(52%) of 2,4-dichlorobenzoic acid which crystallized from benzene as colorless microcrystals, m.p. 158–159° (lit.[29] m.p. 161–162°).

Reaction of IIa with 2,4-dichlorobenzaldehyde in ethereal solution gave 3% of VIIIe and 26% of Xe.

F. Acetaldehyde.—Reaction of 1.5 g. of ylid IIa with 0.9 g. of acetaldehyde in methylene chloride (sealed tube) gave an oily alcohol Xf (45%), λ_{max} 3390 cm.$^{-1}$. It formed a benzoate which crystallized from ethanol as colorless prisms, m.p. 141.5–143.5°.

Anal. Calcd. for $C_{24}H_{22}O_2S$: C, 76.97; H, 5.92; S, 8.56. Found: C, 76.99; H, 5.95; S, 8.27.

Oxidation of 0.1 g. of the benzoate with chromic acid gave 0.03 g. (92%) of benzoic acid, m.p. 120–121°, identical to an authentic sample, and 0.01 g. (15%) of fluorenone-1-dimethyl sulfone.

Dehydration of 0.6 g. of the carbinol Xf with 0.4 ml. of phosphorus oxychloride in pyridine gave a low yield of an oil whose ultraviolet spectrum, λ_{max} 257 mμ, was compatible with its formulation as 9-ethylidene-1-methylthiomethyl-fluorene.

Synthesis of Benzalfluorene Oxides (VIII).—In a representative synthesis 2.5 g. (0.01 mole) of 9-bromofluorene,[30] 1.34 g. (0.01 mole) of p-cyanobenzaldehyde and 1.0 g. of potassium carbonate in 30 ml. of methanol were heated under reflux with stirring for 2.5 hours. Water was added, the precipitate washed thoroughly with water then the p-cyanobenzalfluorene oxide (VIIId) (2.0 g., 66%) crystallized from ethanol as colorless needles, m.p. 152–154°. The following were prepared in an identical manner (see above for analyses): p-nitrobenzalfluorene oxide (VIIIa), 50% yield, m.p. 152–154° (lit.[16] 153°); m-nitrobenzalfluorene oxide (VIIIb), 41%, m.p. 150–151°; 2,4-dichlorobenzalfluorene oxide (VIIIe), 57%, m.p. 187–189°; p-chlorobenzalfluorene oxide, 50%, m.p. 140–141°.

o-Nitrobenzalfluorene oxide could not be prepared in the above manner, the starting materials being recovered unchanged. The following method was then employed. Reduction of 10 g. of o-nitrobenzaldehyde in 100 ml. of methanol with 1.3 g. of sodium borohydride for 1 hour at

room temperature followed by quenching with water gave 9.5 g. (94%) of o-nitrobenzyl alcohol which crystallized from water as colorless needles, m.p. 71.5–73° (lit.[31] m.p. m.p. 74°). To 6.0 g. of this alcohol in 90 ml. of ether was added 8.0 g. of phosphorus tribromide over 0.5 hour at −10° with stirring. The solution was then heated under reflux for 2 hours then quenched with water. Evaporation of the ether layer gave 6.5 g. (77%) of o-nitrobenzyl bromide which crystallized from aqueous ethanol as colorless plates, m.p. 44–46° (lit.[32] m.p. 46–47°). Condensation of 4.5 g. of fluorenone with 4.3 g. of o-nitrobenzyl bromide in 50 ml. of methanol containing 2.0 g. of potassium carbonate, followed by chromatography, gave 0.05 g. (10% based on unrecovered fluorenone) of o-nitrobenzalfluorene oxide (VIIIc) which crystallized from ethanol–benzene as colorless needles, m.p. 185–187° (lit.[18] m.p. 111°).

Reaction of the Ylid IIa with Nitrosobenzene.—A solution of 1.5 g. of ylid IIa and 0.71 g. of nitrosobenzene in 35 ml. of methylene chloride was heated under reflux for 3 hours after which the yellow precipitate (1.7 g., 94%) was filtered. Recrystallization from ethanol gave N-phenylfluorenone ketoxime (XIV) as yellow needles, m.p. 192–193°. The same reaction in ethereal solution gave XIV in 96% yield.

Anal. Calcd. for $C_{19}H_{13}NO$: C, 84.11; H, 4.83; N, 5.16. Found: C, 84.30; H, 4.84; N, 5.29.

Hydrolysis of XIV by stirring in an aqueous ethanolic solution of 6 N sulfuric acid at room temperature for 8 hours gave a quantitative yield of fluorenone, m.p. 81–82°, identical to an authentic sample. Chromatography of XIV on alumina effected hydrolysis of 50% of the sample.

N-Phenylfluorenone Ketoxime (XIV).—To 5.0 g. of 9-bromofluorene[30] in 15 ml. of benzene was added 5 ml. of pyridine. The solution was heated under reflux for 4 hours then cooled overnight affording a precipitate of 3.9 g. (62%) of 1-(9-fluorenyl)-pyridinium bromide, m.p. 194–197° (lit.[17] m.p. 199–200°). To a solution of 0.32 g. of this bromide and 0.1 g. of nitrosobenzene in 10 ml. of ethanol was added 1 ml. of 10% aqueous sodium hydroxide. Quenching with water after 2 minutes gave 0.25 g. (93%) of XIV, identical to that prepared from IIa (above).

(29) E. Roberts and E. E. Turner, *J. Chem. Soc.*, 1846 (1927).

(30) G. Wittig and G. Felletschin, *Ann.*, **555**, 133 (1944).

(31) F. Schenck, *Chem. Ber.*, **67**, 1571 (1934).

(32) J. F. Norris, M. Watt and R. Thomas, THIS JOURNAL, **38**, 1077 (1916).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF WASHINGTON, SEATTLE 5, WASH.]

The Stereochemistry of the Chromic Acid Oxidation of Tertiary Hydrogens[1]

BY KENNETH B. WIBERG AND GORDON FOSTER

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The chromic acid oxidation of (+)-3-methylheptane in 91% acetic acid gave (+)-3-methyl-3-heptanol with 70–85% retention of configuration. The reaction showed a kinetic isotope effect. The mechanistic implications of these and related data are discussed.

We have recently studied the chromic acid oxidation of diphenylmethane in 91–95% acetic acid[2] and have obtained evidence that the reaction involves the formation of the benzhydryl radical in the first step. The data did not, however, permit us to determine the nature of the succeeding steps leading to benzophenone. In order to be better able to obtain information of this type, we have now investigated the oxidation of a hydrocarbon with one tertiary hydrogen. Here, based on the work of Sager and Bradley,[3] we would expect to

be able to study the oxidation of the hydrocarbon to the tertiary alcohol.

