rapid from propionaldehyde than it is from the ester. From these data it was deduced that cyclopropanol has a reasonable lifetime in basic solution, and in agreement with this deduction it was isolated from aqueous solution. A more satisfactory synthetic method is hydride reduction of the ester in ether solution and purification by preparative gas chromatography.

Despite much recent interest in the chemistry of small ring compounds, the intriguing and potentially useful molecule cyclopropanol (I) has apparently excited little attention since its original, inadvertent synthesis by Magrane and Cottle in 1942.² Part of the reason for this neglect may be traced to the fact that, as prepared by the method of Magrane and Cottle, the alcohol was contaminated and could not be obtained in greater than 87% purity. In addition, cyclopropanol readily rearranges to its isomer, propionaldehyde (eq. 1), especially in basic solution.³ Indeed, an attempt to dry a solution of the alcohol over anhydrous potassium carbonate sufficed to destroy it. A small sample of cyclopropanol, again impure, was prepared by Roberts and Chambers⁴ by the air oxidation of cyclopropylmagnesium chloride. No other simple cyclopropanols have been reported in the literature.

The method of Magrane and Cottle for the preparation of cyclopropanol involved the reaction of epichloro-

hydrin with magnesium bromide, ferric chloride, and ethylmagnesium bromide in ether solution. Neither



this method, nor the Grignard synthesis of Roberts and Chambers, appeared to be well adapted to the preparation of substituted cyclopropanols of known structure.⁵ It was felt that other methods for the synthesis of these interesting compounds should be explored, and to that end a study of the hydrolysis of cyclopropyl acetate was undertaken and is reported herein.

The preparation of cyclopropanols by the hydrolysis of the corresponding esters appeared worthy of investigation because two recent synthetic advances have made cyclopropyl esters easily available. The first of these advances was the observation of Emmons and Lucas⁶ that peroxytrifluoroacetic acid converts

(1) (a) Alfred P. Sloan Fellow, 1960–1964; (b) National Science Foundation Cooperative Fellow, 1959–1960.

(2) J. K. Magrane and D. L. Cottle, *J. Am. Chem. Soc.*, **64**, 484 (1942).

(3) C. W. Stahl and D. L. Cottle, *ibid.*, **65**, 1782 (1943).

(4) J. D. Roberts and V. C. Chambers, *ibid.*, **73**, 3176 (1951).

(5) See, however, C. H. DePuy, L. R. Mahoney, and K. L. Eilers, *J. Org. Chem.*, **26**, 3616 (1961).

(6) W. D. Emmons and G. B. Lucas, *J. Am. Chem. Soc.*, **77**, 2287 (1955).