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Concurrent Carbon-to-Oxygen Rearrangement, Cyclization, and Decarboxylation in the Reaction of 3,3,3-Triarylpropionic Acids with Lead Tetraacetate

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The reaction of 3,3,3-triphenylpropionic acid (Ia) with lead tetraacetate in benzene, chlorobenzene, or acetonitrile solution gives phenyl 3,3-diphenylacrylate as the major product. Also formed are phenyl 3,3-diphenyl-3-(3,3,3-triphenylpropionoxy)propionate, 4,4-diphenyl-3,4-dihydrocoumarin, 1,1,2-triphenylethyl acetate, triphenylethylene, triphenylmethane, benzophenone, and phenol. The relative amounts of products formed by carbon-to-oxygen rearrangement, decarboxylation, and cyclization are the same for reactions in chlorobenzene or acetonitrile at 80°. For reactions conducted in chlorobenzene at 80 and 120°, calculations based on quantitative product analyses show that ΔH^* for carbon-to-oxygen rearrangement is less by 8 kcal./mole than ΔH^* for decarboxylation, and that ΔS^* is 17 e.u. lower for the former process than for the latter one. Saponification of the esters formed by reaction of 3,3-diphenyl-3-p-methoxyphenylpropionic acid (Ib) and 3,3-diphenyl-3-p-nitrophenylpropionic acid (Ic) with lead tetraacetate, followed by acidification, gives mixtures in which the only substituted phenols present are the para isomers. Quantitative analyses of the phenols show that the migratory aptitudes of phenyl, p-methoxyphenyl, and p-nitrophenyl are 1.0, 13, and 0.10, respectively, for reactions in chlorobenzene at 100°. These relative rates are correlated by a Hammett plot using σ^+ constants with $\rho = -1.33$. At 70° the relative migratory aptitudes of phenyl and p-methoxyphenyl are the same in benzene or acetonitrile, and in chlorobenzene at 100° the over-all rate of reaction of Ib is, qualitatively, somewhat faster than that of Ic. On the basis of these results and those reported previously for the thermal decomposition of the t-butyl peresters of Ia, Ib, and Ic, it is suggested that the reaction of the acids with lead tetraacetate probably does not involve acyloxy radicals, that it does not proceed by competing ionic and radical mechanisms, and that it may involve participation by a neighboring aryl group in the rate-determining decomposition (either homolytic or heterolytic) of an intermediate lead(IV) carboxylate derived from the substrate.

Introduction

Although the oxidative decarboxylation of aliphatic acids by lead tetraacetate has achieved the stature of a standard synthetic tool,[1] many details of the mechanism of this important reaction are obscure. The proposals that have been made in this regard include both radical[1i,2] and ionic[1i,1l,3] schemes, as well as concerted processes which have been invoked occasionally to account for the products obtained from dibasic acids.[1g,m] While it seems highly probable that carbonium ions can be involved in the final stage of the reaction,[4] the possibility that these species could have been formed by oxidation of radical precursors cannot be ignored.[4] Thus the fundamental question of whether the initial oxidative attack is a homolytic or heterolytic process has remained unanswered.

It seemed that insight into the mechanism of the reaction might be gained from study of a system in which there existed the possibility of trapping intermediates such as the acyloxy radical ($RCO_2 \cdot$) or the corresponding cation (RCO_2^+). Choice of such a system is made difficult by the extreme facility with which aliphatic acyloxy radicals lose carbon dioxide, and by the expectation of similar behavior on the part

of the acyloxonium ion. Nevertheless, it was felt that these difficulties could be circumvented, at least in part, in a system which would allow rapid intramolecular reactions of these species to compete with their decarboxylation.

Recent work has shown that several reactions which ordinarily lead to decarboxylation give aryl esters or lactones when applied to the 3,3,3-triarylpropionic acids and certain of their derivatives. These products must result from intramolecular attack of reactive species generated at the carboxyl function upon one of the aromatic nuclei, and they are formed under the conditions of the Kolbe electrolysis[5a] and the Hunsdiecker reaction,[5b,c] as well as by decomposition of 3,3,3-triarylpropionyl peroxides[5d-g] and the corresponding peresters.[5h] In most of these cases the nature of the reactive intermediate has not been identified with certainty; however, evidence in support of a mechanism involving acyloxy radicals has been presented for the perester decompositions.[5h] In any event, it seemed likely that anomalous products of the type mentioned might result from the reaction of 3,3,3-triarylpropionic acids with lead tetraacetate, and that a study of this system might provide information as to the nature of the initial species formed in the oxidative decarboxylation reaction. The outcome of such a study is recorded in the present paper.

Results

The products formed by the action of lead tetraacetate upon 3,3,3-triphenylpropionic acid (Ia) in benzene, chlorobenzene, or acetonitrile solution at temperatures ranging from 80 to 130° are phenyl 3,3-diphenylacrylate (II), phenyl 3,3-diphenyl-3-(3,3,3-

(1) Cf. (a) G. Büchi, R. E. Erickson, and N. Wakabayashi, J. Am. Chem. Soc., **83**, 927 (1961); (b) A. C. Cope, C. H. Park, and P. Scheiner, ibid., **84**, 4862 (1962); (c) E. Grovenstein, Jr., D. V. Rao, and J. W. Taylor, ibid., **83**, 1705 (1961); (d) N. A. LeBel and J. E. Huber, ibid., **85**, 3193 (1963); (e) E. E. van Tamelen and S. P. Pappas, ibid., **85**, 3297 (1963); (f) C. A. Grob, M. Ohta, E. Renk, and A. Weiss, Helv. Chim. Acta, **41**, 1191 (1958); (g) C. A. Grob, M. Ohta, and A. Weiss, Angew. Chem., **70**, 343 (1958); (h) D. Ginsburg, Bull. soc. chim. France, 1348 (1960); (i) J. Jacques, C. Weidmann, and A. Horeau, ibid., 424 (1959); (j) L. L. McCoy and A. Zagalo, J. Org. Chem., **25**, 824 (1960); (k) J. Kazan and F. D. Greene, ibid., **28**, 2965 (1963); (l) K. Kitahonoki and Y. Takano, Tetrahedron Letters, 1597 (1963); (m) L. R. C. Barclay, C. E. Milligan, and N. D. Hall, Can. J. Chem., **40**, 1664 (1962); (n) L. H. Zalkow and N. N. Girotra, Chem. Ind. (London), 704 (1964); (o) A. J. Weinheimer and L. H. Kelly, Abstracts of the 18th Southwest Regional Meeting of the American Chemical Society, Dallas, Texas, Dec., 1962, p. 44.

(2) M. S. Kharasch, H. N. Friedlander, and W. H. Urry, J. Org. Chem., **16**, 533 (1951).

(3) (a) W. A. Mosher and C. L. Kehr, J. Am. Chem. Soc., **75**, 3172 (1953); (b) ibid., **82**, 5342 (1960).

(4) E. J. Corey and J. Casanova, Jr., ibid., **85**, 165 (1963).

(5) (a) H. Breederveld and E. C. Kooyman, Rec. trav. chim., **76**, 297 (1957); (b) J. W. Wilt and D. D. Oathoudt, J. Org. Chem., **23**, 218 (1958); (c) J. W. Wilt and J. L. Finnerty, ibid., **26**, 2173 (1961); (d) W. Rickatson and T. S. Stevens, J. Chem. Soc., 3960 (1963); (e) D. B. Denney, R. L. Ellsworth, and D. Z. Denney, J. Am. Chem. Soc., **86**, 1116 (1964); (f) R. L. Ellsworth, Ph.D. Thesis, Rutgers University, 1960; (g) H. M. Weiss, Ph.D. Thesis, Rutgers University, 1962; (h) W. H. Starnes, Jr., J. Am. Chem. Soc., **85**, 3708 (1963).

triphenylpropionoxy)propionate (III), triphenylethylene (IV), 1,1,2-triphenylethyl acetate (V), 4,4-diphenyl-3,4-dihydrocoumarin (VI), triphenylmethane (VII), benzophenone (VIII), and phenol (IX), as well as traces of unidentified materials. Compounds II, III, IV, and V could be isolated from the reaction