The information on the oxidation of compounds of this type is meager. However, both Roček,[4] and Sager and Bradley[3] agree that the predominate reaction is the attack at the tertiary hydrogen, that the alcohol is the first isolable compound to be formed, and that further reaction involves the rate-controlling dehydration of the alcohol. The latter authors also observed a kinetic isotope effect, indicating that carbon–hydrogen bond cleavage occurred in the rate-determining step.
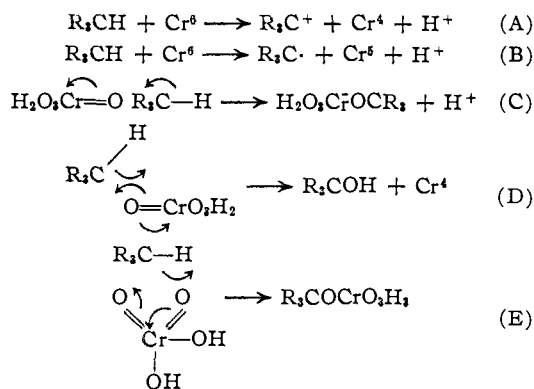
As in the case of the oxidation of diphenylmethane,[2] the rate-determining step may involve any one of the five reactions

(2) K. B. Wiberg and R. J. Evans, *Tetrahedron*, **8**, 313 (1960).

(3) W. F. Sager and A. Bradley, THIS JOURNAL, **78**, 1187 (1956).

(4) J. Roček, *Coll. Czech. Chem. Comm.*, **22**, 1509, 1519 (1952).

$$R_3CH + Cr^6 \longrightarrow R_3C^+ + Cr^4 + H^+ \quad (A)$$

$$R_3CH + Cr^6 \longrightarrow R_3C\cdot + Cr^5 + H^+ \quad (B)$$

$$H_2O_3Cr\!=\!O \quad R_3C\!-\!H \longrightarrow H_2O_3CrOCR_3 + H^+ \quad (C)$$

$$R_3C \overset{H}{\diagup} \quad \longrightarrow R_3COH + Cr^4 \quad (D)$$
$$O\!=\!CrO_3H_2$$

$$R_3C\!-\!H$$
$$O \quad O \longrightarrow R_3COCrO_3H_3$$
$$\overset{}{Cr}\!-\!OH \quad (E)$$
$$OH$$

Roček[5] has observed that steric effects are not important in the chromic acid oxidation of hydrocarbons, tertiary hydrogens being attacked much more rapidly than primary hydrogens, and large alkyl groups attached to the reacting center having a small accelerating effect on the rate. Considering the large steric effects associated with backside nucleophilic substitution, it is clear that mechanism C, involving backside electrophilic substitution, must be eliminated from consideration. In view of the fact that triethylmethane reacts two and one-half times as rapidly as isobutane,[5] mechanisms D and E are also unlikely. The activated complexes for these types of reactions must assume a geometry in which the three alkyl groups are closer together than in the ground state, and thus rate retardation by large alkyl groups should be observed. However, mechanisms A and B in which the reacting carbon approaches a trigonal configuration in the activated complex will accommodate this observation. It should be noted that solvolytic reactions are generally accelerated by increasing the size of the alkyl group on the reacting carbon.[6]

With these conclusions in mind, we may consider the other available data. The activation energy for the oxidation of methylcyclohexane is 19 kcal./mole.[7] This must be corrected for the enthalpy change of the prior equilibrium leading to a protonated chromium species. Since no data on the latter quantity are available, a minimum value for the activation energy for the rate-determining step will be estimated as follows. The oxidation of diphenylmethane,[2] which follows the same rate law as the oxidation of methylcyclohexane, has an observed activation energy of 16 kcal./mole. It would seem reasonable to assume that the activation energy for the rate-determining step is at least 5 kcal., particularly in view of the large kinetic isotope effect which was observed ($k_H/k_D = 6.4$). The activation energy for the rate-determining step for the oxidation of methylcyclohexane must be 3 kcal. greater than that for diphenylmethane (the difference in observed activation energy) and thus a minimum value of 8 kcal. will be assigned to the rate-determining step of the oxidation of the former.

A reaction between a hydrocarbon and chromic acid having an activation energy of at least 8 kcal. per mole must involve a considerable degree of carbon–hydrogen bond stretching in the rate-determining step. If the reaction involves mechanism A, a considerable degree of carbonium ion character would be developed at the tertiary carbon, and if the reaction involves mechanism B, a considerable degree of free radical character would be developed at this carbon in the activated complex.

It is well known that certain bicyclic systems show marked enhancement of reactivity of one of the epimers at a given carbon due to anchimeric assistance by the neighboring methylene groups. For example, exo-bornyl derivatives undergo solvolysis at a rate 3.5×10^5 as great as that of cyclohexyl derivatives, whereas the endo isomers react only 1.5 times as fast as the latter.[8] Similarly, camphene hydrochloride undergoes solvolysis at a rate 6000 times as fast as t-butyl chloride.[9] It has been observed by Roček[5] that anchimeric assistance does not occur in the chromic acid oxidation of camphane or of isocamphane, both of which have reacting hydrogens in the exo-position. Thus, in view of the magnitude of the activation energy, it appears unlikely that a cationic center is developed in the rate-determining step.

A related piece of evidence may be found in a comparison of the relative rates of oxidation of p., s. and t. hydrogens with those of a hydrogen atom abstraction reaction, and the solvolysis of the corresponding halides (which involves the formation of a cationic center). The relative reactivities in hydrogen abstraction reactions vary considerably with the attacking reagent. The reaction with bromine atoms was chosen as a model for this type of reaction since the activation energies for the reaction of bromine atoms with hydrocarbons are comparable to the activation energy for the reaction of chromic acid with hydrocarbons (taking into account the prior equilibrium-forming chromic acid). The data are shown in Table I. It can be seen that the relative rates of bromination and oxidation are quite similar, whereas the range of rates for solvolysis is considerably greater. Thus, this comparison again favors mechanism B.

TABLE I

RELATIVE RATES OF OXIDATION, BROMINATION AND SOLVOLYSIS

Type of compound	Relative rate[5] of oxidation	Rel. rate[10] of H. abstr. by Br.	Rel. rate[11] of SN1 solv. of RCl
Primary	1	1	?
Secondary	65	82	50
Tertiary	3500	1640	2.5×10^6

One further argument may be presented. The oxidations of toluene, diphenylmethane and triphenylmethane were clearly shown to involve hydrogen atom abstraction by our previous work.[2]

(5) J. Roček, paper presented at the Symposium on Oxidation, Queen Mary College, London, April, 1959. We wish to thank Dr. Roček for permission to quote his results prior to publication.

