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# Mechanism of Hydrogenation of Unsaturated Cyclopropanes

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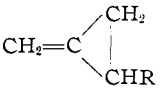
Saturation of the double bond in vinyl- and alkylidenecyclopropanes by catalytic hydrogenation appears to be normally accompanied by varying amounts of hydrogenolysis of the cyclopropane ring. A study has been made of the effects of substituents on the course of this reaction and evidence is presented which suggests that hydrogenation of the two groups of compounds may proceed through a common carbanion intermediate formed by an initial transfer of hydride from the catalyst. These studies have confirmed the proposed structure[13] IIIb for the pyrolysis product of Feist's ester IVc and have led to a new synthesis of alkylidenecyclopropanes.

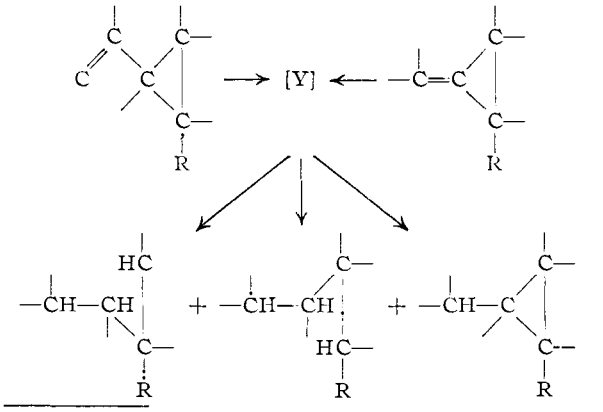
Among the considerable physical and chemical data which have been presented in support of the view that the combination of a cyclopropane ring with an adjacent unsaturated grouping has some of the properties of a conjugated system[1-4] are numerous examples of catalytic 1,4-addition of hydrogen to vinylcyclopropanes.[2,3,5] Recently it has been pointed out, however, that such conjugate addition reactions probably are less a result of ground state resonance interactions than of the ability of the cyclopropane ring to transmit conjugation in the transition state or in certain reactive intermediates,[6] such as, for example, the highly resonance stabilized cyclopropylcarbinyl cation.[7]

The possibility that a related resonance-stabilized intermediate may be operative during the hydrogenation of vinylcyclopropanes is suggested by a number of examples of hydrogenolytic ring cleavage which have been reported to proceed under conditions which do not affect the related saturated cyclopropanes. This idea is further supported by the recent observations that methylenecyclopropane (I) and hypoglycin (II) likewise



I, R = H
II, R = $CH_2CH(NH_2)COOH$

undergo hydrogenolysis under conditions which do not affect the saturated derivatives.[8,9] Moreover, cleavage of the ring in both vinyl- and alkylidenecyclopropanes appears to occur exclusively at the ring bonds adjacent to the unsaturated linkage[10,12] even though this results from an over-all 1,3- rather than 1,4-addition of hydrogen to the latter compounds. It is thus suggested that the courses of these hydrogenolyses might be interpreted in terms of a hydrogenation intermediate, [Y], common to both vinyl- and alkylidenecyclopropanes



(1) (a) E. P. Carr and C. P. Burr, THIS JOURNAL, **40**, 1590 (1918); (b) I. M. Klotz, *ibid.*, **66**, 88 (1944); (c) J. D. Roberts and C. Green, *ibid.*, **68**, 214 (1946); (d) R. H. Eastman, *ibid.*, **76**, 4115 (1954); (e) R. H. Eastman and J. C. Selover, *ibid.*, **76**, 4119 (1954); (f) R. H. Eastman and S. K. Freeman, *ibid.*, **77**, 6642 (1955); (g) M. T. Rogers, *ibid.*, **69**, 2544 (1947); (h) R. P. Mariella and R. R. Raube, *ibid.*, **74**, 518, 524 (1952).

(2) R. Van Volkenburgh, K. W. Greenlee, J. M. Derfer and C. E. Boord, *ibid.*, **71**, 172, 3595 (1949).

(3) (a) R. W. Kierstead, R. P. Linstead and B. C. L. Weedon, *J. Chem. Soc.*, 3610, 3616 (1952); (b) 1799, 1803 (1953); (c) V. A. Slabey and P. H. Wise, THIS JOURNAL, **74**, 3887 (1952); (d) V. A. Slabey, *ibid.*, **74**, 4930 (1952).

(4) (a) W. A. Bone and W. H. Perkin, *J. Chem. Soc.*, **67**, 108 (1895); (b) R. C. Fuson and F. N. Baumgartner, THIS JOURNAL, **70**, 3255 (1948); (c) C. F. H. Allen and R. Boyer, *Can. J. Research*, **9**, 159 (1953); (d) E. P. Kohler and J. B. Conant, THIS JOURNAL, **39**, 1404 (1917).

(5) (a) J. Nickl, *Ber.*, **91**, 553 (1958); (b) B. A. Kazanskii, M. Yu Lukina, A. I. Malyshev, V. T. Aleksanyan and Kh. E. Steriu, *Izvest. Akad. Nauk. SSSR, Otdel. Khim. Nauk.*, 36 (1956).

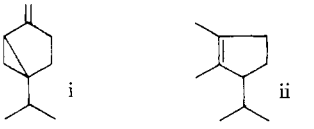
(6) For a general discussion of the relationship between the reactivity and conjugative effects of unsaturated cyclopropanes see (a) E. N. Trachtenberg and G. Odian, *Chemistry & Industry*, 490 (1958); (b) THIS JOURNAL, **80**, 4018 (1958).

(7) J. D. Roberts and R. H. Mazur, *ibid.*, **73**, 2509, 3542 (1951).

(8) J. T. Gragson, K. W. Greenlee, J. M. Derfer and C. E. Boord, *bid.*, **75**, 3344 (1953).

(9) (a) R. S. de Ropp, J. C. Van Meter, E. C. De Renzo, K. W. McKerns, C. Pidacks, P. H. Bell, E. F. Ullman, S. R. Safir, W. J. Fanshawe and S. B. Davis, *ibid.*, **80**, 1004 (1958); (b) S. Wilkinson, *Chemistry & Industry*, 17 (1958).

