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(42) The possibility exists, as pointed out by a referee, that a $Cu_8(SPh)_{12}^{4-}$ cluster does not form because of nonbonding repulsions of the phenyl groups. The validity of this argument can be tested by employing less bulky R groups on the bridging mercaptide ligands.

Disproportionation of Saturated Alkali Metal Ketyls to Give Enolates and Alcoholates: a General Reaction That Has Been Overlooked[1a]

Valentin Rautenstrauch*[1b] and Michel Geoffroy[1c]

Contribution from the Research Laboratories, Firmenich SA, 1211 Genève 8, and the Département de Chimie Physique, Université de Genève, 1211 Genève 4, Switzerland. Received October 13, 1976

Abstract: The reactions between 2,2-dimethylcyclohexanone-6-d_2 (3-6-d_2) and lithium, sodium, and potassium in THF and in liquid ammonia/THF at ca. −75 °C are investigated. The corresponding ketyls (3-6-d_2)⁻·M⁺ are formed in high yield, are transient, and decay, by disproportionation to give the enolate of 3-6-d_2 and the alcoholate of 2,2-dimethylcyclohexanol-1-d-6-d_2 (4-1-d-6-d_2), by dimerization to give the dialcoholates of the pinacols 5-6-d_2-$6'$-d_2, and by abstraction of a proton or a hydrogen atom from the medium to give the alcoholate of 4-6-d_2. Partitioning between these decay modes differs somewhat for the lithium, sodium, and potassium ketyls, but is in each case unaffected when the concentration of the ketone precursor is changed drastically. This suggests that the ion pairs [(3-6-d_2)⁻·M⁺]₁, the primary products, rapidly associate, and that the decay reactions then proceed within an associated species, probably within the ion quadruplets [(3-6-d_2)⁻·M⁺]₂. The dissolving metal reductions of 3-6-d_2 using lithium, sodium, and potassium in liquid ammonia/THF containing excess *tert*-butyl alcohol or ethanol at ca. −75 °C are investigated. Disproportionation of the ketyls strongly competes with the protonation of the ketyls, the key step of the general mechanism proposed by House. Protonation of the enolate formed by disproportionation regenerates the ketone, which is then rereduced.

Evaluation of the large body of published experimental results led House to propose[2] that the dissolving metal reduction of saturated ketones proceeds via the main sequence: (1) reduction, ketone → ketyl; (2) protonation, ketyl → ketyl radical; (3) reduction, ketyl radical → α-hydroxycarbanion; and (4) protonation, α-hydroxycarbanion → alcohol. To account for the empirical rule that the more stable diastereomeric alcohol is often the predominant product, he proposed that diastereomeric ketyl radicals and/or α-hydroxycarbanions equilibrate via inversion, and that the stabilities of these pyramidal species parallel those of the corresponding alcohols. Furthermore, he suggested that these species dimerize[3] in part, concurrently with steps 2 and/or 3, to give the pinacolates and/or the pinacols. He stressed that the association[3] of the ketyls may be playing a crucial role, but left open its extent and timing.

We find[4] that saturated ketyls with a hydrogen atom in an α position disproportionate[5] readily to give the enolates and the alcoholates. We hypothesize that this reaction takes place via the branched sequence (1) reduction, ketone → ketyl ion pair; (2) association, ketyl ion pair → ketyl ion quadruplet; (3) quasi-intramolecular decay via (a) disproportionation, ketyl ion quadruplet → enolate + alcoholate, (b) dimerization, ketyl ion quadruplet → pinacolates; (4) protonations, (a) enolate → ketone, (b) alcoholate → alcohol, (c) pinacolates → pinacols. We suggest that this sequence is kinetically favorable and that protonations of the ketyl ion pair and the ketyl ion quadruplet according to House's general mechanism compete, often inefficiently, with steps 2 and 3a, 3b, respectively. The ketone which is liberated through protonation of the enolate (4a) is reduced in turn. In the absence of a proton source, the new reaction dominates and the enolate survives and can be trapped. Under these conditions a third decay mode, a reaction

with the THF and the liquid ammonia, which we also ascribe to the ketyl ion quadruplet, comes to light.