(6) H. C. Brown and R. S. Fletcher, THIS JOURNAL, 71, 1845 (1949). They observed, for example, that triethylcarbinyl chloride underwent solvolysis in 80% ethanol at a rate three times that for t-butyl chloride.

(7) J. Roček, Coll. Czech. Chem. Comm., 22, 1509 (1957).

(8) S. Winstein, B. K. Morse, E. Grunwald, H. W. Jones, J. Corse, D. Trifan and H. Marshall, THIS JOURNAL, 74, 1127 (1952).

(9) F. Brown, E. D. Guges, C. K. Ingold and J. F. Smith, Nature, 168, 65 (1951).

(10) P. C. Anson, P. S. Fredricks and J. M. Tedder, J. Chem. Soc., 918 (1959). These data are for 400°K. and the ratios would be significantly greater at 25°.

(11) A. Streitwieser, Jr., Chem. Revs., 56, 571 (1956); the data are for 80% ethanol.
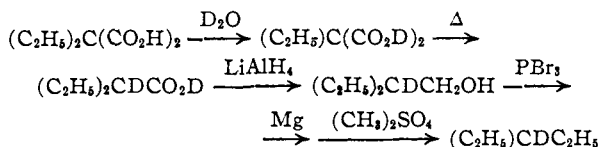
The ionization potentials of the corresponding free radicals are known, and if there should be a change in mechanism in going from the aralkyl hydrocarbons to the aliphatic hydrocarbons, the latter reacting by hydride abstraction, then there should be a marked decrease in the ionization potentials of the radicals derived from the latter. As is shown in Table II, this is not the case, and thus all of the hydrocarbons probably react in the same fashion. This conclusion is further strengthened by the stereochemical results which are reported in this paper.

TABLE II

IONIZATION POTENTIALS OF FREE RADICALS

Radical	Ionization potential, e.v.
Benzyl	7.76[12]
Benzhydryl	7.32[13]
Triphenylmethyl	6.51[14]
t-Butyl	7.42[15]

The kinetic isotope effect for the reaction deserves consideration. Sager and Bradley observed a small isotope effect which may be estimated from their data to be about $k_H/k_D = 1.6$. However, the method by which they prepared the deuterium-labeled hydrocarbon (the reaction of the tertiary Grignard reagent with deuterium oxide) does not lead to an isotopically pure material. In our hands, this reaction gave 3-ethylpentane-3d containing only 60% of one deuterium. Thus the isotope effect may be considerably larger than 1.6.

An isotopically pure sample of 3-ethylpentane-3d was prepared as follows. Diethylmalonic acid was repeatedly equilibrated with deuterium oxide, and then converted to 2-ethylbutyric-2d acid-d by heating. Lithium aluminum hydride reduction was followed by conversion of the alcohol to the bromide. The Grignard reagent formed from the latter reacted with dimethyl sulfate to give 3-ethylpentane-3d containing 97% of one deuterium as determined by mass spectrometric analysis.

$$(C_2H_5)_2C(CO_2H)_2 \xrightarrow{D_2O} (C_2H_5)C(CO_2D)_2 \xrightarrow{\Delta}$$

$$(C_2H_5)_2CDCO_2D \xrightarrow{LiAlH_4} (C_2H_5)_2CDCH_2OH \xrightarrow{PBr_3}$$

$$\xrightarrow{Mg} \xrightarrow{(CH_3)_2SO_4} (C_2H_5)CDC_2H_5$$

The rates of oxidation were determined spectrophotometrically under pseudo-first order conditions using 95% acetic acid as the solvent. Good first-order kinetics were observed. As a check on the rate of oxidation of 3-ethylpentane, the rate of oxidation of 3-ethylhexane was also determined. The data of Roček[5] indicate that the latter should be slightly more reactive than 3-ethylpentane. The kinetic data are summarized in Table III.

The value of the kinetic isotope effect thus obtained is somewhat lower than the true value because some of the oxidation occurs at the secondary positions. The observed value may be corrected by

(12) F. P. Lossing, K. U. Ingold and I. H. S. Henderson, J. Chem. Phys., 22, 621 (1954): J. B. Farmer, I. H. S. Henderson, C. A. Mc-Dowell and F. P. Lossing, ibid., 22, 1948 (1954).

(13) A. G. Harrison and F. P. Lossing, to be published.

(14) N. S. Hush and J. A. Pople, Trans. Faraday Soc., 51, 600 (1955).

(15) F. P. Lossing and J. B. de Sousa, THIS JOURNAL, 81, 281 (1959).

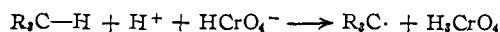$$\frac{k_H}{k_D} = \frac{r}{1 - (r - 1)(n^s k_H{}^s/k_H{}^t)}$$

where r is the observed isotope effect, $k_H{}^s$ is the rate of oxidation of a secondary hydrogen, $k_H{}^t$ is the rate of oxidation of a tertiary hydrogen, and n^s is the number of secondary hydrogens. Roček[5] has found the ratio $k_H{}^s/k_H{}^t$ to be ~ 0.02 and thus the corrected isotope effect for 3-ethylpentane is 3.1.
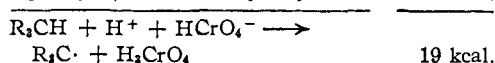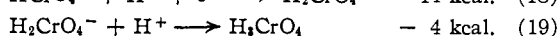
TABLE III

KINETIC ISOTOPE EFFECT FOR HYDROCARBON OXIDATION

Solvent: 95% acetic acid $T = 25.0°$ [HClO₄] $= 0.666M$

Compound	[RH]	$k_{obs} \times 10^5$, sec.$^{-1}$	k, 1. mole^{-1} sec.$^{-1}$ $\times 10^4$	k_H/k_D
$(C_2H_5)_3CH$	0.119	1.97	1.64	
		1.91		2.53
$(C_2H_5)_3CD$	.120	0.778	0.648	
		0.778		
$(C_2H_5)_2CH$	.108	2.22	2.05	
$\quad\vert$				
$\quad C_4H_7$		2.22		