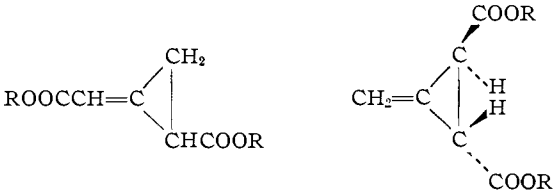
(10) An apparent exception to this generalization is the reported partial hydrogenation of sabinine (i) to give ii.[11] The structure of the latter compound has not been rigorously established. Although the physical constants of its dihydro derivative are in good agreement with those of an authentic sample of 1,2-dimethyl-3-isopropylcyclopentane, no comparison with the expected product, 1,3-dimethyl-3-isopropylcyclopentane, has been made. Moreover, no effort has been made to establish the position of the double bond; B. Kazanskii, *Ber.*, **62**, 2205 (1929).



(11) F. Richter, W. Wolff and W. Presting, *ibid.*, **64**, 871 (1931).

(12) Hydrogenolysis of the ring bond opposite the unsaturated linkage in hypoglycin has also been reported; C. von Holt and W. Leppla, *Angew. Chem.*, **70**, 25 (1958). However, when conditions for the hydrogenation of I or II were employed which were demonstrated to have no effect on their cyclic dihydro derivatives, the products detected corresponded only to cleavage of the bonds adjacent to the unsaturated ring carbon.[8,9a] The inability of these compounds to undergo 1,4-addition of hydrogen with cleavage of the ring bond opposite the double bond is in accord with the expected lack of interaction between these bonds due to the perpendicular orientation of the ring bond to the plane of the exocyclic $\pi$-orbital. The absence of conjugative effects in methylenecyclopropanes is also seen in the presence of only end absorption in the ultraviolet spectra of hypoglycin[9a] (II), Feist's acid[16b] (IVa) and methylenecyclopropane-1,1-dicarboxylic acid (Va) (*vide infra*).

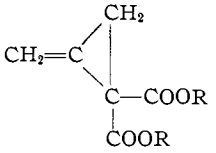
In order to confirm the above hypothesis and to shed more light on the nature of the intermediate [Y], hydrogenations have been carried out on three alkylidenecyclopropanes, and comparisons have been made of the effects of different substitution of vinyl- and alkylidenecyclopropanes on the course of hydrogenation of these compounds. These studies have led to a new synthesis of alkylidenecyclopropanes and a conclusive confirmation of the proposed structure IIIb[13] for the pyrolysis product of Feist's ester (IVc).[13-16]



IIIa, R = $CH_3$
IIIb, R = $C_2H_5$



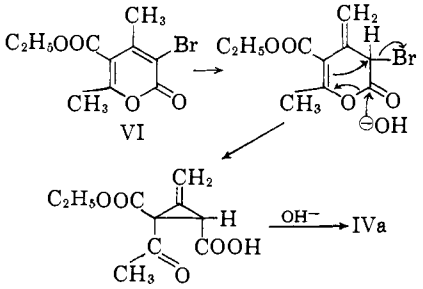
IVa, R = H
IVb, R = $CH_3$
IVc, R = $C_2H_5$



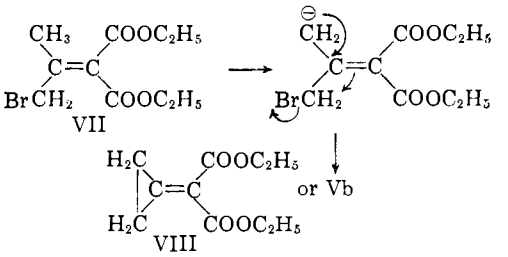
Va, R = H
Vb, R = $C_2H_5$

**Methylenecyclopropane-1,1-dicarboxylic Acid (Va).**—At the outset of this investigation two unequivocal syntheses of methylenecyclopropanes I and IV had been reported. Since the preparation of the parent hydrocarbon, I, by metallic reduction of 2-chloromethylallyl chloride[8] was inapplicable for the synthesis of V, it was hoped that a consideration of the mode of formation of Feist's acid (IVa)[14,15] would provide a synthetic approach.

Feist's acid is formed by treatment of ethyl bromoisodehydracetate (VI) with aqueous alkali[14,15] and can be envisioned to arise by way of the transformations



It therefore seemed likely that formation of the carbanion of the bromoester VII might similarly result in direct internal displacement of bromide ion, a transformation that finds further analogy in the intermediate formation of cyclopropanones on alkaline treatment of α-haloketones.[17] While the possibility of VIII being formed could not be excluded, this appeared unlikely in view of the known tendency of isopropylidenemalonic ester to alkylate at the α-carbon atom.[18]



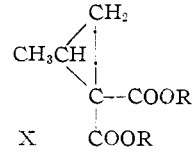
In point of fact, bromination of diethyl isopropylidenemalonate (IX) with N-bromosuccinimide proceeded smoothly to give an oil, VII, which decomposed upon attempted distillation. Treatment of the crude bromoester with sodium hydride provided only diethyl isopropylidenemalonate (IX) in low yield, presumably formed by intermolecular debromination of the bromoester by its anion. However, when the crude bromoester was treated with potassium *t*-butoxide in *t*-butyl alcohol, an oil was obtained which could be separated by vapor chromatography into two components, a dehydrobromination product, $C_{10}H_{14}O_4$ (Vb), and IX. No evidence for a third volatile fraction corresponding to VIII was found. Alkaline hydrolysis of the ester mixture provided a mixture of acids which was separable into Va and isopropylidenemalonic acid by chromatography on silica.