Ia, X = -H
b, X = -OCH$_3$
c, X = -NO$_2$
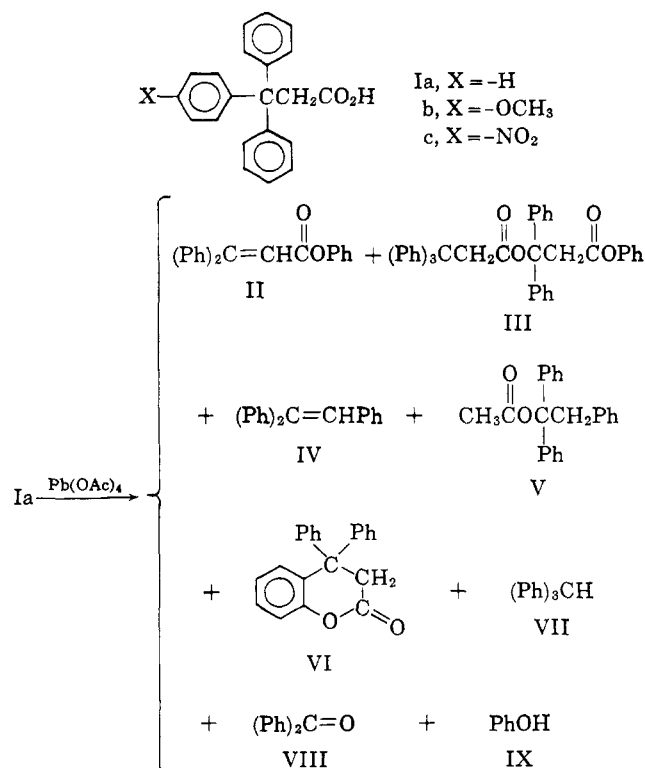
mixtures by classical procedures, while isolation of pure samples of the other products was achieved by means of gas chromatography. All of these substances except III and V were identified by comparing their physical and spectral properties with those of authentic specimens. Ester II, the major product of the reaction, was isolated in yields as high as 26%, and it is possible that the reaction may have preparative value for compounds of this type. However, no attempts were made to find optimum synthetic conditions.

The other phenyl ester (III) was always formed in very low yield (1–4%). Molecular weight measurements and elemental analyses of III are in accord with the structure given, as are the infrared, n.m.r., and mass spectral properties of the substance. Chemical evidence for the structure was also obtained, in that the products formed from the material by saponification, followed by acidification, were found to be Ia, IX, and 3,3-diphenylacrylic acid (XI). The failure to isolate 3,3-diphenyl-3-hydroxypropionic acid (X) as a hydrolysis product was not unexpected, since the experimental conditions were designed to favor dehydration of this compound to XI.


X
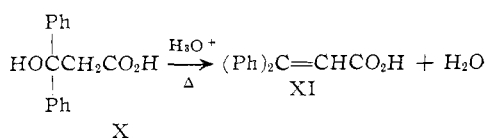
Although V had been described previously in the literature,[6] a sample of the material was not readily

(6) L. Hellerman and R. L. Garner, J. Am. Chem. Soc., 57, 139 (1935).

available. In the present work it was possible to isolate in 6% yield a substance whose melting point was close to that reported for V, and which gave infrared and n.m.r. spectra that were consistent with this structure. Further proof for the correctness of the structural assignment came from gas chromatography experiments, which caused conversion of the material to acetic acid and triphenylethylene. A similar decomposition of V was found to occur in the mass spectrometer.

The lactone VI had been reported as a minor product from the thermal decomposition of t-butyl 3,3,3-triphenylperpropionate,[5h] and an independent preparation of the material was mentioned briefly.[5h] Experimental details of this rather unusual synthesis, which involves dehydrogenative cyclization of Ia with chromic acid, are given in the present paper. The structure of the lactone was established by n.m.r. and infrared measurements and by elemental analysis.

The mass spectrum of VI is of particular interest. In addition to the expected parent ion at m/e 300, a very intense peak appears at m/e 257. The formation of this ion presumably involves loss of ketene and hydrogen from the parent molecule, and its structure is tentatively formulated as XII. Since 4-phenyl-

XII
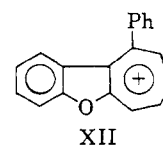
3,4-dihydrocoumarin apparently undergoes a similar type of fragmentation,[7] it appears that the phenomenon may have some generality.

Quantitative data for several reactions of Ia with lead tetraacetate are presented in Table I. The percentages reported for Ia and III are the amounts isolated, whereas the values given for the remaining products were determined by programmed temperature gas chromatography. Since V was converted to IV and acetic acid under the conditions of the analysis, the yields reported for IV include the amounts of this product formed from V. An analysis for acetic acid would have allowed IV and V to be determined separately, but unfortunately the only column that gave satisfactory results for all of the other products did not give good results for acetic acid. Because of failure to account for this acid, and for certain other reasons (see Experimental section for details), the yields reported for all compounds analyzed by the chromatographic technique are somewhat in error. However, it should be noted that even large errors of the type cited would have had only minor effects on the accuracy of the relative yields reported in the last column of Table I. Semiquantitative analysis for compounds II and IV by means of a classical isolation procedure gave results that were in satisfactory agreement with those obtained by chromatography.

Further information as to the nature of the carbon-to-oxygen aryl migration occurring in this system was provided by examining the reactions of 3,3-diphenyl-3-p-methoxyphenylpropionic acid (Ib) and 3,3-diphenyl-3-p-nitrophenylpropionic acid (Ic) with lead tetraacetate. The previously unreported p-nitro acid

(7) U. K. Pandit and I. P. Dirk, Tetrahedron Letters, 891 (1963).

TABLE I

REACTIONS OF 3,3,3-TRIPHENYLPROPIONIC ACID WITH LEAD TETRAACETATE[a]

| Expt.	Solvent	T, °C.[c]	Reacn. time, hr.	Pb(IV) convn., %	Recovery, % Ia (free)	Ia (salt)	II	III	IV[d]	VI	VII	VIII	IX	Material balance, %[e]	Mole ratio [II + (III/2) + IX]:IV:VI
1	Chlorobenzene	120	30	100	23.2	11.9	44.3	2.0	13.1	0.5	0.3	1.4	0.7	96.4	77.2:22.0:0.8
2	Chlorobenzene	120	30	100	21.9	10.6	44.1	2.0	14.5	0.2	.7	1.0	1.1	95.1	75.9:23.8:0.3
3	Chlorobenzene	80	190	<100	21.2	0	63.9	3.6	6.8	3.5	.5	2.2	3.6	102.2	87.1:8.5:4.4
4	Chlorobenzene	80	190	100	17.2	0	70.7	3.6	7.4	2.9	.8	1.3	1.7	104.1	87.8:8 8:3.4
5	Acetonitrile	80	50	<100	21.2	33.8	46.2	0.7	4.4	1.9	0	1.4	0	109.1	88.1:8.3:3.6
6	Acetonitrile	80	110	100	4.0	50.3	67.5	.7	5.9	6.5	0	2.4	0	136.5[f]	84.5:7.4:8.1
7[g]	Chlorobenzene	80	200	<100	39.7	19.8	34.2	4.4	1.8	4.4	1.5	0.9	0	106.4	85.5:4.2:10.3

[a] Equimolar quantities of Ia and lead tetraacetate, 5 ml. of solvent/mmole Ia.   [b] Based on Ia added initially.   [c] ±0.5°.   [d] Includes product formed from V; cf. Experimental section.   [e] Based on phenyl groups.   [f] High value thought to be owing largely to incomplete removal of solvent from neutral product fraction; however, see Experimental section.   [g] Oxygen bubbled through reaction mixture.

TABLE II

REACTIONS OF SUBSTITUTED 3,3,3-TRIPHENYLPROPIONIC ACIDS WITH LEAD TETRAACETATE[a]

Expt.	Acid	Solvent	T, °C.[b]	Reaction time, hr.	Pb(IV) conv., %	Recov. acid, %[c]	Mole ratio XC₆H₄OH:C₆H₅OH	Migratory aptitude XC₆H₄-:C₆H₅- [d]
8	Ib	Chlorobenzene	100	55	100	32.5	86.2:13.8	12.5
9	Ib	Chlorobenzene	100	56	100	[e]	87.0:13.0	13.4
10	Ib	Benzene	70	200	<100	11.4	89.6:10.4	17.2
11	Ib	Benzene	70	200	<100	13.3	93.9:6.1	30.8
12	Ib	Acetonitrile	70	101	100	9.0	91.0:9.0	20.2
13	Ib	Acetonitrile	70	45	100	5.4	91.0:9.0	20.2
14	Ic	Chlorobenzene	100	55	<100	68.4	4.7:95.3	0.099
15	Ic	Chlorobenzene	100	75	100	46.0	5.1:94.9	0.107

[a] Equimolar quantities of acid and lead tetraacetate, 5 ml. of solvent/mmole acid.   [b] ±0.5°.   [c] Recovered as free acid; no Pb(II) salt of the starting acid was detected in any of these experiments.   [d] $2(\text{mole } \% \text{ XC}_6\text{H}_4\text{OH})/(\text{mole } \% \text{ C}_6\text{H}_5\text{OH})$.   [e] Not determined.