Unlabeled Substrate, Lithium, THF. We have recently shown[6] that the reaction of 2,2,6,6-tetramethylcyclohexanone (1) with metallic lithium in THF at ca. −75 °C gives the corresponding, persistent ketyl, 1⁻·Li⁺,[7] in high yield. This ketyl was characterized by its typical rigid medium ESR spectrum and was shown to undergo characteristic chemical reactions such as, in particular, that with water or deuterium oxide: deuteronation produces the corresponding O-deuterated ketyl radical, which cleanly disproportionates[5] to give back the ketone 1, and the corresponding alcohol, 2,2,6,6-tetramethylcyclohexanol, with deuterium atoms in the 1-position and in the hydroxyl group, 2-1-d-O-d. On workup with water the hydroxylic deuterium atom is exchanged and the alcohol with one deuterium atom in the 1-position, 2-1-d, is isolated.

When saturated ketones such as 2,2-dimethylcyclohexanone (3), with a hydrogen atom in an α position are treated with lithium in the same manner, a metal-consuming reaction again takes place, but the resulting solutions do not exhibit an ESR signal. Hydrolysis with deuterium oxide and workup with water again predominantly gives ca. 1:1 mixtures of the ketone and the corresponding alcohol, but now the ketone contains ca. one deuterium atom, in the α position, and the alcohol is unlabeled. These results, contrasted with that for the persistent ketyl (1⁻·Li⁺), demonstrate that the lithium ketyls with an α-hydrogen atom are formed as expected, apparently again in high yield, that they are transient under the conditions of their formation, and that decay mainly leads, overall, to the formation of 1:1 enolate/alcoholate mixtures. ESR experiments (see below) support the conclusion that these ketyls are transient. Overall, the main decay reaction (→ enolate/alcoholate) seemingly brings about a transfer of the hydrogen

atoms in the α position of ca. half the substrate molecules to the 1 position of the other half. To study this transfer in an unambiguous manner, it is necessary to "invert" the labeling experiment with respect to the one with $1^-\cdot Li^+$, i.e., to label the substrate in the α position(s).

We had attributed[6] the persistence of $1^-\cdot Li^+$ to the shielding effect exerted by the methyl groups, which blocks the dimerization to give pinacolates and the reaction with the medium, and had expected a gradual change from persistence to transience for less and less shielded ketyls. In fact, even quite hindered ketyls with an α-hydrogen atom turn out to be transient, largely through the new decay mode.

Labeled Substrate, Lithium, THF. We report experiments, all carried out at ca. −75 °C, with a single, typical, deuterium-labeled substrate, 2,2-dimethylcyclohexanone-6-d_2 (3-6-d_2), which was chosen for the following reasons. It contains, in a six-membered ring, the -COCD$_2$- grouping —unlabeled substrates of this general type have probably been used most commonly in previous studies[2]—but only one such grouping, the other α position being blocked by methyl groups. The substrate, the corresponding alcohol, and the corresponding pinacols have NMR and mass spectra which allow ready detection of deuterium atoms in the 1 and in the (single) α positions, and can be subjected to gas chromatography.

Exposure of THF solutions of this ketone (3-6-d_2, see eq 1) with two deuterium atoms in the 6 position (purity:[8a] ≥ 98%