Evidence in support of structure V was found in the presence of a peak at 11.00 μ corresponding to terminal methylene absorption in the infrared spectra of both the ester Vb and acid Va. The double bond stretching peak of the starting material at 6.09 μ had disappeared and the ester showed a single carbonyl band at 5.75 μ.[19] The double bond was shown to be out of conjugation with the carbonyl groupings by the presence of only end absorption in the ultraviolet ($\epsilon_{200\ m\mu}$ 2200, Vb in ethanol). A simple confirmation of the structure was provided by the nuclear magnetic resonance (n.m.r.) spectra of Va and Vb. The spectrum of each compound displayed two weakly split peaks of similar intensity (Va, 35 and 163 c.p.s. in $D_2O$; Vb, 49 and 180 c.p.s. in $CCl_4$) expected for two pairs of similarly oriented protons.[20] In contrast, the ring protons in the alternative structure VIII would be expected to give a single peak with no splitting. Feist's acid (IVa) showed similar n.m.r. absorption in deuterium oxide at 30 and 147 c.p.s.[16] with previously unreported splitting of each peak into a triplet ($J$ = 2.5 c.p.s.).

Hydrogenations of Va were carried out at atmospheric pressure in ethyl acetate with both platinum and 10% palladium-on-charcoal catalysts. A total of 1.86 and 1.58 moles of hydrogen, respectively, was absorbed very rapidly with no further

(13) M. G. Ettlinger, THIS JOURNAL, **74**, 5805 (1952).
(14) (a) F. Feist, *Ber.*, **26**, 747 (1893); (b) *Ann.*, **436**, 125 (1924).
(15) F. R. Goss, C. K. Ingold and J. F. Thorpe, *J. Chem. Soc.*, **123**, 327 (1923).
(16) (a) A. S. Kende, *Chemistry & Industry*, 544 (1956); (b) M. G. Ettlinger, *ibid.*, 166 (1956); (c) A. T. Bottini and J. D. Roberts, *J. Org. Chem.*, **21**, 1169 (1956).
(17) (a) R. B. Loftfield, THIS JOURNAL **72**, 632 (1950); (b) **73**, 4707 (1951).
(18) A. C. Cope and E. M. Hancock, *ibid.*, **60**, 2644 (1938).
(19) The corresponding diacid Va showed strongly split carbonyl absorption in the infrared even in dilute solution at 5.69 and 5.99 μ. Similar peaks were observed in the spectrum of 2-methylcyclopropane-1,1-dicarboxylic acid.
(20) Peak positions are measured relative to benzene as an external standard at a radiofrequency of 40 mc.

uptake on longer stirring. A single recrystallization of the product provided *n*-propylmalonic acid. However, by chromatography on silica of the crude product from the palladium-catalyzed reduction a second compound was isolated that was indistinguishable from authentic 2-methylcyclopropane-1,1-dicarboxylic acid (X, R = H). No

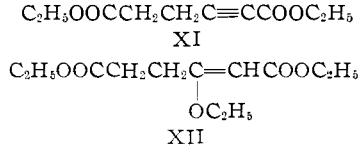


X

other products were observed. Hydrogenation of the mixture of diethyl isopropylidenemalonate and Vb likewise yielded a small amount of X (R = $C_2H_5$) along with *n*-propyl- and isopropylmalonic esters. Diethyl ethylmethylmalonate, which might have been expected to be formed in analogy to the observed courses of hydrogenation of methylenecyclopropane (I) and hypoglycin (II) (*vide supra*), could not be detected in the reaction mixture.

**Dimethyl *trans*-3-Methylenecyclopropane-1,2-dicarboxylate (IVb).**—Feist's acid (IVa) was prepared according to the published procedure[14a,15] and converted to its dimethyl ester IVb. Both compounds were hydrogenated in ethyl acetate solution with 10% palladium-on-charcoal catalyst and found to absorb 1.12 and 1.25 moles of hydrogen, respectively. Although previous investigators reported the isolation of 3-methylcyclopropane-1,2-dicarboxylic acid as the sole product,[14b,21,22] chromatography of the hydrogenated acid on silica has now provided a small yield of ethylsuccinic acid. Dimethyl ethylsuccinate could also be observed by vapor chromatography of the hydrogenated ester. No other hydrogenolysis product was detected. Long treatment of 3-methylcyclopropane-1,2-dicarboxylic acid under identical conditions was without effect.

**Methyl 2-Carbomethoxycyclopropylideneacetate (IIIa).**—The conclusion by Kon that Feist's ester (IVc), undergoes an unusual rearrangement on pyrolysis to give XI[22] went unquestioned for twenty years until Ettlinger proposed the alternative structure IIIb[13] on the basis of the absence of acetylenic absorption in the infrared. The chemical evidence presented by Kon is in accord with

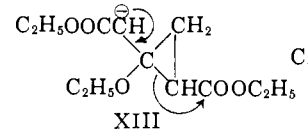


XI

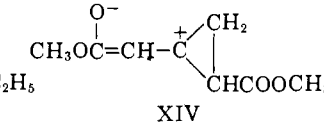


XII

either structure. Thus, treatment with sodium ethoxide was shown to give the enol ether XII which may be envisioned to arise by addition to the unsaturated linkage of either IIIb or XI followed in the former case by ring scission *via* a reverse Michael reaction (XIII, arrows). Similarly, either structure might yield the observed β-ketoadipic and levulinic acids under aqueous alkaline and acidic conditions, respectively. Equally uninformative, although of particular interest in this study, was Kon's isolation of adipic acid by saponification of the hydrogenated pyrolysis product.