The isotope effect observed here is considerably lower than that for the oxidation of diphenylmethane $(k_H/k_D = 6.4)^2$ even though the activation energy for the oxidation of the latter is less than that for the oxidation of the aliphatic hydrocarbons. The reason for this probably lies in the fact that the initial reaction is endothermic. An estimate of the heat of reaction[16] for

$$R_3C{-}H + H^+ + HCrO_4^- \longrightarrow R_3C\cdot + H_3CrO_4$$

may be made from the following partial reactions

$R_3CH \longrightarrow R_3C\cdot + H\cdot$	89 kcal.	(17)
$H\cdot \longrightarrow {}^1/_2H_2$	-52 kcal.	(17)
${}^1/_2H_2 \longrightarrow H^+ + e^-$	0 kcal.	
$HCrO_4^- + H^+ + e^- \longrightarrow H_2CrO_4^-$	-14 kcal.	(18)
$H_2CrO_4^- + H^+ \longrightarrow H_3CrO_4$	$- 4$ kcal.	(19)

$$R_3CH + H^+ + HCrO_4^- \longrightarrow$$
$$R_3C\cdot + H_3CrO_4 \qquad 19 \text{ kcal.}$$

Although this is only a rough estimate, it is apparent that the enthalpy change is close to the observed activation energy. Thus, the activation energy for the reverse reaction must be quite small, and the new bond to hydrogen being formed in the activated complex must be fairly strong. Under these circumstances, the vibrational frequency for the symmetrical stretching mode in the activated complex should be high, and should involve the hydrogen, leading to a large zero-point energy difference between bonds to hydrogen and to deuterium in the activated complex. As a result, the zero-point energy difference in the ground state will in large measure be cancelled by the difference in the activated complex, leading to a small kinetic isotope effect.

(16) This assumes that hydrogen atom transfer occurs rather than electron transfer with the liberation of a proton. Electron transfer would appear relatively unlikely since it would result in the formation of a proton in a region in which it could only poorly be solvated.
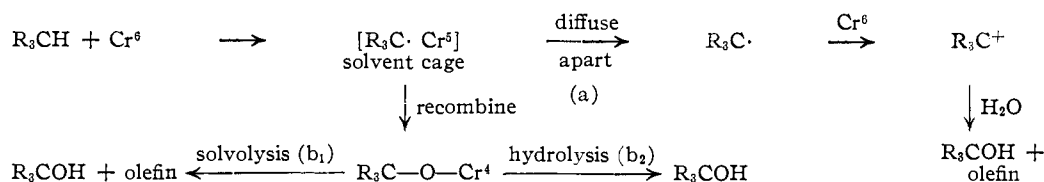
(17) T. L. Cottrell, "The Strengths of Chemical Bonds," Academic Press, Inc., New York, N. Y., 1954, p. 272.

(18) Based on the approximate electrode potential given by F. H. Westheimer, Chem. Revs., 45, 419 (1949), for an aqueous solution.

(19) Acids derived from lower oxidation states usually have small positive enthalpies of ionization, that for sulfurous acid for example being 4 kcal./mole (K. S. Pitzer, THIS JOURNAL, 59, 2365 (1937)).

The larger isotope effect observed with diphenylmethane is also accommodated by this argument. The bond dissociation energy for diphenylmethane[16] is 11 kcal./mole less than that for an aliphatic tertiary hydrogen, whereas the activation energy is only 3 kcal. less. Thus the reverse reaction for diphenylmethane must have an activation energy 8 kcal./mole greater than that for the aliphatic hydrocarbon. Therefore both the new and old bonds to hydrogen in the activated complex for the diphenylmethane oxidation will be weak, resulting in a large isotope effect.

These data are all in accord with the assumption that the initial reaction involves hydrogen atom abstraction. However, they do not give information concerning the fate of the free radical species formed. The reactions which are possible are

converted to the acid phthalate, which was separated from neutral materials and reconverted to the alcohol by lithium aluminum hydride reduction. The alcohol thus obtained had $[\alpha]^{23}$D $+0.41°$ (l = 1, neat). The other sample was dissolved in pentane and stirred with an excess of basic permanganate solution. Any secondary alcohol or ketone will be rapidly oxidized by this reagent whereas the tertiary alcohols are unreactive. The alcohol thus obtained had $[\alpha]^{22}$D $+0.42°$ (l = 1, neat). The good agreement between the values obtained in these ways is strong indication that the observed rotation is that of the alcohol, and not due to the presence of an impurity.

The initial reaction by chromium(VI) leads ultimately to the formation of either chromium(V) or (IV). The previously obtained data on these

$$R_3CH + Cr^6 \longrightarrow \underset{\text{solvent cage}}{[R_3C\cdot\ Cr^5]} \xrightarrow[\text{apart}]{\text{diffuse}} R_3C\cdot \xrightarrow{Cr^6} R_3C^+$$

$$\Big\downarrow \text{recombine} \qquad\qquad (a) \qquad\qquad\qquad\qquad \Big\downarrow H_2O$$

$$R_3COH + \text{olefin} \xleftarrow{\text{solvolysis } (b_1)} R_3C\!-\!O\!-\!Cr^4 \xrightarrow{\text{hydrolysis } (b_2)} R_3COH \qquad\qquad \underset{\text{olefin}}{R_3COH +}$$

The three paths may be distinguished by examining the stereochemistry of the reaction. Starting with an optically active alkane, the species first formed, and still in the solvent cage, will retain its asymmetry. However, once the radical has diffused out of the solvent cage, it will no longer be asymmetric,[20] and the product thereby formed would be racemic. If, however, the radical and the chromium(V) recombine in the solvent cage, the chromium(IV) ester thus formed would have the same configuration as the hydrocarbon.[21] The ester may be hydrolyzed with chromium–oxygen bond cleavage (b_2) giving the alcohol with complete retention of configuration, or it may undergo solvolysis (b_1) with carbon–oxygen bond cleavage giving the alcohol with partial inversion of configuration, in analogy with the solvolysis of the acid phthalate of 3,5-dimethyl-3-hexanol.[22]

Optically pure (+)-3-methylheptane was prepared from (−)-2-methyl-1-butanol[23] by the method described by Burwell and Gordon.[24] The oxidation was carried out in 91% acetic acid in the presence of 0.96 M perchloric acid. After a time corresponding to approximately 60% reaction of the hydrocarbon (and 15% reaction of chromic acid), the reaction mixture was quenched and the alcohol 3-methyl-3-heptanol was isolated. Initial purification was effected by vapor phase chromatography using a silicone substrate on Celite. The subsequent purification was effected by two independent methods. One sample of the alcohol was

species suggest that they do not react further by disproportionation, but rather are capable of reacting with the substrate either directly or in the case of chromium(IV) via the reaction with chromium (VI) to form chromium(V) which then reacts with the substrate.[2,25] Thus since the intermediate chromium species effect part of the oxidation, it is important to establish that the activity of the alcohol is not due exclusively to a reaction by one of these reagents. One way in which to eliminate the reactions of the intermediate chromium species is to add cerous ion which is rapidly oxidized by these species, but not by chromic acid itself. The addition of 0.045 M cerous ion led to a marked reduction in the amount of alcohol isolated at a given time. This is in accord with the supression of the reactions due to the intermediate species since, under the conditions used, the amount of alcohol formed is rate controlled. The alcohol thus obtained, after purification with permanganate, had a rotation of $[\alpha]^{24}$D $+0.50°$ (l = 1, neat). Thus, both the reaction of chromium(VI) and of the intermediate chromium species appear to give optically active alcohol, and the degree of retention of asymmetry is about the same for the two reactions. This suggests that the two reactions are mechanistically similar.