$$(1)$$

$$(2)$$

$$(3)$$

$$(4)$$

$$(5)$$
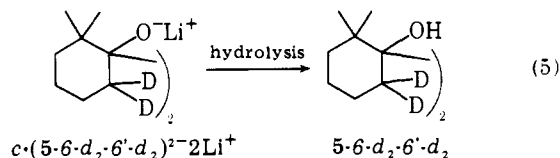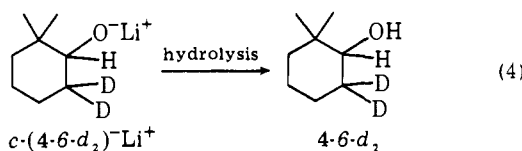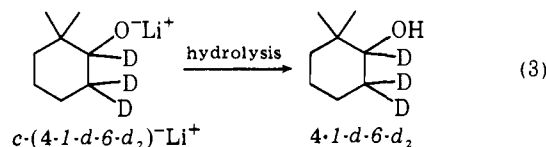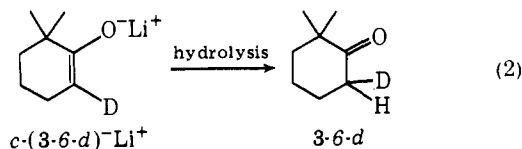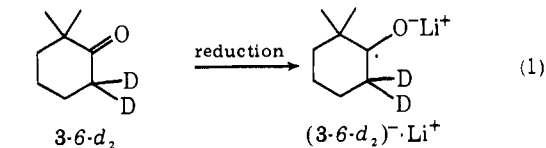
of 3-6-d_2) to metallic lithium at ca. −75 °C and subsequent hydrolysis of the resulting solution gives as main products, in a ca. 1:1 molar ratio, the ketone with one deuterium atom in the 6 position, 3-6-d (see eq 2), and the 2,2-dimethylcyclohexanol with one deuterium atom in the 1 position and two deuterium atoms in the 6 position, 4-1-d-6-d_2 (see eq 3). The THF solutions must have contained ca. 1:1 mixtures of the corresponding enolate, c-(3-6-d)$^-Li^+$,[9] and of the corresponding alcoholate, c-(4-1-d-6-d_2)$^-Li^+$,[9] respectively (hydrolyses: eq 2 and 3). Two general mechanisms for the formation of the enolate/alcoholate mixtures need to be considered. The ketyl,[7] once formed (eq 1), either disproportionates[5] directly (Scheme I), or reacts with (unreacted) substrate and a reduction step then follows. For clarity, we explicitly intro-
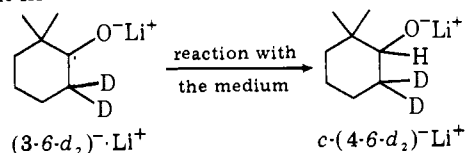
Scheme I
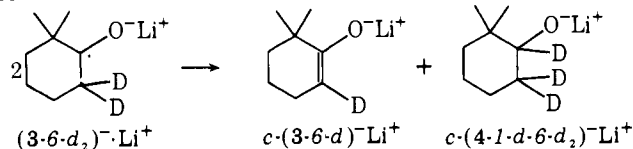
duce[10] the more likely mechanism of the latter type: the ketyl may react with the substrate to give the alcoholate and the α-keto radical r-(3-6-d)·,[9] and the latter may then be reduced, by the ketyl or the metal, to give the enolate (Scheme II). As

Scheme II
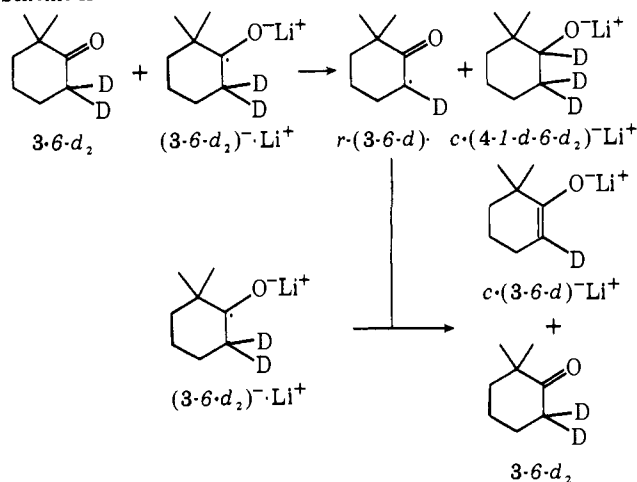
minor components, the hydrolysates contain, apart from small amounts of unreacted 3-6-d_2 and traces of unlabeled **3**, the alcohol with a hydrogen atom in the 1 position and two deuterium atoms in the 6 position, 4-6-d_2 (see eq 4), and the pinacols, with two deuterium atoms in each 6 position, 5-6-d_2-6'-d_2 (see eq 5). Accordingly, two other, minor decay reactions of the ketyl can be identified; the ketyl abstracts hydrogen atoms or protons from the medium to give the alcoholate c-(4-6-d_2)$^-Li^+$ (Scheme III, hydrolysis leads to 4-6-d_2,

Scheme III

eq 4), and dimerizes to give the pinacolates c-(5-6-d_2-6'-d_2)$^{2-}2Li^+$ [9] (Scheme IV, hydrolysis leads to 5-6-d_2-6'-d_2, eq 5).