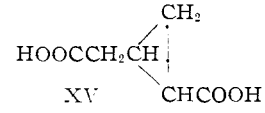
XIII



XIV

It was found convenient to prepare the pyrolysis product by vapor chromatography of Feist's ester (IVb) at 210°. In this manner the more volatile decomposition products were removed simultaneously and a colorless isomeric oil containing about 6% of the starting material (*vide infra*) was obtained free from contamination by side products. The spectra of this compound provided strong evidence in support of structure IIIa. As Ettlinger had previously observed, there was no acetylenic absorption in the infrared, but a sharp medium intensity peak at 5.68 μ appeared next to the ester carbonyl band at 5.80 μ. The former band is apparently characteristic of double bonds of alkylidenecyclopropanes[8] and is observed in this case in spite of the nearby carbonyl absorption because of enhanced intensity due to conjugation with the ester grouping. In contrast, this band is too weak to be observed in the spectra of IV or V. The structure was further supported by the presence of a maximum in the ultraviolet spectrum at 203 mμ (ε 12,200). The considerable shift from the calculated maximum at 222 ± 5 mμ[23] is predictable from the expected abnormally high energy of the dipolar form XIV, due to the electronegative character of the cyclopropane ring.[24] The n.m.r. spectrum of IIIa ($CCl_4$ solution) showed a poorly resolved multiplet centered at 17 c.p.s. corresponding to a single olefinic proton, and two strongly split groups of peaks centered at 169 and 191 c.p.s. corresponding to the ring tertiary and secondary protons, respectively.[20] Contamination of the sample by roughly 6% Feist's ester (IVb) was estimated by the areas of two weak triplets at 39 and 153 c.p.s. that increased in intensity upon addition of IVb to the sample.

Hydrogenation of the pyrolysis product in ethyl acetate with 10% palladium-on-charcoal catalyst led to the uptake of 1.39 moles of hydrogen. The isolation of the previously unreported saturated cyclic acid XV by hydrolysis of the product left



XV

no doubt about the cyclic nature of III. No other products were isolated, but the presence of both adipic and 2- or 3-methylglutaric acids could be demonstrated by paper chromatography. Vapor chromatography of the esters confirmed the presence of these compounds and also permitted de-

(21) M. G. Ettlinger, S. H. Harper and F. Kennedy, *J. Chem. Soc.*, 922 (1957).

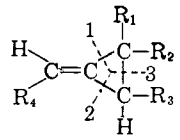
(22) G. A. R. Kon and H. R. Nanji, *ibid.*, 2557 (1932).

(23) A. T. Nielson, Abstracts, American Chemical Society, 132nd Meeting, New York, N. Y., 14-P.

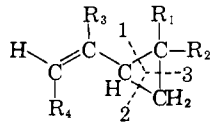
(24) (a) A. D. Walsh, *Trans. Faraday Soc.*, **45**, 179 (1949); (b) C. A. Coulson and W. E. Moffit, *Phil. Mag.*, [7] **40**, 1 (1949).

TABLE I

COURSE OF HYDROGENATION OF SOME UNSATURATED CYCLOPROPANES



| | | Molar equiv. $H_2$ absorbed | Bonds cleaved |
|---|---|---|---|
| I[8] | $R_1 = R_2 = R_3 = R_4 = H$ | (?)[d,i] | 1, 2 |
| II[9a] | $R_1 = CH_2CH(NH_2)COOH$, $R_2 = R_3 = R_4 = H$ | 1.2[c,h] | 1, 2 |
| IIIa[a] | $R_1 = R_4 = COOCH_3$, $R_2 = R_3 = H$ | 1.39[b,g] | 1, 2 (3?) |
| IVa[a] | $R_1 = R_3 = COOH$, $R_2 = R_4 = H$ | 1.12[b,g] | 1, 2 |
| IVb[a] | $R_1 = R_3 = COOCH_3$, $R_2 = R_4 = H$ | 1.25[b,g] | 1, 2 |
| Va[a] | $R_1 = R_2 = COOH$, $R_3 = R_4 = H$ | 1.58,[b,g] 1.86[b,h] | 1 |
| Va[a] | $R_1 = R_2 = COOH$, $R_3 = R_4 = H$ | 1.92[c,h] | k |

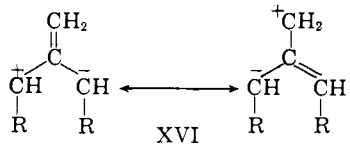


| | | | |
|---|---|---|---|
| XVII[2,3d] | $R_1 = R_2 = R_3 = R_4 = H$ | 1.2–1.3[f,i] | 1, 2 |
| XVIII[2,3c] | $R_3 = CH_3$, $R_1 = R_2 = R_4 = H$ | 1.02,[d,i] 1.15[f,i] | 1, 2 |
| XIX[3c] | $R_3 = C_2H_5$, $R_1 = R_2 = R_4 = H$ | 1.01[d,i] | .. |
| XX[3c] | $R_3 = R_4 = CH_3$, $R_1 = R_2 = H$ | 1.21[d,i] | 1, 2 |
| XXI[3c] | $R_3 = CH_3$, $R_4 = C_2H_5$, $R_1 = R_2 = H$ | 1.24[d,i] | 1, 2 |
| XXII[3a] | $R_1 = R_2 = COOH$, $R_3 = R_4 = H$ | 1.9[b,h] | 1 |
| XXIII[3b] | $R_1 = COOC_2H_5$, $R_2 = COCH_3$, $R_3 = R_4 = H$ | 1.9[e,h] | 1 |
| XXIV[5a] | $R_1 = R_2 = COOC_2H_5$, $R_3 = CH_3$, $R_4 = H$ | 1.8[c,h] | 1 |

[a] This work. [b] Ethyl acetate. [c] Methanol. [d] Ethanol. [e] Acetic acid. [f] Gas phase. [g] 10% Palladium-on-charcoal. [h] Platinum. [i] Copper chromite. [j] Raney nickel. [k] Not determined.

tection of the products of hydrogenation of Feist's methyl ester (IVb) (*vide supra*) present as an impurity. While the two isomeric methylglutaric esters could not be differentiated by the methods used, it is probable on the basis of analogy with the above cases that in fact only the 2-methyl derivative was formed.

The mechanism of formation of the pyrolysis product is of considerable interest. It seems reasonable that the reaction proceeds through the resonance stabilized intermediate XVI (R = $COOCH_3$) which could collapse in one of two ways to give either starting material or product. According to calculations by Burr and Dewar the parent system XVI (R = H) should have considerable resonance energy.[25] However, a simple valence bond tautomerism cannot be excluded as a possible alternative.