was prepared in 26% yield by adapting a procedure which had already been successfully applied to the synthesis of Ib,[5c,8] viz., alkylation of ethoxymagnesiomalonic ester[9] XIII with the appropriate triaryl halide, followed by saponification and decarboxylation. That
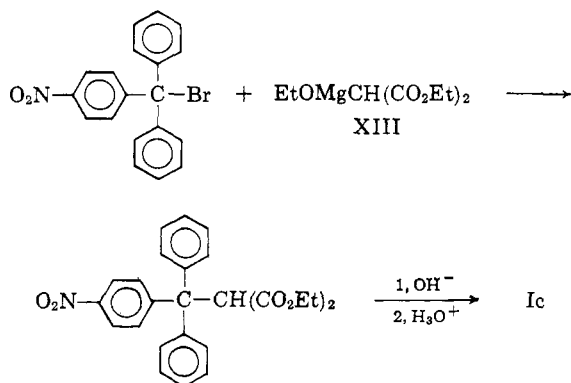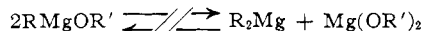

the nitro halide could be successfully employed as an alkylating agent is noteworthy in view of the known susceptibility of the nitro group to attack by conventional Grignard reagents.[10]

Saponification of the neutral product fractions obtained from reactions of Ib or Ic with lead tetraacetate, followed by acidification, gave mixtures containing

considerable quantities of phenols. Careful examination of these mixtures by programmed temperature gas chromatography showed that the only substituted phenols present were the para isomers. Quantitative application of the chromatographic technique gave the relative amounts of phenol and para-substituted phenol formed in each case, and these results were used to calculate migratory aptitudes for the carbon-to-oxygen rearrangement. The data relating to these experiments are summarized in Table II.

Discussion

One of the more interesting aspects of the results just presented is their clear demonstration that lead tetraacetate can convert the carboxyl group into a reactive species which is able to attack an unsaturated linkage. Some evidence for this process has appeared in the literature; however, no case appears to have been described previously in which the attack was followed by rearrangement. An example which apparently involves attack of the intermediate upon an adjacent aromatic nucleus is the formation of 3,4-benzocoumarin from biphenyl-2,2'-dicarboxylic acid,[11] while attack on an unconjugated double bond is exemplified by the conversion of endo-5-bicyclo[2.2.1]heptene-2,3-dicarboxylic acid to the dilactone XIV.[12] Of possible pertinence in this connection is the reported

(8) G.-A. Holmberg, Acta Acad. Aboensis Math. Phys., 16, No. 6 (1949).

(9) The structure of this interesting reagent has not been elucidated, and it is pictured in the form shown merely for convenience. In this connection it is interesting to note that a similar material, n-butylmagnesium isopropoxide, does not appear to exist in solution as an equilibrium mixture [D.

$$2\text{RMgOR}' \; \rightleftharpoons \; \text{R}_2\text{Mg} + \text{Mg(OR}')_2$$

Bryce-Smith and B. J. Wakefield, Proc. Chem. Soc., 376 (1963)].

(10) Cf. M. S. Kharasch and O. Reinmuth, "Grignard Reactions of Nonmetallic Substances," Prentice-Hall, Inc., New York, N. Y., 1954, pp. 1237–1242.

(11) W. R. Moo e and H. Arzoumanian, J. Org. Chem., 27, 4667 (1962).

(12) R. Criegee in "Newer Methods of Preparative Organic Chemistry," translated and revised by C. O. Edens, Jr., and B. Graham, Interscience Publishers, Inc., New York, N. Y., 1948, p. 5. This unusual transformation appears to have been largely forgotten, although it would appear to have particular significance in relation to the mechanism of the Grob bisdecarboxylation reaction.[1f,g] The nature of the reaction leading to XIV is obscured by the incorrect structural formulas given in the reference; however, Dr. R. H. Perry, Jr., of this laboratory has recently confirmed that it does proceed as shown above. Details of his procedure will be given in a forthcoming publication.
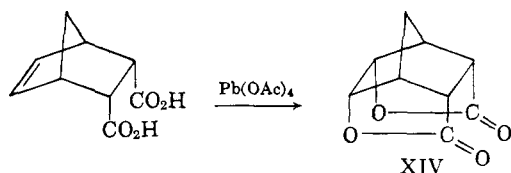
formation of lactone XVI from norquassinic acid (XV)[13]; this reaction may involve attack of the intermediate upon a double bond formed by enolization. The use of lead tetraacetate to introduce acetoxy groups into olefins and aromatics[14] should also be noted, since
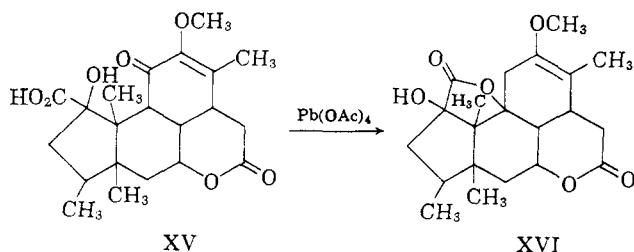
this appears to be the intermolecular analogy for reactions like those just mentioned.

In attempting to arrive at a mechanistic interpretation of the reaction of I with lead tetraacetate, it will be instructive to compare the present results with those derived from parallel study of the thermal decomposition of the related *t*-butyl peresters.[5h] Although the product distributions obtained for the two systems are similar, they differ in a number of important ways.

In the first place, the reactions of acid Ia and its perester counterpart are at variance with regard to the relative amounts of products formed by the three extent processes: carbon-to-oxygen rearrangement, decarboxylation, and cyclization. Quantitative analysis of the products resulting from decomposition of *t*-butyl 3,3,3-triphenylperpropionate in chlorobenzene solution at 120° shows that the relative extents to which these processes occur are in this case approximately 58:35:7, respectively.[15] Comparison of this ratio with the ratio [II + (III/2) + IX]:IV:VI[16] obtained from the reaction of Ia with lead tetraacetate under comparable conditions (experiments 1 and 2, Table I) reveals a dissimilarity between the two systems which is clearly significant, and which is also borne out by comparing thermodynamic activation parameters for the competitive processes. The quantities of interest in the latter connection can be obtained from the equations[17]

$$\Delta H_d{}^* - \Delta H_r{}^* = R[\ln\ (k_r/k_d)_{T_1} -$$
$$\ln\ (k_r/k_d)_{T_2}]T_2 T_1/(T_2 - T_1)$$
$$\Delta S_d{}^* - \Delta S_r{}^* = [(\Delta H_d{}^* - \Delta H_r{}^*)/T_1] - R\ln\ (k_r/k_d)_{T_1}$$

where the subscripts d and r refer to decarboxylation and rearrangement, respectively. For the lead tetraacetate reaction the ratio [II + (III/2) + IX]:IV may be set equal to k_r/k_d. Using the data from experiments 1–4 (Table I), one obtains $\Delta H_d{}^* - \Delta H_r{}^* = 8$ kcal./mole and $\Delta S_d{}^* - \Delta S_r{}^* = 17$ e.u., whereas similar calculations based on data obtained for decomposition of the corresponding perester in chlorobenzene in the temperature range 100–120°[5h,15] give 4 kcal./mole and 9 e.u., respectively. Because of experimental uncertainties, these numbers are all only approximate, and their theoretical significance cannot be determined in the absence of detailed mechanistic information. At any rate, the entropy values obtained for both systems are in accord with cyclic transition states for rearrangement. A possible interpretation of the enthalpies will be given later.

A further area of difference between the perester and lead tetraacetate reactions is in the relative rearrangement tendencies of the various aryl groups. In a study of the decomposition behavior of the *t*-butyl peresters derived from acids Ib and Ic it was found that the carbon-to-oxygen migratory aptitudes of *p*-methoxyphenyl and *p*-nitrophenyl, relative to that of phenyl,[18] were 4.0 and 0.25, respectively, for reactions carried out in chlorobenzene solution at 100°.[5h] These values may now be compared with those obtained from reactions of the acids with lead tetraacetate under identical conditions of solvent and temperature (experiments 8, 9, 14, and 15; Table II). Although the order of the groups is the same for both systems, the differences in the numerical values are clearly outside the range of experimental error. For the perester system it was reported that the migratory aptitudes could be correlated by a Hammett plot. When σ-constants are used, the correlation is poor, but with σ⁺-constants it is excellent and gives $\rho = -0.78$ for reactions in chlorobenzene at 100°.[5h] A similar situation obtains for the lead tetraacetate system, in that average migratory aptitudes determined in experiments 8, 9, 14, and 15 are correlated by σ^+ rather than σ. However, ρ is now found to be -1.33.

While the available data do not provide a basis for a complete mechanistic description of the lead tetraacetate reaction, they do allow certain reasonable inferences to be made about the processes which occur. First of all, it is clear that the reaction must involve the conversion of the carboxyl group into a reactive species which is not present in the related perester system. Since all of the evidence available to date indicates that the perester decompositions are not concerted, they are believed to involve acyloxy radicals.[5h] Therefore, if this conclusion is accepted, it follows that the lead tetraacetate reaction must occur (at least to some extent) *via* a mechanism which does not require the intermediacy of these radicals.[19] Furthermore, in

(13) Z. Valenta, A. H. Gray, S. Papadopoulos, and C. Podešva, *Tetrahedron Letters*, **20**, 25 (1960).