Scheme IV
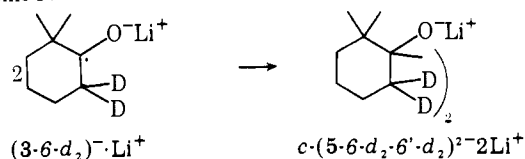
Analysis, Results. Using THF as the solvent and working at ca. −75 °C throughout, the reaction time and the concentration of the substrate are varied and the reproducibility of each set of experiments is controlled. The hydrolysates are analyzed by gas chromatography; this gives the proportions in which the (unseparated) mixtures of deuterium-labeled ketones {3, 3-6-d, 3-6-d_2}, the (unseparated) mixtures of labeled alcohols {4-6-d_2, 4-1-d-6-d_2}, and the (separable) mixtures of pinacols {5-6-d_2-6'-d_2} (the meso and the racemic forms, purity:[8b,19] ≥95% of 5-6-d_2-6'-d_2) are present. After distillation, the ketones, alcohols, and pinacols are isolated by gas chromatography. The deuterium content of the pinacols is then controlled and the distribution of the label in the ketones

Table 1. Reaction of 3-6-d_2 with Alkali Metals in THF and Liquid Ammonia/THF; Ketone and Alcohol Mixtures Obtained after Hydrolysis

Run	Metal, medium[a]	Addition mode	Initial concn[b] in 3-6·d_2, M	Ratio[c] metal/3-6-d_2, g-atom/mol	Total contact time,[d] min	% composition[e] of {3-6-d_2, 3-6-d, 3}			% composition of {4-1-d-6-d_2, 4-6-d_2, 4-d}		
						3-6-d_2	3-6-d	3	4-1-d-6-d_2[e]	4-6-d_2[f]	4-d[g]
1	Li pieces in THF		0.26	10	300	3	91	6	80	20	
2			0.26	10	300	4	92	4	79	21	
3			0.20	10	300	4	96		83	17	
4			0.20	10	360	3	97		90	10	
5			0.16	10	360		100		86	14	
6			0.077	13	360		100		85	15	
7			0.038	25	420	9	91		78	22	
8			0.038	25	300	4	96		78	22	
9			0.038	25	120	53	47		80	20	
10			0.038	25	70	97	3		80	20	
11	Dissolving Li in NH$_3$/THF	Normal	0.028	2	5	29	71		46	51	3
12			0.028	2	12	20	80		47	50	3
13			0.028	3	70	26	74		50	50	
14			0.028	2	120	36	64		47	53	
15	Solution of Li in NH$_3$/THF	Inverse[h]	0.028	4	90	3	97		51	49	
16		Inverse[i]			60	16	84		46	51	3
17	Dissolving Li in NH$_3$/THF	Normal	0.028	0.3	10	85	15		45	51	4
18			0.0028	3	60	3	93	4	58	42	
19			0.0028	20	270	6	94		51	46	3
20	Dissolving Na in NH$_3$/THF	Normal	0.028	2	20	5	88	7	80	15	5
21	Solution of Na in NH$_3$/THF	Inverse[h]	0.028	2	20	11	89		84	8	8
22		Inverse[i]		4	75	7	90	3	84	12	4
23	Dissolving Na in NH$_3$/THF	Normal	0.028	0.3	75	76	24		90	10	
24			0.0028	2	30		97	3	79	7	14
25	Dissolving K in NH$_3$/THF	Normal	0.028	2	20	3	93	4	81	10	9
26			0.0028	3	30		100		88	5	7