XVI

## Discussion

A summary of the results of hydrogenation of alkylidene- and vinylcyclopropanes is given in Table I. Unfortunately, a variety of conditions has been employed which permits only a rough correlation of the course of these reactions. In particular, it is seen that equivalent substitution in each system has a similar influence on the course of the reaction. Thus, vinylcyclopropane (XVII) and the alkyl substituted derivatives II and XVIII–XXI in no case are observed to undergo more than about 25% hydrogenolysis, while two carbonyl substituents on the same carbon atom (Va and XXII–XXIV) strongly facilitate ring cleavage in either class of compounds. It is of interest that only one mode of ring scission, that involving cleavage at the carbonyl-bearing carbon atom, was observed in the latter cases. These data support the original supposition that hydrogenolytic ring cleavage in both alkylidene- and vinylcyclopropanes proceeds through a common intermediate.

Conflicting hypotheses on the mechanism of hydrogenation of double bonds have recently been discussed.[26–28] Each of these suggestions envisions hydrogenation to proceed from an initial chemisorption of the organic molecule on the catalyst followed by a stepwise attack by hydrogen, but the initial reaction with a hydrogen atom is variously represented as an attack by a proton,[28] hydride ion[26] or hydrogen radical[27] from the catalyst surface. The above data (Table I) strongly suggest that in the cases studied the half-hydrogenated olefin–metal complex has the properties of a carbanion and thus is formed by a transfer of hydride ion from the catalyst. It is questionable whether it is permissible to generalize this mechanism beyond these systems, although it is of interest that Brewster[26] has been able to rationalize the steric course of hydrogenation of ketones in a similar manner.

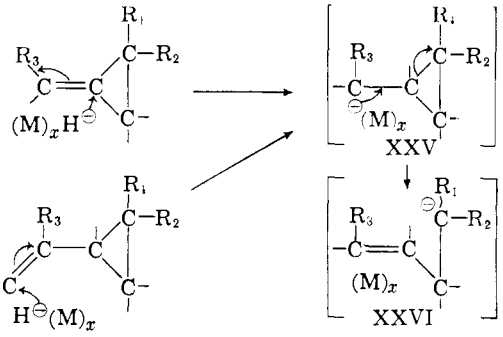
(25) J. G. Burr and M. J. S. Dewar, *J. Chem. Soc.*, 1201 (1954).

(26) J. H. Brewster, THIS JOURNAL, **76**, 6361 (1954).

(27) W. A. Bonner, C. E. Stehr and J. R. DoAmaral, *ibid.*, **80**, 4732 (1958).

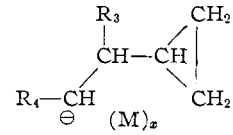
(28) F. J. McQuillin, *Chemistry & Industry*, 251 (1957).

Attack by hydride on either vinyl- or alkylidenecyclopropanes can be envisioned to give the common carbanion–metal complex XXV



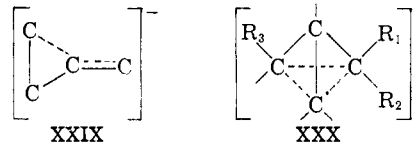
This anion may then undergo ring scission (XXV, arrows) to give XXVI or abstract a proton from the catalyst (or solvent) to give the "normal" 1,2-addition product. Protonation of the cleavage product XXVI followed by saturation of the double bond would lead in each case to the observed acyclic products. The high degree of specificity of ring cleavage in Va and XXII–XXIV (Table I) is then explained by the increased driving force for ring scission of XXV through stabilization of the resulting anion by two adjacent carbonyl groups. On the other hand, initial attack by a proton on Va or XXII–XXIV clearly would not favor hydrogenolysis at the observed bond since the electronegatively substituted carbonium ion corresponding to XXVI where $R_1$ and $R_2$ are carbonyl groups would be highly unstable. The intermediate formation of an acyclic olefin during the partial hydrogenation of isopropenylcyclopropane has previously been observed[5b]; a mixture of 2-methyl-1- and 2-methyl-2-pentenes, which were mutually interconvertible under the reaction conditions, was detected.

This reasoning does not exclude the intermediate formation of a free radical, which might undergo ring scission in a similar manner. However, the observation by Slabey that conditions that exclusively caused 1,2-addition of hydrogen to 2-cyclopropyl-1-alkenes (XVIII and XIX, Table I) were not completely selective in the hydrogenation of 2-cyclopropyl-2-alkenes (XX and XXI, Table I),[3c] appears to invalidate this alternative. In each of these cases the initial attack of hydrogen can occur at either of the two olefinic carbon atoms although only one mode of attack, that giving the cyclopropylcarbinyl anion XXV, will lead to ring cleavage. The property of alkyl substituents to weaken the acidity of hydrocarbons by destabilization of the conjugate carbanion[29] favors a relatively selective attack of hydride on 2-cyclopropyl-1-alkenes to give the primary anion XXVII which cannot give ring cleavage, rather than the much less stable tertiary anion XXV ($R_3$ = alkyl). In contrast, hydride attack on 2-cyclopropyl-2-alkenes is expected to be less selective due to the relatively smaller difference in the energies of the incipient secondary (XXVIII) and tertiary anions. If, instead, a free radical had been initially formed, the reverse order of selectivity to that observed would have been expected due to the opposite effect of substitution on the stability of free radicals.[30,31]



XXVII, $R_3$ = alkyl, $R_4$ = H
XXVIII, $R_3$ = $R_4$ = alkyl

The competition between the two olefinic carbon atoms for the initial hydride attack may also explain the observed higher percentage of ring cleavage of the pyrolysis product IIIa relative to that observed with Feist's ester (IVb) (Table I). Thus, the cyclopropylcarbinyl anion XXV ($R_3$ = $COOCH_3$) derived from IIIa should be favored over XXV ($R_3$ = H) derived from IVb due to stabilization of the former anion by the neighboring ester grouping. It is, however, not entirely clear from these arguments why 1,1-dicarbonyl-substituted vinyl- and alkylidenecyclopropanes undergo only a very small percentage of 1,2-addition (*cf.* Va and XXII–XXIV in Table I) as it is not obvious that there should be grossly different factors involved in the selectivity of hydride attack in these cases. However, if one assumes that cyclopropylcarbinyl anions may be delocalized through carbon–carbon hyperconjugation with the adjacent ring bonds (*cf.* XXIX),[32] the selectivity in these cases may then be explained since electron-withdrawing



substituents should favor an increased distribution of electrons toward the ring and thus provide resonance stabilization of XXV. Moreover, the effect of two electronegative groups on the same carbon atom might be expected to have a much stronger stabilizing influence by the delocalization of the charge than if the substituents were on different carbon atoms (*cf.* the observed percentage of hydrogenolysis in IVa *versus* Va and XXII in Table I). This is a consequence of the probable capacity of the *p*-orbital of the cyclopropylcarbinyl anion to overlap with only one of the adjacent ring $\sigma$-bonds at a time because of specific steric requirements for