A sample of 3-methyl-3-heptanol was prepared and was resolved using the brucine salt of the acid phthalate. After eight recrystallizations of the head fraction, the acid phthalate had come to a constant rotation. The alcohol obtained from the acid phthalate had $[\alpha]^{22}$D $+0.67°$. Although this rotation is considerably lower than that for the other simple tertiary alcohol which has been resolved (3,5-dimethyl-3-hexanol, $[\alpha]^{25}$D 2.9°),[22] it is known that an isobutyl group normally confers upon a compound a larger rotation than does a n-butyl group.[22,26] Also, a similar alcohol, tetra-

(20) W. v. E. Doering, M. Farber, M. Sprecher and K. B. Wiberg, THIS JOURNAL, **74**, 3000 (1952).

(21) Recombination of radicals within a solvent cage has been postulated for a number of reactions, notably in the decomposition of azobis-isobutyronitrile (cf. C. Walling, "Free Radicals in Solution," John Wiley and Sons, Inc., New York, N. Y., 1957, pp. 76–79). The present case should be a favorable one for this type of recombination since the latter would have a large negative enthalpy of reaction.

(22) W. v. E. Doering and H. Zeiss, THIS JOURNAL, **72**, 147 (1950).

(23) We wish to thank the Dow Chemical Co., for a generous gift of this alcohol.

(24) R. L. Burwell, Jr., and George S. Gordon III, THIS JOURNAL, **70**, 3128 (1948).

(25) W. Watanabe and F. H. Westheimer, J. Chem. Phys., **17**, 61 (1949); J. Hampton, A. Leo and F. H. Westheimer, THIS JOURNAL, **78**, 306 (1956).

(26) P. A. Levene and R. E. Marker, J. Biol. Chem., **97**, 379 (1932).

hydrolinalool, although it has not been resolved, has been obtained with a specific rotation of approximately 0.67° by the hydrogenation of linalool of probable high optical purity.[27] Thus, the rotation which has been observed for 3-methyl-3-heptanol is probably close to the maximum rotation.

The racemization of (+)-3-methyl-3-hexanol in the reaction medium used for the oxidation was studied. Using one-half the length of time employed for the oxidation, the alcohol was found to undergo 13% racemization, and this should be a reasonable estimate of the extent of racemization of the alcohol formed in the oxidation. The corrected rotations for the alcohol are then +0.48° for that isolated in the absence of cerous ion, and +0.57° for that isolated in the presence of the latter. The retention of asymmetry under the two conditions was therefore 72 an 85%, respectively.

There are few data bearing on the absolute configuration of tertiary alcohols. The principal work is that of Prelog and Watanabe[27,28] who have applied the asymmetric synthesis technique previously developed by Prelog and his co-workers[29] to the determination of the absolute configuration of tetrahydrolinalool (3,7-dimethyl-3-octanol). Using this configuration and making the assumption that the substitution of an n-butyl group for an isohexyl group will not affect the sign of rotation,[26] it is concluded that the oxidation proceeded with retention of configuration.

This conclusion is supported by several related observations. First, the solvolysis of the acid phthalate of 3-methyl-3-heptanol in 91% acetic acid led to the formation of a mixture of olefin, acetate and alcohol, the ratio of the latter two being about 1:2. The oxidation led to the formation of a markedly smaller amoung of acetate (~2%) and this would be in accord with the hypothesis that most of the reaction proceeded via chromium–oxygen bond cleavage. Second, the degree of retention of asymmetry is higher than might be expected on the basis of the available solvolytic studies.[30] We have found that the solvolysis of the acid phthalate of 3-methyl-3-heptanol in 91% acetic acid gave the alcohol with only 43% inversion of configuration. Third, the oxidation of cis-decalin gave a mixture of ketone and alcohol, the latter being predominently, if not entirely, cis-9-decalol.[31] Since trans-9-decalol is the thermodynamically more stable isomer, the formation of cis-decalol must have involved a reaction giving retention of configuration.

The accumulation of these results strongly suggests that the reaction proceeds via the formation of

a chromium(VI) ester followed by solvolysis with chromium–oxygen bond cleavage. However, if this were the only path by which the reaction proceeded, 100% retention of configuration would have been obtained.

Necsoiu and Nenitzescu[32] have recently shown that when the chromic acid oxidation of hydrocarbons is carried out in the presence of azide ion, organic azides are formed. A parallelism between the amount of azide formed and the stability of the carbonium ion which might be formed was observed.

Both of the above observations may be accommodated if one assumes that the chromium(IV) ester is formed and that it may react by either chromium–oxygen or carbon–oxygen bond cleavage. The former will give complete retention of configuration whereas the latter would lead to racemization accompanied by inversion of configuration.[30] The proportion of carbon–oxygen bond cleavage would be expected to increase as the stability of the carbonium ion which would be formed increases, and this will account for the relative proportion of azide formed in the several cases. This hypothesis may be tested in two ways. First, the azide formed should be partially optically active and this activity should correspond to inversion of configuration. Second, if an optically active hydrocarbon which will lead to a more stable carbonium ion that the simple tertiary aliphatic case (such as 2-butylbenzene) is oxidized, a lower degree of retention of asymmetry would be expected.

The other possible explanation for the partial racemization which occurs in the oxidation is that the cage recombination is not completely efficient, and that about 10–20% of the radicals initially formed diffuse away from the solvent cage.

It may also be noted that the mechanism which has been proposed will account for the rearrangement which has been observed in the chromic acid oxidation of t-amylbenzene (which gives acetophenone) and related compounds.[33] Carbon–oxygen bond cleavage in the intermediate chromium (IV) ester should be particularly favored in those cases in which a neighboring group (such as phenyl) may assist in the formation of the carbonium ion, and this will lead to rearranged products.