[a] Runs 11-26: liquid ammonia/THF, ca. 5.8:1 by volume. [b] Estimated error: runs 1-10, ca. 5%, runs 11-26, ca. 10%. [c] Estimated error: ca. 10%. [d] Runs 1-10: including (variable) induction period. [e] Estimated, absolute analytical error: 2-3%. [f] Estimated, absolute analytical error for 4-d_2: 2-3%, in the location of the label, 4-6-d_2: ca. 5%. [g] Estimated, absolute analytical error for 4-d: 2-3%; the label is not located. [h] Rapid addition (at once) of the substrate. [i] Slow addition (ca. 30 min) of the substrate, otherwise under the conditions of the preceding run.
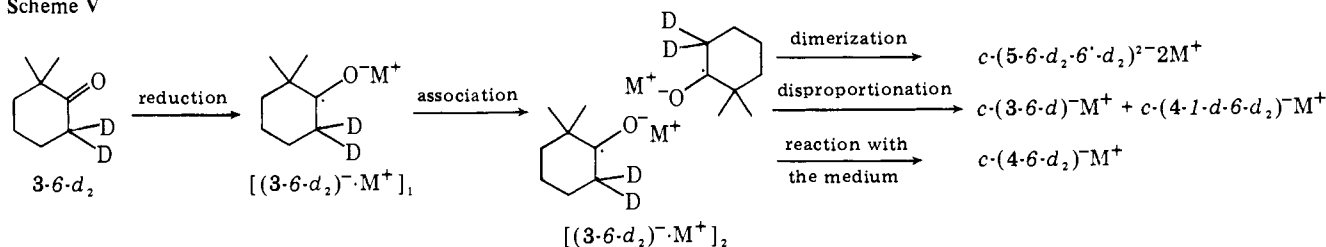
and the alcohols is determined by combination of low resolution mass spectrometry and ^{1}H NMR spectrometry. Mass spectrometric analysis gives the ratios of the ketones 3, {3-d}, {3-d_2}, and of the alcohols {4-d_2}, {4-d_3} with high precision, but does not readily indicate the positions at which the deuterium atoms are located. The positional assignments are more conveniently made by ^{1}H NMR spectrometry, but the analytical error is larger. ^{1}H NMR spectrometric analysis consistently shows, however, that the ketones and pinacols have the deuterium label(s) in the 6 positions only, and that the alcohols have the label(s) in the 6 and, in part, in the 1 positions only. These distributions are in accord with the mass spectrometric data and, moreover, are the only reasonable ones on chemical grounds. We therefore rely on the mass spectrometric data in the case of 3, 3-6-d, 3-6-d_2, 5-6-d_2-6'-d_2, and 4-1-d-6-d_2. In the case of the alcohols {4-d_2}, we distinguish between the positional isomers, 4-1-d-6-d and 4-6-d_2, by ^{1}H NMR spectrometry using Eu(fod)$_3$ shift reagent to screen the 1 and 6 positions. We find only 4-6-d_2; on chemical grounds, only the formation of this isomer is reasonable. The compositions of the mixtures {3, 3-6-d, 3-6-d_2} and {4-6-d_2, 4-1-d-6-d_2} so determined are reported in Table I (runs 1-10). Combination of the data in Table I with the results of the gas chromatographic analyses leads to values for the molar ratios 3-6-d/4-1-d-6-d_2 in the hydrolysates. These[19] are found to be ca. 1.0 in all experiments, but the analytical error is rather large.[13a] Surprisingly, the proportions of pinacols 5-6-d_2-6'-d_2 are found to be the same in every run within the analytical error, which is, unfortunately, large. These proportions are conveniently expressed as the ratios 5-6-d_2-6'-d_2/4-1-d-6-d_2; these[19] are found to be 0.2-0.3.[12b] The material balances[19] are 75-95%. Within experimental error, the entire product composition

which reflects (eq 2-5) the decay reactions (Schemes {I, II}, III, IV) seems to be independent of the initial concentration in the substrate within the range 0.26-0.038 M (6.8-fold dilution), and of the degree of conversion (runs 9 and 10). Very little of the label is lost in the course of each run.

Labeled Substrate, Lithium, Liquid Ammonia/THF. The reaction between the metallic lithium and the ketone in THF solution starts sluggishly; the rate varies from run to run, and in the course of a run, as is normal for a two-phase reaction of this type. This precludes systematic monitoring; also, the accessible concentration range is limited.[13] With the results for the lithium/THF system in hand, we therefore progress to a liquid ammonia/THF medium in which both the metal and the substrate are soluble. In this system—similar ones have occasionally been used previously[2]—monitoring of the progressing decay reactions, greater dilution, and inverse addition should all be possible. The reactions with the metals are again carried out at ca. −75 °C, the resulting solutions are quenched with ammonium chloride, and the ammonia is evaporated. After hydrolytic workup the products are isolated and analyzed as before.