(29) (a) P. D. Bartlett, S. Friedman and M. Stiles, THIS JOURNAL, **75**, 1771 (1953); (b) G. S. Hammond, "Steric Effects in Organic Chemistry," edited by M. S. Newman, John Wiley and Sons, Inc., New York, N. Y., 1956, p. 439.

(30) G. W. Wheland, "Resonance in Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1955, p. 400.

(31) Additional evidence supporting initial hydride attack is found in the observed preferential cleavage of hypoglycin (II) at bond 2 (Table I)[9a] which is predicted on the basis of the greater stability of the resulting primary carbanion intermediate XXVI ($R_1$ = $R_2$ = H) relative to the alternatively formed secondary carbanion XXVI ($R_1$ = $CH_2CH(NH_2)COOH$, $R_2$ = H).

(32) The assumption that cyclopropylcarbinyl anions can achieve added stabilization by hyperconjugation with the ring is supported by the abnormally low dipole moments of halocyclopropanes and the low basicity of cyclopropylamine. These compounds are isoelectronic with the cyclopropylcarbinyl anion and probably exhibit these abnormal properties because of similar delocalization; (a) M. T. Rogers and J. D. Roberts, THIS JOURNAL, **68**, 843 (1946); (b) J. D. Roberts and V. C. Chambers, *ibid.*, **73**, 5030 (1951).

maximum overlap. It is expected that the steric requirements in this case are similar to those reported for the cyclopropylcarbinyl cation analogous to XXIX.[33] Although the same steric restrictions would not apply if XXV existed as a resonance stabilized "non-classical" carbanion XXX, molecular orbital calculations have indicated that, in contrast to the analogous highly stabilized carbonium ion, this would be an unfavorable species.[7]

## Experimental[34]

**Diethyl Bromoisopropylidenemalonate (VII).**—Diethyl isopropylidenemalonate (50 g.), prepared according to the method of Cope and Hancock,[18] was refluxed with stirring with 44.3 g. of N-bromosuccinimide and 1.0 g. of benzoyl peroxide in 100 ml. of carbon tetrachloride with illumination by a G. E. 150 watt projector spot lamp. The reaction required from 45 to 85 minutes to reach completion as indicated by a negative starch–iodide test for N-bromosuccinimide. The resulting mixture was diluted with 100 ml. of carbon tetrachloride and cooled in an ice-bath. After filtration of the precipitated succinimide, the filtrate was evaporated *in vacuo* at room temperature. The residual pale yellow oil (68.4 g.) was used without purification in the following experiment.

**Diethyl Methylenecyclopropane-1,1-dicarboxylate (Vb).**—To a vigorously stirred, refluxing solution of 6.23 g. of potassium metal in 500 ml. of freshly distilled dry *t*-butyl alcohol was added under nitrogen 44.8 g. of the above crude bromoester over an 8-minute period. The mixture was refluxed with continued stirring for a total of 15 minutes and then immediately cooled in an ice-bath. After addition of 1.5 ml. of glacial acetic acid, the neutral suspension was filtered through diatomaceous earth and the filter pack washed thoroughly with ether. The combined solutions were concentrated *in vacuo*, diluted with ether and then washed several times with water. After having been dried over sodium sulfate, the solution was again evaporated *in vacuo* and the residue distilled at 0.15 mm. The bulk of the volatile material distilled at 65–69°, weight 15.5 g. (49%). Vapor chromatography of the resulting colorless oil showed the presence of two major components in approximately equal amounts, and a small quantity of each was collected for characterization. The slower moving component had a hold-up time identical to that of authentic diethyl isopropylidenemalonate, and was identified as this compound from its infrared and ultraviolet spectra. The faster moving component Vb had only end absorption in the ultraviolet and showed maxima in the infrared at 5.75 and 11.00 $\mu$. Its n.m.r. spectrum showed weakly split peaks centered at 49 and 180 c.p.s. and typical O-ethyl absorption ($J$ = 7.2 c.p.s.) centered at 98 (quadruplet) and 214 c.p s. (triplet), respectively.[20]

*Anal.* Calcd. for $C_{10}H_{14}O_4$: C, 60.59; H, 7.12. Found: C, 60.34; H, 7.31.

Attempts to use sodium hydride in benzene for this cyclization were unsuccessful. The reaction proceeded only very slowly and the addition of a drop of ethanol did not affect the rate. When several drops of dimethylformamide were added, a vigorous reaction ensued but diethyl isopropylidenemalonate, isolated in 38% yield, was the only product identified.

**Methylenecyclopropane-1,1-dicarboxylic Acid (Va).**—A solution of 0.37 g. of potassium hydroxide and 0.110 g. of vapor chromatographically purified diethyl methylenecyclopropane-1,1-dicarboxylate in 2.2 ml. of 90% ethanol was refluxed for 15 minutes under a nitrogen atmosphere. The solution was then cooled and the solvent removed *in vacuo*. The residue was diluted with several ml. of water and acidified with a slight excess of sulfuric acid. The resulting solution was repeatedly extracted with ether and the extracts dried over sodium sulfate and evaporated to dryness *in vacuo*. Several recrystallizations of the residue from ethyl acetate–cyclohexane gave 0.040 g. (51%) of the acid, m.p. 141–143° dec. Like its ester, the acid had only end absorption in the ultraviolet, and the n.m.r. spectrum of a 40% $D_2O$ solution showed multiplets at 35 and 163 c.p.s. in addition to water absorption.[20]

*Anal.* Calcd. for $C_6H_6O_4$: C, 50.71; H, 4.26; equiv. wt., 71. Found: C, 50.98; H, 4.56; equiv. wt., 72.