Experimental[34]

(+)-3-Methylheptane.—The hydrocarbon was prepared using the procedure of Burwell and Gordon.[24] Starting with 2-methyl-butanol ($[\alpha]^{25}D$ −5.82°) there was obtained 3-methylheptane ($[\alpha]^{23}D$ +9.5°) in a 42% over-all yield. Purification of the hydrocarbon was effected by distillation through a spinning brush column having an efficiency equivalent to 30 theoretical plates.

Oxidation of 3-Methylheptane.—To 500 ml. of a 91% acetic acid solution containing sodium dichromate (0.33 M) and perchloric acid (0.995 M) at 8° was added 5.0 g. of 3-methylheptane. The reaction vessel was shaken from time to time. After 15 min., the reaction mixture was poured into 2 l. of 0.25 N aqueous sodium hydroxide solution. The mixture was extracted with three 250-ml. portions of methylene chloride. The organic extract was washed with excess sodium bicarbonate solution, and then dried over potassium carbonate. Distillation from potassium carbonate gave

It may be noted that all methylalkylcarbinols, except methylisopropylcarbinol and methylisobutylcarbinol have essentially the same optical rotation.

(27) V. Prelog and E. Watanabe, *Ann.*, **603**, 1 (1957).

(28) The configuration for tetrahydolinalool given in the above paper is reversed from the correct one; R. H. Cornforth, J. W. Cornforth and V. Prelog, in press.

(29) V. Prelog, *Bull. Soc. Chim. France*, 987 (1956).

(30) W. v. E. Doering and H. H. Zeiss, THIS JOURNAL, **75**, 4733 (1953); A. Streitwieser, Jr., *Chem. Revs.*, **56**, 631, 655 (1956).

(31) Prof. P. v. R. Schleyer has informed us of his observation that cis-decalin on oxidation with chromium trioxide in either acetic anhydride or aqueous acetic acid gives cis-9-decalol as the only alcohol, and similarly, trans-9-decalin gives only trans-9-decalol. We wish to thank him for informing us of his results prior to publication.

(32) I. Necsoiu and C. D. Nenitzescu, *Chemistry & Industry*, 377 (1960).

(33) Unpublished results from this Laboratory.

(34) All rotations were taken neat in a 1-dm. tube unless otherwise noted.

2 ml. of material having b.p. 65–80° at 20 mm., consisting of 3-methyl-3-heptanol, 3-methyl-3-heptyl acetate and ketones. The alcohol was isolated by preparative scale vapor phase chromatography using Ucon Polar–Celite as the packing. The material thus obtained had an infrared spectrum identical with that of authentic 3-methyl-3-heptanol. The amount of alcohol isolated was on the order of 0.35 g., and approximately 2 g. of hydrocarbon was recovered. The ratio of alcohol to acetate in the product was about 50:1.

Purification of 3-Methyl-3-heptanol via the Acid Phthalate.—A solution of 3.6 g. of 3-methyl-3-heptanol (α^{22}D + 0.57°), obtained by the oxidation of 3-methylheptane ($[\alpha]^{23}$D + 9.5°), in 5 ml. of benzene was added to 1.15 g. of potassium sand in 30 ml. of benzene with stirring. When the reaction was completed, the benzene solution was forced by nitrogen pressure into a solution of 4.3 g. of freshly recrystallized phthalic anhydride in 40 ml. of benzene, and the reaction mixture was stirred overnight. It was poured into water, the aqueous layer was extracted with pentane, and then acidified. The hydrogen phthalate was extracted with pentane. The pentane solution was dried over anhydrous sodium sulfate, and the solvent was evaporated leaving 4.8 g. of the acid phthalate, $[\alpha]^{23}$D $-1.27°$ ($l = 1$, c 32.8, ethanol).

The hydrogen phthalate was dissolved in 25 ml. of dry ether and added to 1 g. of lithium aluminum hydride in 25 ml. of dry ether. The mixture was heated to reflux for 1 hour and was then decomposed with 30% Rochelle salt solution. The ether layer was dried over anhydrous sodium sulfate and distilled giving 1.8 g. of 3-methyl-3-heptanol, $[\alpha]^{23}$D + 0.41°, n^{26}D 1.4268, d^{25} 0.823. The infrared spectrum was identical with that of an authentic sample of 3-methyl-3-heptanol.

Purification of 3-Methyl-3-heptanol via Alkaline Permanganate.—To a mixture of 0.5 g. of potassium permanganate and 1.0 g. of sodium hydroxide in 20 ml. of water was added 0.7 g. of 3-methyl-3-heptanol obtained from the oxidation. After stirring overnight, the alcohol was extracted with pentane. Evaporation of the solvent followed by vapor phase chromatography gave 0.45 g. of 3-methyl-3-heptanol, $[\alpha]^{22}$D +0.42°, n^{26}D 1.4264.

Oxidation of 3-Methylheptane in the Presence of Cerous Ion.—The oxidation was carried out as described above, except that 0.045 M cerous ion was added. The amount of alcohol declined to 0.13 g., which on purification via alkaline permanganate had $[\alpha]^{24}$D +0.50°, n^{26}D 1.4265.

Resolution of 3-Methyl-3-heptanol.—3-Methyl-3-heptanol was prepared by the reaction of methylmagnesium chloride with 3-heptanone. The alcohol was converted to the acid phthalate[35] by mixing 520 g. (4.0 moles) of 3-methyl-3-heptanol with 593 g. (4.0 moles) of freshly recrystallized phthalic anhydride and 606 g. (6.0 moles) of dry triethylamine. The mixture was heated to reflux for 12 hours, and then was cooled and treated with an excess of dilute hydrochloric acid. The hydrogen phthalate was taken up in ether, and was extracted from the ether with sodium bicarbonate solution. The aqueous solution was acidified, and the hydrogen phthalate was taken up in pentane in which phthalic acid is insoluble. The pentane layer was dried over anhydrous sodium sulfate and the solvent was evaporated giving 775 g. (70%) of the acid phthalate as a viscous oil.

The hydrogen phthalate was dissolved in 3.5 l. of acetone, the solution was heated to boiling and 1100 g. of brucine was added. On cooling, the solution deposited a white amorphous powder. The latter was recrystallized from 7 l. of acetone and gave a crystalline brucine salt. The head fraction was recrystallized a further eight times to give a salt, m.p. 116–118° dec., which on acidification gave the hydrogen phthalate having $[\alpha]^{23}$D $-2.72°$ ($l = 1$, c 19.5, ethanol). Further recrystallization of the brucine salt did not increase the rotation. The quinidine salt, m.p. 130–131°, was formed from the above hydrogen phthalate. Two recrystallizations of this salt failed to increase the rotation.