(14) *Cf.* W. A. Waters, in "Organic Chemistry," Vol. IV, H. Gilman, Ed., John Wiley and Sons, Inc., New York, N. Y., 1953, pp. 1185–1188.

(15) W. H. Starnes, Jr., unpublished results.

(16) Compounds VII and VIII are not included in this ratio because the mechanisms leading to their formation are uncertain. (However, see the later discussion for a possible route to VIII.) The error in the ratio caused by these omissions is minor, since the yields of VII and VIII are low. Phenol can only be produced as a consequence of carbon-to-oxygen rearrangement and evidently results from partial hydrolysis of II and/or III during the work-up. The product analysis was not sensitive enough to detect the small amounts of carboxylic acid(s) which would be formed in this hydrolysis.

(17) These relationships are easily derived from the Eyring absolute rate equation. In principle, calculations of this type could also be used to compare over-all activation parameters for cyclization and decarboxylation. However, the results would have little value, since the experimental error in the product analysis is of the same order of magnitude as the yield of VI.

(18) Phenyl was assumed to have the value 1.0 for both acids after correcting by the statistical factor of two.

(19) However, an objection to this argument can be raised by considering the possibility that products are formed from radicals in the solvent cage. Caged acyloxy radicals paired with different counter-radicals might be expected to vary in reactivity from each other and from the kinetically free

view of the results which have been obtained in other systems, it is likely that the reaction proceeds by decomposition of a lead(IV) salt of the substrate XVII.[20]

$$RCO_2Pb(OAc)_3$$
XVII
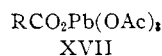
Decomposition of this salt (or any other intermediate) by competing mechanisms whose transition state polarities were widely different should cause the product distribution to be a function of solvent polarity. In fact, however, the results of experiments 3–6 (Table I) show that the distribution of products obtained from Ia is essentially the same in chlorobenzene and the much more polar solvent, acetonitrile. Moreover, experiments 10–13 (Table II) reveal that the relative migratory aptitude of p-methoxyphenyl to phenyl remains the same (within experimental error) when the solvent for the reaction of Ib with lead tetraacetate is changed from acetonitrile to benzene. These results are clearly inconsistent with the operation of competing ionic and radical mechanisms in these reactions.

Since carbon-to-oxygen migratory aptitudes for the perester and lead tetraacetate reactions are correlated by ρ-values which differ appreciably, the charge separations in the transition states for rearrangement must be different for the two systems. The perester rearrangement requires a relatively small ρ and is presumed to occur via acyloxy radicals; thus the involvement of these radicals in the lead tetraacetate-induced rearrangement would require the simultaneous operation of a mechanism whose transition state polarity is actually *greater* than is indicated by the relatively high ρ for this system. The greater the proportion of rearrangement occurring by way of acyloxy radicals, the greater must be the charge separation in the transition state of the competing mechanism, and the greater is the likelihood that the product distribution will be affected by changes in the dielectric properties of the medium. Therefore, the absence of a solvent effect implies that acyloxy radicals can be involved in the lead tetraacetate reaction to only a minor extent and suggests that they may not be formed in this system at all.

Although the available data do not seem to provide a basis for any firm mechanistic conclusions other than those suggested so far, there are indications that concerted processes involving participation by neighboring

radical, and, if the extent of reaction in the cage were sufficiently large (for either or both systems), it might be possible to account for the observed differences in product distribution without invoking a new intermediate for the lead tetraacetate reaction. In any event, the results on hand show quite conclusively that *free* acyloxy radicals cannot be precursors of all the products formed in both cases.

(20) For simplicity, the intermediate is pictured as shown; however, it seems more likely that an equilibrium mixture of lead(IV) carboxylates is present, all of which may be capable of entering the reaction

$$Pb(OAc)_4 \underset{n\ HOAc}{\overset{n\ RCO_2H}{\rightleftharpoons}} (RCO_2)_nPb(OAc)_{4-n}$$
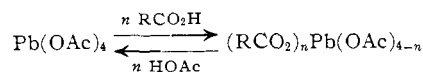
Evidence for the existence of such equilibria comes from isotopic studies [E. A. Evans, J. L. Huston, and T. H. Norris, *J. Am. Chem. Soc.*, **74**, 4985 (1952)] and from the observation that higher acids can be converted to their lead(IV) salts by reaction with lead tetraacetate at temperatures lower than those used for the oxidative decarboxylation reaction [G. B. Bachman and J. W. Wittmann, *J. Org. Chem.*, **28**, 65 (1963)]. The finding that nearly identical product distributions are obtained when an excess of a particular acidic substrate is oxidatively decarboxylated with various lead(IV) carboxylates strongly suggests the involvement of a common product-determining intermediate, which is reasonably formulated as the lead(IV) salt of the substrate.[3a]

aryl groups may be involved in the reaction. For either a heterolytic or homolytic mechanism, the carbon-to-oxygen rearrangement and cyclization processes can be pictured as proceeding through transition states A and B, respectively, while decarboxylation can be considered to occur via C.[21] Quantitative kinetic data are not yet available; however, a compari-

C
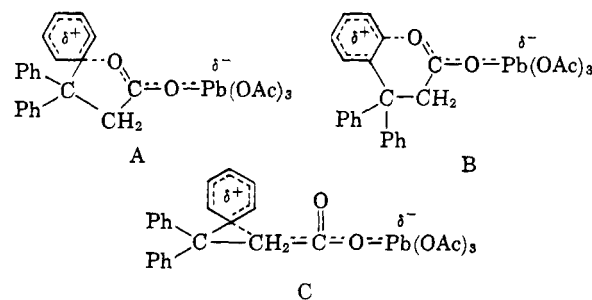
son of experiments 8 and 14 (Table II) with respect to amount of starting material recovered and extent of conversion of lead(IV) indicates that the reaction of Ib is significantly faster than that of Ic—an observation which implies the occurrence of participation. A concerted rearrangement mechanism is consistent with the migratory aptitude data, with the fact that rearrangement is the dominant process, and with the observation that $(\Delta H_d^* - \Delta H_r^*)$ is greater for the lead tetraacetate reaction than for the related perester decomposition. However, the evidence is not conclusive, and the problem requires further study.
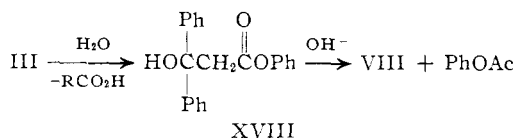
With regard to the final steps leading to the products isolated from the reaction of Ia with lead tetraacetate, it is clear that II–VI can be readily accounted for by mechanisms involving either (1) direct formation of ions without prior intervention of radicals, or (2) electron and/or ligand transfer reactions of carbon radicals with $\cdot Pb(OAc)_n(O_2CR)_{3-n}$ radicals produced concurrently in an initial decomposition step.[4,22] None of the identified products are necessarily derived directly from reactions of radicals. The absence of nonolefinic materials (e.g., phenyl 3,3-diphenylpropionate and 1,1,2-triphenylethane) shows that radical disproportionations are not involved in the formation of II, IV, and VI, while the failure of oxygen to increase the yield of VIII (cf. experiments 3, 4, and 7, Table I)[23] indicates that this product does not result from β-scission of alkoxy radicals formed by autoxidation of the carbon radicals $(Ph)_2\dot{C}CH_2CO_2Ph$ and/or $(Ph)_2\dot{C}CH_2Ph$. A possible source of VIII is compound III. Partial hydrolysis of III during the work-up could give XVIII, which might then undergo base-

(21) That aryl migration proceeds exclusively through a transition state which is of the Ar₁-5 type rather than Ar₂-6 [cf. R. Heck and S. Winstein, *J. Am. Chem. Soc.*, **79**, 3105 (1957)] is shown by the absence of *meta*-substituted phenols in the saponification products of esters derived from Ib and Ic. It is not clear which of the oxygen atoms becomes attached to an aromatic grouping during cyclization and rearrangement; however, attachment to the carbonyl oxygen would appear to be favored by steric factors if these processes are, in fact, concerted.

(22) *Cf.* J. K. Kochi, *Tetrahedron*, **18**, 483 (1962).

(23) The low conversion of starting material observed for experiment 7 was apparently caused by reaction of lead(IV) carboxylates with water formed *in situ*, as was evidenced by the appearance of a dark reddish brown precipitate (presumably PbO₂). However, the good material balance, the similarity of the product distribution to that observed in experiments 3 and 4 (Table I), and the absence of new products all suggest that the major source of water in experiment 7 was not the autoxidation of Ia, or of radicals and products derived therefrom. There are a number of other possible origins of water; however, it seems preferable not to speculate on this question in the absence of pertinent data.

catalyzed cleavage to form VIII and phenyl acetate.

$$\text{III} \xrightarrow[-RCO_2H]{H_2O} \overset{\overset{Ph}{|}}{HOCCH_2COPh} \xrightarrow{OH^-} \text{VIII} + \text{PhOAc}$$
$$\underset{\underset{Ph}{|}}{}$$

XVIII

The presence of the latter substance might account for one of the minor unidentified chromatographic peaks; this possibility remains to be checked.