The infrared spectrum of Va in acetonitrile showed maxima at 5.69, 5.99 and 11.00 $\mu$ which remained unchanged upon dilution of the solution. The positions of the two carbonyl peaks also were not substantially different in the mineral oil mull and dioxane solution spectra. However, the ester obtained by treatment of Va with diazomethane again showed normal ester carbonyl absorption at 5.75 $\mu$. Similar splitting of the carbonyl peak was also observed in the spectrum of methylcyclopropane-1,1-dicarboxylic acid (*vide infra*).

For preparative purposes it was found convenient to hydrolyze the unchromatographed mixture of esters directly. By using a 5-minute reflux period, 1.00 g. of the mixed esters yielded a crude acid mixture on saponification which provided 0.33 g. (46%) of the cyclic acid, m.p. 140–142° dec., along with isopropylidenemalonic acid, m.p. 170–172°. The acids were most satisfactorily separated by adsorption chromatography on silica gel. Attempts to avoid the use of chromatography by employing fractional crystallization were successful occasionally but were complicated by the formation of a weak molecular complex of the two acids.

**Hydrogenation of Methylenecyclopropane-1,1-dicarboxylic Acid (Va).**—(A) A suspension of 0.060 g. of platinum oxide in ethyl acetate was stirred under hydrogen until no more of the gas was absorbed, and an ethyl acetate solution of 0.100 g. of methylenecyclopropane-1,1-dicarboxylic acid was then added and stirring continued. Within 12 minutes 1.86 molar equivalents of hydrogen had been absorbed and no further uptake was observed on longer stirring. Filtration of the reaction mixture and evaporation of the solvent *in vacuo* gave a residue which on one recrystallization from benzene provided 0.070 g. (68%) of *n*-propylmalonic acid, m.p. 93.5–94.5°. Admixture with an authentic sample, m.p. 93.5–95°, caused no depression.

(B) In a similar manner, 0.104 g. of the acid was hydrogenated with 0.130 g. of 10% palladium-on-charcoal catalyst in ethyl acetate. A total of 1.58 molar equivalents of hydrogen was absorbed. Evaporation of the solvent and chromatography of the residue on silica gel provided two crystalline fractions. A single recrystallization from benzene of the larger fraction (0.060 g.) gave pure *n*-propylmalonic acid, m.p. 93.5–95°. The second fraction (0.033 g.) on a single recrystallization from ethyl acetate–cyclohexane provided methylcyclopropane-1,1-dicarboxylic acid, m.p. 113–114°. Admixture with an authentic sample, m.p. 112–113.5°, obtained by hydrolysis of the ester,[35] gave no depression. Hydrogenation of this compound using prereduced platinum oxide in ethyl acetate was without effect. The acid showed abnormal splitting of the carbonyl peak in the infrared at 5.69 and 6.01 $\mu$.

(C) A microhydrogenation of methylenecyclopropane-1,1-dicarboxylic acid in methanol with a prereduced platinum oxide catalyst gave a total hydrogen uptake of 1.92 molar equivalents.

**Hydrogenation of Diethyl Methylenecyclopropane-1,1-dicarboxylate (Vb).**—A sample of Vb (1.0 g.) contaminated by roughly 31% of diethyl isopropylidenemalonate, as determined by vapor chromatography, was hydrogenated in ethyl acetate with 0.050 g. of prereduced platinum oxide catalyst. Vapor chromatography of the crude product showed the presence of three components, diethyl isopropylmalonate, diethyl *n*-propylmalonate and diethyl methylcyclopropane-1,1-dicarboxylate in the approximate ratio of 35:54:11, respectively. There was no peak present corresponding to diethyl ethylmethylmalonate as shown by comparison with an authentic sample. Saponification of the ester mixture followed by chromatography on silica gel and crystallization from ethyl acetate–cyclohexane provided 0.025 g. of methylcyclopropane-1,1-dicarboxylic acid, m.p. 112–113°, and a substance melting at 73–74° that was shown to be a solid compound of *n*-propyl- and isopropylma-

(33) For a discussion of the steric requirements of hyperconjugation in cyclopropylcarbinyl cations see J. D. Roberts, W. Bennett and R. Armstrong, THIS JOURNAL, **72**, 3329 (1950).

(34) Chloroform and carbon tetrachloride were used as solvents for the infrared and n.m.r. spectra, respectively, unless otherwise noted. Melting points are uncorrected. Vapor chromatographic separations were carried out at 200° using an apparatus equipped with a "polar Ucon" column purchased from Wilkens Instrument and Research, Inc.

(35) Diethyl methylcyclopropane-1,1-dicarboxylate was prepared according to the method of R. Marburg, *Ann.*, **294**, 112 (1896).

lonic acids in a 1:1 ratio. Admixture with an authentic 1:1 mixture of these acids, m.p. 73–74°, gave no depression. The melting point of this compound was depressed by admixture with a small amount of either of its components.

**Hydrogenation of *trans*-3-Methylenecyclopropane-1,2-dicarboxylic Acid (IVa).**—Feist's acid (IVa) (0.392 g.), prepared according to the method of Goss, Ingold and Thorpe,[15] was hydrogenated with 0.100 g. of prereduced 10% palladium-on-charcoal catalyst in ethyl acetate solution. A total of 1.12 molar equivalents of hydrogen was absorbed and the product could be partially separated into two components by chromatography on silica gel. The major product was the previously reported *trans*-3-methylcyclopropane-1,2-dicarboxylic acid which was isolated by crystallization from ethyl acetate–cyclohexane in two crystalline modifications: $\alpha$, m.p. 130–131°, and $\beta$, m.p. 138–140°. Each of these forms had previously been observed by different investigators[14b,21,22] along with a third modification, $\gamma$, m.p. 148°, which was not obtained in this work.