A sample of the hydrogen phthalate was reduced with lithium aluminum hydride as described above giving 3-methyl-3-heptanol, $[\alpha]^{22}$D + 0.67°.

Racemization of 3-Methyl-3-heptanol under the Reaction Conditions for Oxidation.—To 225 ml. of the solution used in the oxidations (91% acetic acid, 0.995 M perchloric acid)

was added 1.25 ml. of 3-methyl-3-heptanol ($[\alpha]^{22}$D +0.67°). The solution was maintained at 8° for 7.5 min. for one sample, and for 15 min. for a second sample. The products were isolated as described above and were separated by vapor phase chromatography. In the 7.5-min. run, the ratio of olefin to alcohol to acetate was 1:0.96:0.031 and the alcohol had $[\alpha]^{22}$D +0.58°. In the 15-min. run, the ratio of products was 1:0.26:0.017 and the alcohol had $[\alpha]^{22}$D + 0.50°.

Solvolysis of the Hydrogen Phthalate of 3-Methyl-3-heptanol.—A solution of 10 g. of the acid phthalate ($[\alpha]^{25}$D $-2.1°$) in 400 ml. of 91% acetic acid was heated for 1 hour at 90°. The solution was poured into ice-water, and the mixture was extracted with ether. The ether solution was washed with sodium bicarbonate solution. Acidification of the latter gave 0.4 g. of unreacted acid phthalate. The ether solution was evaporated, and the mixture was separated by vapor phase chromatography. There was obtained 0.75 ml. of 3-methyl-3-heptanol having $[\alpha]^{23}$D $-0.17°$ and 0.45 ml. of 3-methyl-3-heptyl acetate having α^{23}D $-0.54°$. The chromatographic record indicated the ratio of alcohol to acetate to be 1:0.62. In a repetition of the experiment, the ratio of alcohol to acetate was 1:0.52, the alcohol had $[\alpha]^{23}$D $-0.14°$, and the acetate had α^{22}D $-0.43°$.

The two-acetate samples were mixed (α^{23}D $- 0.46°$) and reduced with lithium aluminum hydride (2 g.) in 100 ml. of dry ether. The mixture was decomposed with 30% Rochelle salt solution, and the 3-methyl-3-heptanol was isolated in the usual fashion, $[\alpha]^{22}$D $-0.12°$.

Racemization of 3-Methyl-3-heptanol in 91% Acetic Acid.—A solution of 3 ml. of 3-methyl-3-heptanol ($[\alpha]^{22}$D + 0.67°) in 300 ml. of 91% acetic acid was heated at 90° for 30 min. The alcohol was isolated as described above and had $[\alpha]^{23}$D + 0.43°.

3-Ethylpentane and 3-Ethylhexane.—The hydrocarbons were prepared by the Grignard synthesis of the corresponding tertiary alcohol, dehydration, and catalytic hydrogenation.[36] The alkanes were purified by shaking with aqueous potassium permanganate solution and distillation from sodium. Final purification was effected by vapor phase chromatography using Ucon Polar–Celite as the packing.

3-Ethylpentane-3-d.—Diethylmalonic acid (144 g., 0.9 mole) was equilibrated with deuterium oxide by the addition of 20-ml. portions of the latter, followed by removal under reduced pressure. The equilibration was carried out five times. The resulting acid was heated to 200° for 2 hours and distilled giving 2-ethylbutyric-2d acid-d (95 g.), b.p. 191–193°. The n.m.r. spectrum indicated the presence of some hydrogen in the 2-position. Therefore, the acid was heated to reflux with 30 g. of deuterium oxide containing a small amount of sulfur trioxide, and this treatment was carried out a second time. The n.m.r. spectrum then appeared satisfactory.

The acid (95 g.) in 100 ml. of dry ether was slowly added to 40 g. of lithium aluminum hydride in 1 l. of dry ether. After the addition was completed, the solution was heated to reflux for 1 hour. The excess hydride was decomposed with ethyl acetate, Rochelle salt solution was added and the ether layer was separated. After drying over anhydrous sodium sulfate, the solution was distilled giving 67 g. of 2-ethyl-1-butanol-2d, b.p. 144–146°.

The alcohol (67 g.) was cooled to $-5°$ and 70 g. of phosphorus tribromide was added dropwise with stirring. The mixture was allowed to come to room temperature overnight and distilled, collecting the fraction having b.p. 60–65° at 65 mm. The bromide was washed with water and with sodium bicarbonate solution. Redistillation gave 72 g. of 2-ethyl-1-bromobutane-2d, b.p. 67–68° at 70 mm.

A solution of 38 g. (0.25 mole) of the bromide in 250 ml. of dry ether was slowly added to 6.2 g. of magnesium. Ethyl bromide was used to initiate the reaction. After heating for 2 hours, the ether solution was decanted and added dropwise to 63 g. (0.5 mole) of dimethyl sulfate in 100 ml. of dry ether. The mixture was heated to reflux for 2 hours and allowed to stand overnight. The reaction mixture was treated with water, and with excess sodium hydroxide solution to remove excess dimethyl sulfate. Distillation gave 8 g. of material, b.p. 50–100°, and considerable higher boiling material. The low boiling fraction was shown to

(35) The general procedure of A. G. Davies, J. Kenyon and L. W. F. Salame, *J. Chem. Soc.*, 3148 (1957), was used.

(36) J. Boeseken and A. J. Wildschut, *Rec. trav. chim.*, **51**, 168 (1932); C. E. Boord, A. L. Henne, K. W. Greenlee, W. L. Perilstein and J. M. Derfer, *Ind. Eng. Chem.*, **41**, 609 (1949).

contain 5.1 g. of 3-ethylpentane by vapor phase chromatography.

The above material was purified by shaking with potassium permanganate solution followed by vapor phase chromatography (n^{26}D 1.3929). Final purification was effected by dissolving it in 10 ml. of acetic acid and adding solution of sodium dichromate and perchloric acid in 90% acetic acid until the orange color persisted. Water was added, the hydrocarbon was taken up in ether, washed with sodium bicarbonate solution and isolated by vapor phase chromatography. The mass spectrum, determined at an ionizing potential of 20 v., indicated the presence of at least 97% of one deuterium (based on the parent peaks).