From the foregoing discussion it is clear that the question of neighboring aryl participation in the reaction of I with lead tetraacetate will have to be settled before the conclusion that free acyloxy radicals are not involved can be extrapolated to reactions of the reagent with simple aliphatic acids. At any rate, results obtained in other systems have shown that the rate of the oxidative decarboxylation reaction is strongly dependent on the structure of the acid,[1j,3a,11] and for this reason it seems likely that mechanisms involving the formation of $RCO_2\cdot$ (or RCO_2^+) *in the slow step* are not generally applicable.

Experimental[24]

Elemental microanalyses and molecular weight measurements by the Rast method were performed by Schwarzkopf Microanalytical Laboratory, Woodside, N. Y., unless otherwise noted. Melting points were determined with a Fisher–Johns apparatus and are uncorrected. The n.m.r. spectra were obtained at room temperature with a Varian A-60 instrument using dilute solutions containing tetramethylsilane as an internal standard. Infrared measurements were made with a Perkin–Elmer spectrophotometer, Model 21. The mass spectrometer used was manufactured by Consolidated Electrodynamics Corp. (Type 21-103C), and the gas chromatograph was an F & M instrument, Model 500.

Lead tetraacetate (Matheson Coleman and Bell) was freed of acetic acid by drying *in vacuo* over sodium hydroxide pellets. Benzene (Baker reagent) and petroleum ether (Baker reagent) were dried over sodium wire. Chlorobenzene (Eastman), acetonitrile (Eastman), and pyridine (Baker reagent) were distilled from calcium hydride in a dry atmosphere. All other chemicals used were commercial materials of high purity.

3,3,3-Triphenylpropionic Acid (Ia).—Hellerman's original procedure[25] gave a 50% yield of product melting at 183–184° after recrystallization from absolute ethanol (lit.[5b] m.p. 180–181°). The improved method of Denney, *et al.*,[5e] afforded 84% of the purified product. The n.m.r. spectrum of Ia in $CDCl_3$ solution exhibits singlets at 6.31 (rel. area 2), 2.77 (rel. area 15), and 0.49 τ (rel. area 1) corresponding to the methylene, trityl, and carboxyl hydrogens, respectively.

Diethyl ethoxymagnesiomalonate was prepared according to Wilt and Finnerty.[5c] It was stored in a glass-stoppered vessel as a 2 *M* solution in benzene.

3,3-Diphenyl-3-*p*-methoxyphenylpropionic Acid (Ib).—Alkylation of diethyl ethoxymagnesiomalonate with *p*-anisyldiphenylchloromethane[26] in benzene solution gave a malonic ester derivative which was isolated without purification and converted to Ib in the manner described in the literature.[5c] A typical experiment gave 67% of purified product, m.p. 144.5–144.9° after recrystallization from aqueous ethanol. However, in other experiments the product was found to melt at 159–160°, even though the same recrystallization solvent was employed. The literature gives m.p. 141–142°,[5c] 155–156°,[8] and 156–157°,[27] and the possibility that this acid exhibits polymorphism has been noted.[5c] That this is indeed the case was shown in the present work by spectral comparisons of the low and high melting products. Their infrared spectra in CS_2 solution are identical, as are the n.m.r. spectra in

$CDCl_3$. The aromatic proton resonances (rel. area 14) appear in the n.m.r. spectrum at 2.70–3.45 τ, and they include an A_2B_2 pattern, centered at 3.17 τ, which arises from the disubstituted ring. The six lines of the B portion (rel. area 2) are clearly discernible, but the A branch is partly obscured by an intense peak at 2.88 τ attributed to protons on the unsubstituted rings. The remainder of the spectrum consists of singlets at 6.40 (rel. area 2), 6.35 (rel. area 3), and −0.86 τ (rel. area 1) arising from the methylene, methyl, and carboxyl hydrogens, respectively.

Diphenyl-*p*-nitrophenylbromomethane.—A mixture of diphenyl *p*-nitrophenylmethane[28] (64.1 g., 0.222 mole), N-bromosuccinimide (79.0 g., 0.444 mole), and carbon tetrachloride (300 ml.) was heated under reflux with stirring for 6 hr., then filtered while still hot. The filter cake was extracted repeatedly with several portions of fresh solvent, and the extracts were combined with the original filtrate. Evaporation of the solvent under vacuum left a white solid which was triturated thoroughly with 100 ml. of ice-cold anhydrous ether. The insoluble portion was recovered by filtration and recrystallized from approximately 1.5 l. of anhydrous ether to afford 44.2 g. of diphenyl-*p*-nitrophenylbromomethane as white crystals, m.p. 137–140° (lit.[29] m.p. 136–137°). A second crop weighed 18.4 g. and melted at 135–138°. The combined weight of both crops represents a 77% yield.

The preparation of diphenyl-*p*-nitrophenylbromomethane according to the above method has been described by Saunders and Ware.[30] These workers used a reflux time of 1.5 hr. and obtained a crude product which was converted directly to the corresponding carbinol without isolation. In the present investigation it was found that the 1.5-hr. reflux period gives only 33% of the purified bromide and allows 62% of the starting nitro compound to be recovered from the ether extract.

3,3-Diphenyl-3-*p*-nitrophenylpropionic Acid (Ic).—A solution of diphenyl-*p*-nitrophenylbromomethane (62.15 g., 0.169 mole) in 250 ml. of benzene was stirred at room temperature for 13 hr. while an equivalent amount of diethyl ethoxymagnesiomalonate in benzene (184.5 ml. of 0.916 *M* solution) was added dropwise. After an additional 9 hr. of stirring, the mixture was heated to reflux for 5 min., cooled to room temperature, and shaken with an ice-cold solution of concentrated hydrochloric acid (50 ml.) in water (200 ml.). The aqueous layer was extracted with two 100-ml. portions of ether, and the combined organic layers were washed with two 100-ml. portions of saturated aqueous sodium chloride solution, dried over Drierite, and evaporated under vacuum to afford 84.8 g. of the crude malonic ester derivative as a viscous, orange-red oil. This oil was saponified by refluxing and stirring for 6 hr. with 75 g. of potassium hydroxide, 75 ml. of water, and 650 ml. of 95% ethanol. Evaporation of the ethanol under vacuum left a dark residue, which was taken up in approximately 1500 ml. of water. The aqueous solution was extracted with 1250 ml. of ether in five portions, warmed to expel dissolved ether, cooled, and then poured slowly into a well-stirred mixture of concentrated hydrochloric acid (275 ml.) and several hundred grams of cracked ice. Carbon dioxide escaped from the mixture as it warmed gradually to room temperature. When gas evolution appeared to be complete, the pale green solid was recovered by suction filtration, washed with several portions of water, and dried *in vacuo* at 50°. It weighed 47.6 g., melted over a very wide range, and could not be purified by recrystallization from common solvents or solvent mixtures.

Partial purification of the solid was achieved by dissolving it in chloroform (100 ml.) and subjecting the solution to chromatography on a column (18 in. × 1.75 in.) of silicic acid (Mallinckrodt reagent grade, previously washed with water and dried at 125°) wetted with chloroform, using chloroform (Baker reagent grade containing 0.50% ethanol) as the eluent. The forerun contained 0.27 g. of oily material, which was discarded. A diffuse yellow band was collected in the next 800 ml. of eluent, which afforded 25.41 g. of pale yellow solid upon evaporation. Continued elution removed a dark reddish semisolid material that could not be induced to crystallize and was not examined further.

The yellow solid was dissolved in chloroform and rechromatographed in the manner just described on a column prepared from 1115 g. of silicic acid. The oily material (fraction 1, 1.70 g.) present in the forerun could not be crystallized. A yellow solid

(24) The author is indebted to Miss T. Reid and Messrs. T. J. Denson, T. Hines, H. W. Kinsey, G. R. Taylor, and J. L. Taylor for various spectral measurements, and to Mr. V. H. Rushing for gas chromatographic analyses. Helpful discussions of various analytical problems with Messrs. N. F. Chamberlain and H. E. Lumpkin and Drs. T. Aczel and K. W. Bartz are acknowledged.

(25) L. Hellerman, *J. Am. Chem. Soc.*, **49**, 1738 (1927).

(26) M. Gomberg and C. C. Buchler, *ibid.*, **45**, 207 (1923).

(27) C. F. Koelsch, *J. Org. Chem.*, **25**, 2088 (1960).

(28) D. Y. Curtin and J. C. Kauer, *ibid.*, **25**, 880 (1960).