After repeated recrystallizations from ethyl acetate–cyclohexane the second chromatographic fraction, weight 0.016 g., melted at 93–95° and was tentatively identified as impure $\alpha$-ethylsuccinic acid. On admixture with an authentic sample of this acid, m.p. 100–101°, this substance melted at 95–100°. Further identification of the sample was obtained by paper chromatography using Whatman No. 1 paper and a solvent system of isoamyl acetate, acetic acid, water in a ratio of 11:3:1 which was found to separate the six-carbon diacids, $\alpha$-ethylsuccinic ($R_f$ 81), 2-methylglutaric ($R_f$ 78), *trans*-3-methylcyclopropane-1,2-dicarboxylic ($R_f$ 88) and adipic ($R_f$ 71) acids.[36] Vapor chromatographic comparison of the dimethyl esters of the 93–95° melting acid and authentic $\alpha$-ethylsuccinic acid provided additional confirmation of structure. The latter technique was found particularly effective in separating the above acids, but neither method was capable of distinguishing between 3-methyl- and 2-methylglutaric acids.

Hydrogenation of 3-methylcyclopropane-1,2-dicarboxylic acid under the above conditions was without effect. Vapor chromatography of the dimethyl ester of the re-isolated material showed the presence of only one component.

**Hydrogenation of Dimethyl 3-Methylenecyclopropane-1,2-dicarboxylate (IVb).**—The dimethyl ester of Feist's acid (IVb)( 0.378 g.), m.p. 32.5–34°, prepared by esterification of Feist's acid as described by Jones,[37] was hydrogenated in ethyl acetate with 0.100 g. of prereduced 10% palladium-on-charcoal catalyst. A total of 1.25 molar equivalents of hydrogen was absorbed. Vapor chromatography of the crude hydrogenated mixture showed the presence of dimethyl $\alpha$-ethylsuccinate and dimethyl 3-methylcyclopropane-1,2-dicarboxylate in approximately a 1:4 ratio as determined by estimation of the areas of the peaks. The corresponding acids could be isolated by saponification of the crude esters followed by chromatography of the product on silica gel.

**Methyl Carbomethoxycyclopropylideneacetate (IIIa).**—Pyrolysis of samples of Feist's methyl ester (IVb) was accomplished by vapor chromatography at about 210°. Most of the product appeared as one broad band which emerged 13 minutes after injection of the sample and was collected as a colorless oil in 9% yield. It was subsequently found that similarly low recoveries were also obtained on vapor chromatography of esters known to be thermally stable because of inefficient condensation of the sample, and thus the yield of this isomerization could presumably be greatly improved.

*Anal.* Calcd. for $C_8H_{10}O_4$: C, 56.46; H, 5.92; mol. wt., 170. Found: C, 56.64; H, 6.19; mol. wt. 185 (Rast, $CBr_4$).

The infrared spectrum of this compound had characteristic bands at 5.68 (medium intensity) and 5.80 $\mu$ with no maxima from 6.0 to 6.8 $\mu$, and a methanolic solution of IIIa showed an ultraviolet absorption maximum at 203 m$\mu$ ($\epsilon$ 12,200).[38] The n.m.r. spectrum showed strong O-methyl absorption at 117 c.p.s. and three groups of peaks centered at 17, 169 and 191 c.p.s. in a ratio of roughly 1:1:2, respectively. In addition, two weak triplets, each with approximately an eighth the area of the weaker peaks, were also observed (39 and 153 c.p.s.) and were found to be strengthened by the addition of Feist's dimethyl ester (IVb) to the sample.

**Hydrogenation of Methyl Carbomethoxycyclopropylideneacetate (IIIa).**—Hydrogenation of IIIa (0.197 g.) in ethyl acetate using 0.100 g. of pre-reduced palladium-on-charcoal catalyst led to a total uptake of 1.39 moles of hydrogen. The resulting solution was filtered, evaporated to a small volume and the last traces of ethyl acetate removed by dilution of the residue with ethanol and re-evaporation of the solution. The residue was saponified by boiling for one hour in a solution of 1.2 g. of potassium hydroxide in 10 ml. of 95% ethanol and then evaporating the mixture *in vacuo* to a small volume. The resulting residue was diluted with water, acidified with sulfuric acid and repeatedly extracted with ether. The extracts were dried over sodium sulfate and evaporated to give a semicrystalline residue which could not be purified by chromatography on silica. However, repeated recrystallization from ethyl acetate–cyclohexane gave 0.0116 g. of a saturated cyclic acid, m.p. 187–191° (dependent on rate of heating), corresponding to the expected 2-carboxycyclopropaneacetic acid.

*Anal.* Calcd. for $C_6H_8O_4$: C, 50.00; H, 5.60. Found: C, 50.31; H, 5.87.

Further fractionation of the mother liquors gave a second crystalline substance, m.p. 138–150°, that was principally adipic acid, m.p. 151–153°, and an oily residue which was composed of adipic acid, 2-(or 3)-methylglutaric acid, 2-carboxycyclopropaneacetic acid and the hydrogenation products of Feist's acid. Identification of these substances was achieved by paper chromatographic comparisons with authentic samples (*vide supra*) and by vapor chromatography of the methyl esters.

**Acknowledgments.**—The author is indebted to Dr. J. E. Lancaster for the determination and aid in interpretation of the n.m.r. spectra. Thanks are also due to Mr. L. Brancone, Mr. W. Fulmor and Dr. J. H. Clark and their associates for the analytical and spectral measurements and for the preparation of Feist's acid.

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(36) For methods of separation of dicarboxylic acids by paper chromatography see H. Kalbe, *Z. physiol. Chem.*, **297**, 19 (1954).

(37) D. T. Jones, *J. Chem. Soc.*, **87**, 1062 (1905).

(38) The ultraviolet spectrum was measured on a Cary recording spectrophotometer, model 14, in a 0.1-cm. cell.