Kinetic Method.—Equal volumes of solutions of the hydrocarbon in glacial acetic acid (purified by distillation under reduced pressure from chromium trioxide) and of sodium dichromate (2×10^{-3} M) and perchloric acid (1.333 M) in 90% acetic acid were placed in the two arms of a U-tube which had been sealed onto a 10-mm. Beckman cell. The solutions were degassed under reduced pressure and brought to 25.0°. The solutions were mixed and transferred to the Beckman cell by inverting the tube. The rate of disappearance of chromium(VI) was followed by the change in absorbance at 390 mμ. Plots of log ($A - A\infty$) against time gave a good linear relationship. The rate constants are given in terms of the natural logarithm.

Oxidation of *cis*-Decalin.—Commercial *cis*-decalin was purified by vapor phase chromatography. The hydrocarbon (6 g.) was added to a solution of 50 g. of sodium dichromate, 40 ml. of water and 141 g. of 72% perchloric acid in enough acetic acid to make 1 l. of solution. The oxidation was carried out at 8° for 30 min. The reaction mixture was worked up as described above for the oxidation of 3-methylheptane giving 1.1 g. of material, b.p. 60–70° at 0.5 mm., which was largely *cis*-9-decalol. Recrystallization from aqueous ethanol gave pure *cis*-9-decalol, m.p. 64–65°.[37]

(37) The m.p. of *cis* 9-decalol is 65°, whereas that of the *trans* isomer is 54°; W. G. Dauben, R. C. Tweit and R. L. MacLean, THIS JOURNAL, **77**, 48 (1955).

Lithium Aluminum Hydride Reactions in Pyridine Solution. Reductive Cleavage of Ketones[1]

BY PETER T. LANSBURY

Pyridine has been shown to be an excellent solvent for lithium aluminum hydride reactions. A number of ketones have been reduced to alcohols under mild conditions. However, certain tetraaryl pinacolones undergo facile reductive cleavage to triarylmethanes and benzylic alcohols. Evidence is presented which supports the role of pyridine as a Lewis base that coördinates aluminum hydride and allows the participation of unassociated alkoxides in the reaction scheme leading to normal and cleavage products. Semi-quantitative studies of reaction stoichiometry suggest that all four hydride ions are potentially available from each aluminohydride ion.

The purpose of this report is to bring attention to the usefulness of pyridine as a solvent for lithium aluminum hydride (LAH) reactions. During the past decade, a great volume of literature describing modifications of the reducing action of LAH (as well as other complex metal hydrides) by means of added metal halides or by converting the hydride into alkoxyaluminohydrides has come forth.[2] Less work has been done in investigating solvents other than ethyl ether and tetrahydrofuran for use with LAH.

The limited solubility of many reducible substrates in diethyl ether, plus the inconveniences incurred in purifying and storing anhydrous tetrahydrofuran, aroused our interest in finding other potentially-useful and easily-accessible solvents. The decision to examine pyridine in this connection was somewhat influenced by the report that fluorenes give appreciable concentrations of carbanions in pyridine solution when treated with Triton B.[3] We have observed, similarly, that fluorene and triphenylmethane both give highly-colored

pyridine solutions when treated with LAH at room temperature, whereas no observable reaction occurs in ether under comparable conditions. The enhanced basicity of LAH in pyridine, as compared with ether, affords a convenient method for generating triphenylmethide and related carbanions[4a] in solvents other than liquid ammonia.[4b] Subsequent reactions of these species, such as carboxylation,[5] can then be carried out.

(4) (a) The extent of carbanion formation is not known with certainty; hydrogen–deuterium exchange studies, aimed at determining this information, are presently underway. However, carboxylation experiments (ref. 5) indicate that substantial metalation occurs. The base-strengthening effect of pyridine may result from its tendency to coördinate strongly with incipient AlH_3, thus causing AlH_4^- to release hydride more effectively. Pyridine has a relatively high dipole moment (2.1 D.) which correlates with its unusual coördination ability, relative to other tertiary amines (R. W. Parry and R. N. Keller in "Chemistry of the Coördination Compounds," J. C. Bailar, Jr., Ed., Reinhold Publishing Corp., New York, N. Y., 1956, p. 128). The

$$(C_6H_5)_3C \overset{\delta^+}{-\!-} H \cdots \overset{\delta^-}{-} H \overset{}{-\!-} AlH_3 \quad :N$$

Ionizing power of pyridine (ref. 21) may also facilitate heterolysis of the C–H bond in triphenylmethane. The basicity of LAH in tetrahydrofuran toward methylenic hydrogens in fluorene has previously been noted (H. Dahn and U. Solms, *Helv. Chim. Acta*, **34**, 907 (1951)) and this combination also weakly metalates triphenylmethane. By contrast, neither fluorene nor triphenylmethane shows any active hydrogen with LAH in ether at 35° (F. A. Hochstein, THIS JOURNAL, **71**, 305 (1949)). (b) C. R. Hauser and co-workers (*J. Org. Chem.*, **20**, 1531 (1955)) observed reversion of sodium and lithium triphenylmethide to triphenylmethane when attempting to replace liquid ammonia as solvent by ethers, toluene or triethylamine.

(5) P. T. Lansbury, to be published. In preliminary experiments, triphenylacetic acid and fluorene-9-carboxylic acid have been isolated in 12 and 13% yields, respectively, by pouring the carbanion solutions onto crushed Dry Ice. Higher yields are anticipated when the carbonation step is refined.

(1) Presented at the 137th Meeting of the American Chemical Society, Cleveland, Ohio, April, 1960. A portion of this work also was reported in a preliminary communication, P. T. Lansbury, *Chemistry & Industry*, 151 (1960).

(2) See, for example: (a) H. C. Brown and R. F. McFarlin, THIS JOURNAL, **80**, 5372 (1958); (b) R. F. Nystrom and C. R. A. Berger, *ibid.*, **80**, 2896 (1958); (c) N. G. Gaylord, "Reduction with Complex Metal Hydrides," Interscience Publishers, Inc., New York, N. Y., 1956; (d) N. G. Gaylord, *J. Chem. Ed.*, **34**, 367 (1957); (e) G. A. Olah, THIS JOURNAL, **81**, 3165 (1959); (f) E. L. Eliel and V. G. Badding, *ibid.*, **81**, 6087 (1959); (g) H. C. Brown and B. C. Subba Rao, *ibid.*, **78**, 2582 (1956); (h) M. N. Rerick, "The Mixed Hydrides," Metal Hydrides, Inc., Beverly, Mass., Review.

(3) Y. Sprinzak, THIS JOURNAL, **80**, 5449 (1958).