(29) V. A. Izmail'skiĭ and D. K. Surkov, *J. Gen. Chem. USSR*, **13**, 848 (1943).

(30) W. H. Saunders, Jr., and J. C. Ware, *J. Am. Chem. Soc.*, **80**, 3328 (1958).

(fraction 2, 1.62 g.) contained in the next 400 ml. of eluent gave 0.73 g. of material with m.p.. 184.5–193° upon recrystallization from a mixture of benzene and petroleum ether (b.p. 30–60°). Further elution with 3300 ml. of chloroform afforded 19.61 g. of pale yellow solid (fraction 3). At this point removal of red material began, and the elution was stopped.

Recrystallization of small samples of fraction 3 from benzene-petroleum ether gave products which melted at 164–165° or at 192–194°. The suspicion that these materials were different forms of the same substance was confirmed by comparing their infrared and n.m.r. spectra, which were identical in every respect. (Compare the results reported above for acid Ib.) In chloroform solution the strong infrared bands attributed to the nitro group appear at 1355 and 1528 cm.$^{-1}$, and the carbonyl band lies at 1728 cm.$^{-1}$. The n.m.r. spectrum taken in deuterated acetone solution exhibits singlets at 6.17 (rel. area 2), 2.77 (rel. area 10), and 0.78 τ (rel. area 1) arising from hydrogens on the methylene group, the unsubstituted rings, and the carboxyl group, respectively. The protons on the substituted ring appear as a characteristic twelve-line A_2B_2 pattern centered at 2.21 τ (rel. area 4).

Recrystallization of all of fraction 3 from benzene–petroleum ether using the higher-melting product for seeding gave 15.48 g. (26%) of 3,3-diphenyl-3-p-nitrophenylpropionic acid as tiny, pale yellow crystals, m.p. 192–194°. The melting point was raised to 194–195° by recrystallization from aqueous ethanol and was not changed by a second recrystallization from this solvent.

Anal. Calcd. for $C_{21}H_{17}NO_4$: C, 72.61; H, 4.93; N, 4.03; mol. wt., 347. Found: C, 72.74; H, 4.96; N, 4.12; mol. wt., 347 (mass spectrum).

An attempt to prepare this acid by heating equimolar quantities of diphenyl-p-nitrophenylmethanol and malonic acid in the presence of excess acetic anhydride gave a black tar from which the desired product was recovered in only 3% yield.

4,4-Diphenyl-3,4-dihydrocoumarin (VI).—A solution of 6.04 g. (0.0200 mole) of Ia in 60 ml. of warm glacial acetic acid was combined with a solution prepared from 16.0 g. (0.160 mole) of chromic anhydride in 30 ml. of water, and the mixture was heated under reflux with stirring for 20 min. It was then poured into approximately 200 g. of a mixture of cracked ice and water and allowed to stand for 1 hr. The precipitated solid was recovered by suction filtration, washed three times with cold water, sucked dry on the filter, and then dissolved in 100 ml. of ether. Extraction of the ether solution with three 50-ml. portions of 1 N aqueous sodium carbonate removed 2.67 g. (44% recovery) of unreacted Ia, which was isolated from the combined extracts in the usual way. The acid melted at 183–185° and was shown to be identical with the starting material by the usual comparisons. Evaporation of the ether left a residue, which was refluxed and stirred for 45 min. with 25 ml. of 20% aqueous sodium hydroxide. The resulting mixture was diluted with an equal volume of water and extracted with three 50-ml. portions of ether. These were combined, dried over Drierite, and evaporated to give 0.36 g. of clear, viscous oil that was shown to be mostly benzophenone (10% yield, based on the amount of starting material consumed) by infrared and mass spectral analysis. Following adjustment to pH 2 with concentrated hydrochloric acid, the aqueous moiety was extracted with four 50-ml. portions of ether. Evaporation of the extracts afforded 0.82 g. of white solid, m.p. 138.5–149.5°, which was conveniently purified by redissolving it in 50 ml. of ether and extracting the solution with 100 ml. of 1 N aqueous sodium carbonate in three portions. Removal of ether from the dried organic phase left 0.65 g. (19% yield, based on reacted starting material) of 4,4-diphenyl-3,4-dihydrocoumarin, m.p. 150–151.5°. Recrystallization from cyclohexane gave snow-white clusters melting at 150–151.2°.

Anal. Calcd. for $C_{21}H_{16}O_2$: C, 83.98; H, 5.37; mol. wt., 300. Found: C, 84.03; H, 5.30; mol. wt., 300 (mass spectrum).

The origin of the intense peak appearing in the mass spectrum of this compound at m/e 257 has already been discussed. The infrared spectrum of VI in CS_2 solution shows a characteristic 3,4-dihydrocoumarin carbonyl band at 1795 cm.$^{-1}$, as well as a strong band at 698 cm.$^{-1}$ attributable to monosubstituted phenyl. Bands that appear at 758 and 753 cm.$^{-1}$ (shoulder) are assignable to mono- and *ortho*-disubstituted phenyl, although it is not clear which is which.[31] The n.m.r. spectrum in $CDCl_3$ exhibits a singlet at 6.45 τ (rel. area 2) arising from the protons on the methylene

group, and the aromatic protons appear as a complex multiplet in the region 2.50–3.25 τ (rel. area 14).

Phenyl 3,3-Diphenylpropionate.—A mixture of 3,3-diphenylpropionic acid (20.8 g., 0.0919 mole) and thionyl chloride (65 g., 0.55 mole) was stirred under nitrogen for 220 min. and then refluxed gently for 20 min. Most of the excess reagent was removed under vacuum, and the residue was dissolved in 40 ml. of petroleum ether (b.p. 30–60°). This solution was concentrated overnight on a rotary evaporator at about 10 mm. pressure; then the crude acyl halide was redissolved in 60 ml. of petroleum ether and added dropwise in a dry atmosphere to a well-stirred solution of phenol (8.65 g., 0.0919 mole) in pyridine (100 ml.). The temperature of the mixture was kept at 4–12° during the addition by external cooling. When the addition was complete (50 min.) the cooling bath was removed, and after 3 hr. of stirring at ambient temperature, the mixture was placed in the refrigerator and allowed to stand overnight. It was then diluted with 100 ml. of ether and washed in succession with 300 ml. of ice-cold water, 100 ml. of ice-cold 10% sulfuric acid, two 150-ml. portions of chilled 5% sodium bicarbonate (an additional 200 ml. of ether was added at this point to redissolve the solid that had separated), and two 150-ml. portions of saturated sodium chloride solution. After treatment with Drierite, the organic moiety was evaporated under vacuum to afford 25.3 g. of solid melting at 70.5–72°. Recrystallization of this material from absolute ethanol gave 19.3 g. (69%) of phenyl 3,3-diphenylpropionate as tiny white needles, m.p. 72.5–73.5° (lit.[5a] m.p. 84–85°), unchanged by further recrystallization from the same solvent. A second crop weighed 2.6 g. and melted at 70.5–72°.

The failure of the melting point to agree with that reported in the literature has not been explained; however, the product obtained in the present work was shown to be homogeneous by programmed temperature gas chromatography, and its structure was confirmed by spectral measurements. A carbonyl stretching band appears in the infrared spectrum (CS_2) at 1770 cm.$^{-1}$ (reported[5a] for this compound, 1761 cm.$^{-1}$). The mass spectrum shows a small parent peak at m/e 302, as well as large fragments at m/e 209 ($C_{15}H_{13}O$), 180 ($C_{14}H_{12}$), and 167 ($C_{13}H_{11}$). The n.m.r. spectrum ($CDCl_3$) exhibits a doublet at 6.82 τ (rel. area 2, $J \sim$ 8 c.p.s.) attributed to the α-protons, a triplet at 5.41 τ (rel. area 1, $J \sim$ 8 c.p.s.) arising from the β-proton, and complex multiplets in the aromatic region at 2.65–3.10 (rel. area 13) and 3.15–3.42 τ (rel. area 2). The latter multiplet is tentatively assigned to the protons *ortho* to oxygen.