The products, general trends, and material balances are found to be the same as those observed in the first series of experiments; data on nine experiments (runs 11-19) are given in Table I. The product composition is again independent of the initial concentration of the substrate, now within the range 0.028-0.0028 M (normal addition), of the degree of conversion (run 17) and, importantly, now also of the mode of addition, for normal, rapid inverse (run 15), and slow inverse (run 16) addition. Again, very little of the label is lost in each run. In the experiments at ca. 0.028 M, the ratio[19] 3-6-d/4-1-d-6-d_2 is again close to unity, but on dilution to ca. 0.0028 M, this ratio

Scheme V

That the decay, whatever its mechanism, is indeed very rapid is indicated by ESR experiments. Solutions of the persistent $1^-\cdot Li^+$ in liquid ammonia/THF can be generated by adding 1 at ca. -75 °C to lithium solutions; when frozen (ca. 77 K), these exhibit a rigid medium ESR spectrum due to $[1^-\cdot Li^+]_2$, which is identical with that found for THF solutions.[6] "Titration", either of the blue lithium solutions or of the light red-brown solutions of $1^-\cdot Li^+$, with solutions of 3, causes the ESR signals of the solvated electrons and of $[(1^-\cdot Li^+)]_2$ (rigid medium spectrum), respectively, to disappear as quickly as the solutions can be mixed at ca. -75 °C. Neither in these experiments, nor in analogous, more "difficult" ones in THF, can signals due to $3^-\cdot Li^+$ be detected.

As concerns dimerization, Scheme V is a refinement of Scheme IV, the association, ketyl ion pair $[(3\text{-}6\text{-}d_2)^-\cdot M^+]_1$ $\rightarrow$ ketyl ion quadruplet $[(3\text{-}6\text{-}d_2)^-\cdot M^+]_2$, now being taken into account, and the mechanistic analysis can be terminated at this level. As regards disproportionation, Scheme V is also a refinement of Scheme I, association and disproportionation now being linked kinetically. Scheme II[11] (cf. ref 10) involving the ion pairs $[(3\text{-}6\text{-}d_2)^-\cdot M^+]_1$ (and the related scheme involving the ion quadruplets $[(3\text{-}6\text{-}d_2)^-\cdot M^+]_2$) can thus be neglected. Mechanistically, disproportionation[5] within the ion quadruplets (Scheme V) may either involve direct abstraction of a deuterium atom[15] or prior electron transfer ("disproportionation"[5]) to give a ketone-ketone dianion pair and subsequent transfer of a deuteron, or a blend of both modes. As concerns the reaction with the medium, Scheme V (purposely left incomplete concerning the stoichiometry) supplants Scheme III. Dual mechanisms, analogous to those discussed for disproportionation, can be postulated for the reaction of the ion quadruplets with solvent molecules in the contacting solvent shell. Since the reaction with the medium apparently comes only into play after association, it can be speculated that the electron transfer/deprotonation mode is operating; otherwise, it is difficult to see why direct hydrogen atom abstraction does not already set in before association. By inference it can perhaps be speculated that the analogous mode also operates in the case of disproportionation. Partitioning between the three decay modes depends on the nature of the bridging metal ions and of the solvation shell, as one would expect.

Overall Primary Kinetic Isotope Effect. We have an additional piece of evidence which could, in principle, shed light on the mechanism of the disproportionation: an overall primary kinetic isotope effect k_H/k_D of ca. 2.7 is found when the lithium ketyl with one deuterium atom in the 6 position, $(3\text{-}6\text{-}d)^-\cdot Li^+$, generated in THF at ca. -75 °C, disproportionates. The substrate is itself obtained ($\geq 98\%$ of $3\text{-}6\text{-}d^{8a}$) by reduction, disproportionation, and hydrolysis (runs 1-10). The run with $3\text{-}6\text{-}d$ (ca. 0.16 M initial concentration) gives the ketone mixture[8a] {74% of $3\text{-}6\text{-}d_1$, 26% of 3} and the alcohol mixture[8a] {27% of $4\text{-}1\text{-}d\text{-}6\text{-}d$, 73% of $4\text{-}6\text{-}d$}. The analyses are, in principle, done as before (see below). The ratios $3\text{-}6\text{-}d/3$ and $4\text{-}6\text{-}d/4\text{-}1\text{-}d\text{-}6\text{-}d$ are approximate values for k_H/k_D and are in good agreement. $4\text{-}6\text{-}d/4\text{-}1\text{-}d\text{-}6\text{-}d$ is the more reliable value (small amounts of $3\text{-}6\text{-}d$ may not have reacted); we neglect the reaction with the medium. The disproportionation of $3^-\cdot Li^+$