Reactions of Ia with Lead Tetraacetate. A. Semiquantitative Product Analysis. Isolation of Phenyl 3,3-Diphenylacrylate (II), Phenyl 3,3-Diphenyl-3-(3,3,3-triphenylpropionoxy)propionate (III), and 1,1,2-Triphenylethyl Acetate (V).—Lead tetraacetate (4.43 g., 0.0100 mole) was added to a solution of Ia (3.02 g., 0.0100 mole) in chlorobenzene (50 ml.), and the mixture was stirred at the reflux temperature for 4 hr. under a condenser equipped with a Drierite tube. After cooling to room temperature, the solid (fraction A) was removed by suction filtration and washed while on the filter with several small portions of benzene. An infrared spectrum of A (Nujol mull) was identical with that of an authentic sample of anhydrous lead(II) acetate. The combined filtrate and washings were extracted with 150 ml. of 2 N aqueous sodium carbonate in four portions, and the cloudy extracts were clarified by extraction with two 75-ml. portions of ether. The aqueous phase was warmed to remove dissolved ether, acidified (pH 2) with concentrated hydrochloric acid, cooled to 5–10°, and filtered to recover a white solid (fraction B), which was washed thoroughly with water, dried under vacuum to constant weight (0.72 g.), and identified as unreacted Ia by infrared and melting point comparisons. After combination with the ether extracts, the organic phase was washed with two 50-ml. portions of saturated sodium chloride solution, dried over Drierite, and evaporated *in vacuo* to afford 2.49 g. of viscous material (fraction C) which gradually solidified upon standing. A portion of this oil (2.18 g.) was stirred and refluxed for 9.5 hr. with 4.0 g. (0.71 mole) of potassium hydroxide dissolved in 50 ml. of 80% ethanol. Removal of the ethanol under vacuum followed by addition of ether (40 ml.) gave two layers, which were separated. The ether layer was washed with three 25-ml. portions of saturated sodium chloride solution, dried with Drierite, and freed of solvent by vacuum evaporation. Analysis of the residue (0.41 g.) by n.m.r. showed that it consisted almost entirely of triphenylethylene (18% yield, corrected to original weight of C). The aqueous layer was warmed until free of ether, adjusted to pH 2 with concentrated hydrochloric acid, and filtered to collect 1.05 g. of pre-

(31) *Cf.* L. J. Bellamy, "The Infra-red Spectra of Complex Molecules," John Wiley and Sons, Inc., New York, N. Y., 1959, pp. 76–77.

cipitated solid (fraction D) whose infrared spectrum (Nujol mull) was very similar to that of an authentic sample of 3,3-diphenyl-acrylic acid.[32] However, quantitative n.m.r. analysis of D showed that it contained 73% (0.77 g., 39% yield, corrected) of this acid and 27% (0.28 g.) of Ia. The total amount of Ia recovered was, therefore, 1.00 g. (35%). (Other experiments showed that the presence of Ia in fraction D was probably caused by partial solubility of its sodium salt in the organic phase; see below.) Treatment of the acidified aqueous moiety with a slight excess of a solution of bromine and potassium bromide in water[33] caused precipitation of 2,4,6-tribromophenol (1.00 g., 35% yield, corrected), m.p. 91.5–95.5° (lit.[34] m.p. 96°), whose identity was confirmed by comparing its infrared and n.m.r. spectra with those of an authentic specimen.

A similar experiment was performed starting with 15.1 g. (0.0500 mole) of Ia, 250 ml. of chlorobenzene, and 22.2 g. of lead tetraacetate. The reflux time was 30.5 hr., and the product was separated into fractions A, B, and C in the manner described above. Fraction C was boiled with 500 ml. of methanol and filtered to recover 1.00 g. of white solid that melted largely at 291–294°. This material was apparently the sodium salt of the starting acid (yield, 6%), since it had a strong infrared band at 1550 cm.$^{-1}$ (Nujol mull) and was converted to Ia by treatment with concentrated hydrochloric acid. The methanol solution was concentrated and chilled, and the white solid that precipitated was recovered. This material weighed 3.98 g., melted at 125–126°, and was shown to be phenyl 3,3-diphenylacrylate (26% yield) by comparison (mixture melting point, infrared and n.m.r. spectra) with an authentic sample of m.p. 128–129° (lit. m.p. 121°,[32] 123.5–124.5°[5b]) prepared by the method of Patai and Ikan.[32]

In other experiments fraction C was extracted with hot petroleum ether (b.p. 30–60°, approximately 30 ml. per gram of C), and the insoluble material was boiled with methanol and filtered. After concentration, the methanol solution was chilled and then filtered to recover the tiny, colorless crystals of phenyl 3,3-diphenyl-3(3,3,3-triphenylpropionoxy)propionate that had precipitated. The material was usually quite pure at this stage but could be recrystallized, if necessary, from methanol. Yields of this ester reported in Table I are the amounts of product melting at or slightly below the melting point of the pure compound, which is 188.5–189.5°.

Anal. Calcd. for $C_{42}H_{34}O_4$: C, 83.69; H, 5.69; O, 10.62; mol. wt., 603. Found: C, 83.58; H, 5.58; O, 10.87[35]; mol. wt., 583 (Rast).

The infrared spectrum of the compound in CS_2 shows strong absorptions at 1770 and 1748 cm.$^{-1}$ (shoulder). These bands may be compared with the carbonyl stretching frequencies of phenyl 3,3-diphenylpropionate and compound V (see below), which are 1770 and 1755 cm.$^{-1}$, respectively. Qualitative comparisons of the mass spectrum of III with the spectra of compounds Ia and II suggested that III may have undergone conversion to these two substances under the conditions of this analysis. The occurrence of an intense peak in the spectrum of III at m/e 243 is particularly significant, since it provides strong evidence for the presence of a trityl group. The n.m.r. spectrum of III in $CDCl_3$ solution shows two poorly resolved peaks arising from the methylene groups (total rel. area 4) at 6.09 and 6.11 τ, a multiplet in the aromatic region centered at 3.35 τ (rel. area 2) which is very similar in appearance to the 3.15–3.42 τ multiplet of phenyl 3,3-diphenyl-propionate, and a peak corresponding to the remaining aromatic protons at 2.85 τ (rel. area 28). When deuterated pyridine is used as the n.m.r. solvent, the methylene groups are completely separated into singlets appearing at 5.78 (rel. area 2) and 5.88 τ (rel. area 2), and the aromatic protons now give rise to a complex pattern in the 2.40–3.30-τ region (rel. area 30 after correcting for weak solvent peaks at 2.44 and 2.81 τ).

Compound III (199.3 mg., 0.3307 mmole) was refluxed for 6.0 hr. with a solution of potassium hydroxide (0.25 g., 4.5 mmoles) in 90% ethanol (10 ml.). After removal of the ethanol *in vacuo*, the residue was dissolved in 30 ml. of water, and the solution was extracted with three 50-ml. portions of ether. These were com-

bined, dried over Drierite, and evaporated. No residue remained. The aqueous phase was warmed to expel ether and acidified (pH 2) at the boiling point with concentrated hydrochloric acid. The cloudy mixture, which had a strong phenolic odor, was chilled in the refrigerator and then filtered to recover 156.5 mg. of white solid, m.p. 138–139.5°. Analysis of this material by n.m.r. showed that it was a mixture of Ia (58.6 wt. %, 91.7 mg., 92% yield) and 3,3-diphenylacrylic acid (41.4 wt. %, 64.8 mg., 87% yield). A mixture of these two acids having the composition indicated by the n.m.r. analysis was prepared from authentic samples. The melting point of the known mixture was 139–141.5°, and its infrared spectrum (CS_2) was identical with that of the mixture obtained previously. Treatment of the filtrate with a slight excess of brominating solution[33] precipitated 60 mg. (55% yield) of 2,4,6-tribromophenol, m.p. 92.5–95.5°, which was identified by the usual spectral comparisons.

Further concentration of the methanol solution from which III had been obtained caused precipitation of crude II, which was identified in the usual way. Occasionally it was possible to obtain a small additional amount of III by recrystallizing the petroleum ether-soluble material from methanol. Usually, however, the only product which could be obtained in this way was II.

In another experiment 4.43 g. (0.0100 mole) of lead tetraacetate was allowed to react with 3.02 g. (0.0100 mole) of Ia in 50 ml. of benzene for 45 hr. at the reflux temperature. Fraction C was subjected to chromatography on 75 g. of Merck reagent grade alumina, eluting first with petroleum ether (b.p. 30–60°) and then with benzene–petroleum ether mixtures containing increasingly higher proportions of benzene. The initial oily fractions (about 15% of the material charged to the column) resisted purification. When the proportion of benzene to petroleum ether reached about 50:50 (by volume), a white solid (approximately 15% of C) was removed. Recrystallization of this material from methanol gave white prisms which showed ester carbonyl absorption in the infrared (CS_2) at 1755 cm.$^{-1}$, and which were converted (apparently quantitatively) into acetic acid and triphenylethylene under the conditions used for analysis of fraction C by gas chromatography (see below). The n.m.r. spectrum ($CDCl_4$) exhibited singlets at 7.98 (rel. area 3) and 5.96 τ (rel. area 2), as well as a complex pattern in the 2.62–3.60-τ region (rel. area 15). Therefore, the substance was 1,1,2-triphenylethyl acetate. The yield of purified product, m.p. 181.5–183.5° (lit.[6] m.p. 175.5°, cor.) was 0.20 g. (6%). Further elution of the column gave oily materials which were intractable.

B. Quantitative Product Analysis.—A solution of Ia in the desired solvent (5 ml. per mmole of Ia) was prepared in a round-bottom flask containing a Teflon-coated magnetic stirring bar and equipped with a reflux condenser bearing a Drierite tube. The solution was stirred and thermostated in an oil bath at the desired temperature for at least 30 min. Lead tetraacetate (1.00 mmole per mmole of Ia) was then added rapidly, and stirring was continued. In experiment 7 (Table I) the addition of oxygen was begun during the preliminary thermostating period and was continued throughout the course of the reaction. Cylinder oxygen was allowed to pass in succession through Drierite, Molecular Sieves (Linde No. 5A), a saturator containing dry chlorobenzene, and then into the reaction mixture through a tube extending below the liquid level.

The products of the reaction were separated into fractions A, B, and C in the way described in part A, above. In cases where all of the lead(IV) did not react, PbO$_2$ precipitated during the first extraction with sodium carbonate and was removed by filtration. For runs using chlorobenzene it was sometimes necessary to dilute the organic phase with additional benzene or with ether in order to achieve clean separations during extraction. When acetonitrile was used, the filtrate from fraction A was freed of solvent *in vacuo*, and the residue was taken up in benzene before proceeding with the work-up.

If the infrared spectrum (Nujol mull) of fraction A showed bands in the 700–750 cm.$^{-1}$ region, the material was boiled and stirred at least 20 min. with concentrated hydrochloric acid (20–30 ml. per gram of A). The cooled mixture was extracted completely with several portions of ether, which were combined, dried over Drierite, and evaporated under vacuum to afford a white solid which always proved to be Ia, as was shown by infrared and n.m.r. analysis. Similar analysis of fraction B showed that it was also Ia.

Fraction C was analyzed by programmed temperature gas chromatography using a 10 ft. × 0.25 in. column containing 15% GE XE-60 (Applied Science Laboratories, Inc.) on 40–60

(32) S. Patai and R. Ikan, *J. Org. Chem.*, **21**, 1379 (1956).

(33) R. L. Shriner, R. C. Fuson, and D. Y. Curtin, "The Systematic Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1959, p. 264.

(34) "Handbook of Chemistry," N. A. Lange, Ed., McGraw-Hill Book Co., Inc., New York, N. Y., 1956, p. 701.

(35) The neutron activation analysis for oxygen was performed by Dr. R. L. Hull of this laboratory.

mesh Chromosorb P. Helium (120 ml./min.) was used as the carrier gas, and the temperature was raised at the rate of 8°/min. over the range 100–320°. Peaks were identified by retention times and by infrared, n.m.r., and mass spectral analysis of trapped samples. Phenyl 3,3-diphenylpropionate, 1,1,2-triphenylethane, and 1,1,1-triphenylethane[36] were shown to be absent by comparing the chromatograms of fraction C containing added samples of these materials with those of the original mixtures. Calibration runs on standard mixtures showed that compositions could be determined to within ±3% of the actual values. It was necessary to include chlorobenzene in these standards, since a few per cent of this material always remained in fraction C obtained from runs where it was used as the solvent. Chromatograms of fraction C invariably exhibited a few minor peaks in addition to those that were identified. On the assumption that the g.c. sensitivity factors of these components were identical with that of IV, they were estimated to comprise 4–8% of the weight of C, and none of them ever amounted to more than 2% of this weight. For purposes of calculation it was always necessary to correct the weight of C for the amounts of III that were isolated, since this compound gave no chromatographic peak under the conditions used.

The principal errors in the analysis of C would appear to be those arising from failure of the chromatographic technique to account for small amounts of benzene and sodium 3,3,3-triphenylpropionate present in the samples and for the acetic acid formed from V during the analysis. Another possible source of error would be failure to account for acetic acid formed *in situ* from phenyl 3-acetoxy-3,3-diphenylpropionate. Although no firm evidence for the presence of this compound was obtained, in some preliminary qualitative experiments it was noticed that the peaks in the n.m.r. spectra of the C fractions at about 6 and 8 τ were broader and more intense (relative to the olefinic hydrogen peak of II, which appears at 0.40 τ in CDCl₃) than they should have been if they were due entirely to compound V. The presence of phenyl 3-acetoxy-3,3-diphenylpropionate would account for this observation if the resonances of its methyl and methylene protons were sufficiently close to those of the corresponding protons of V. In any event, the fairly good material balances obtained for most of the experiments summarized in Table I can be taken as evidence for the general reliability of the analytical scheme. It is apparent that none of the sources of error just cited will affect the accuracy of the relative percentages of (II + IX):IV:VI (assuming, of course, that the chromatographic conversion of acetates to the corresponding olefins was always quantitative). Therefore, since III is only a small fraction of [II + (III/2) + IX] it is believed that the numbers of principal interest, namely, those for the ratio given in the last column of Table I, are not seriously in error.

(36) M. Gomberg and L. H. Cone, *Ber.*, **39**, 2963 (1906).

Reactions of Ib and Ic with Lead Tetraacetate. Migratory Aptitudes.—These reactions were carried out in the way described in part B, above, using 5.00 mmoles each of acid and lead tetraacetate and 25 ml. of solvent. Fractions A and B were examined in the usual way. Fraction C was saponified by refluxing and stirring for at least 6 hr. with 2.8 g. (50 mmoles) of potassium hydroxide and 25 ml. of 95% ethanol. Most of the solvent was removed under vacuum, and the residue was dissolved by adding 25 ml. of water and 25 ml. of ether. The layers were separated, and the aqueous portion was extracted with 75 ml. of ether in three portions. After two washings with 40-ml. portions of saturated sodium chloride solution, the combined ether layers were evaporated under vacuum to give a viscous, oily residue (0.05–0.15 g.) which was shown (by a variety of analytical techniques) to contain no aryl esters. The aqueous layer was acidified (pH 2) with concentrated hydrochloric acid, extracted at least twice with an equal volume of ether, and then continuously extracted with ether for a day or longer. In experiments with Ib the aqueous moiety gave a negative test for phenols with brominating solution[33] at the end of this time. For reactions starting with Ic several drops of the solution were decolorized, and the mixture became cloudy. However, since experiments with standard mixtures of phenol and *p*-nitrophenol (see below) showed that these compounds would have been completely removed by the extraction procedure, the positive test must have been due to reaction of the reagent with a nonphenolic product (perhaps 3-phenyl-3-*p*-nitrophenylacrylic acid?). Following treatment with Drierite and removal of solvent *in vacuo*, the ratios of phenolic products contained in the residue from the combined ether extracts were determined by programmed temperature gas chromatography (temperature increase 8°/min. from 125 to 260°, helium flow rate 120 ml./min.), usually on a 4 ft. × 0.25 in. column containing 15% Carbowax 20,000 on 40–60 mesh Chromosorb P. In some of the experiments starting with Ib, equally good results were obtained with the column used in the analysis of fraction C from acid Ia (see above). The peaks corresponding to phenol, *p*-methoxyphenol, and *p*-nitrophenol were shown to be homogeneous by infrared and mass spectral analysis of trapped samples. No peaks having the correct retention times for the *ortho* and *meta* isomers of the substituted phenols were detected. The analytical scheme was checked by carrying standard mixtures of phenol with *p*-methoxy- or *p*-nitrophenol through the entire procedure, beginning with the alcoholic caustic treatment. Recoveries were essentially quantitative, and the percentages found never differed from the original values by more than ±1%.

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Acid-Catalyzed Amide Hydrolysis Assisted by a Neighboring Amide Group[1]

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The acid-catalyzed hydrolysis of *o*-benzamido-N,N-dicyclohexylbenzamide (I) in aqueous acetic acid containing sulfuric acid at 80° occurs at the N,N-dicyclohexylamide linkage and is at least 10⁴ times faster than the hydrolysis of the less sterically hindered model compound, N,N-dicyclohexylbenzamide (IV), under the same conditions. Several mechanisms are presented by which the *o*-benzamido group may participate in the hydrolysis by acting as a general base, a nucleophile, or, when protonated, as a general acid. Support for the intermediate formation of benzoylanthranil (V) has been obtained by isolating this compound from a reaction in which compound I was cleaved in dry dioxane containing hydrogen chloride, and by showing that V rapidly hydrolyzes to the acid obtained from the hydrolysis of I.

Because of the great biological importance of proteolytic reactions, there has been considerable interest in intramolecular assistance to amide hydrolysis.[2] In cases in which the amide group has not under-

gone prior protonation, intramolecular assistance can be afforded either by strong basic groups, such as an alkoxide anion[3] or the nitrogen atom of the conjugate base of another amide function,[4] or by general acids,

(2) M. L. Bender, *Chem. Rev.*, **60**, 88 (1960); T. C. Bruice, *Brookhaven Symp. Biol.*, **No. 15**, 52 (1962).
(3) T. C. Bruice and F. H. Marquardt, *J. Am. Chem. Soc.*, **84**, 365 (1962).