drops to ca. 0.5: the enolate is apparently not stable under the conditions. The yield of pinacols is again approximately the same in every run. In some respects the results nevertheless differ characteristically from those obtained in the first series of experiments. Both the reaction with the medium and dimerization are more important: $4\text{-}6\text{-}d_2/4\text{-}1\text{-}d\text{-}6\text{-}d_2^{19}$ is ca. 50:50 (previous series: ca. 20:80), and $5\text{-}6\text{-}d_2\text{-}6'\text{-}d_2/4\text{-}1\text{-}d\text{-}6\text{-}d_2^{19}$ is 0.6-0.8 (previous series: 0.2-0.3). When the metal is added to ca. 0.028 M solutions (a concentration acceptable for synthetic application, although already rather low), conversion is initially very rapid (runs 11 and 12) and then slows down. We believe that this is due to a phase separation: conversion is rapid while the metal dissolves in the colorless, homogeneous[20] solution, and slow by the time it is fully "dissolved" to give a dark blue, opaque mixture. There is no slowdown on inverse addition or on dilution (0.0028 M, normal addition). Monitoring is nevertheless difficult. To obtain a product composition at the initial stages of the overall reaction, <1 equiv of lithium is therefore used (run 17).

Labeled Substrate, Sodium or Potassium, Liquid Ammonia/THF. Analogous experiments can be carried out with sodium and potassium in the liquid ammonia/THF medium at ca. -75 °C. Data for seven experiments (runs 20-26) are given in Table I. The products, general trends, and material balances are the same as those found in the two series of experiments with lithium. $3\text{-}6\text{-}d/4\text{-}1\text{-}d\text{-}6\text{-}d_2^{19}$ is found to be close to unity in all cases. In some respects the results with these metals, which behave similarly, differ from the previous ones. The pinacols are barely detectable (lithium in THF and in liquid ammonia/THF gives differing, sizable amounts). Little reaction with the medium occurs (more with lithium in liquid ammonia/THF, little with lithium in THF). Conversions are high (slow down with lithium in liquid ammonia/THF). Slightly more of the label is lost to the medium: more of unlabeled 3 and some of the alcohol(s) containing one deuterium atom, {4-d}, are found ({4-d} is also formed, to a lesser extent, in the runs with lithium in liquid ammonia/THF); the distribution of the label in {4-d} is not determined. The results show that the sodium ketyl, $(3\text{-}6\text{-}d_2)^-\cdot Na^+$, and the potassium ketyl, $(3\text{-}6\text{-}d_2)^-\cdot K^+$, are formed, are transient, and that their formation and decay correspond exactly to those of the lithium ketyl, $(3\text{-}6\text{-}d_2)^-\cdot Li^+$; only the partitioning between the decay modes differs somewhat.

Mechanism, ESR Experiments. Previous ESR studies[14] show that saturated alkali metal ketyls have contact ion structures and indicate qualitatively that the ion pairs, which must be the primary products formed on reaction between the metal and the ketones, associate[3] rapidly and completely to give ion quadruplets and larger ion clusters. All the findings presented above suggest uniquely that such association of the lithium, sodium, and potassium ketyl ion pairs, $[(3\text{-}6\text{-}d_2)^-\cdot M^+)]_1$ (M^+ = Li^+, Na^+, K^+),[7] precedes all three decay reactions. The simplest hypothesis is that dimerization and disproportionation within the ion quadruplets $[(3\text{-}6\text{-}d_2)^-\cdot M^+]_2$,[7] the first species formed on association, are so rapid that further association is excluded. The reaction with the medium must then also be ascribed to the ion quadruplets. We thus hypothesize that the only reaction of the ion pairs is their extremely rapid and efficient association to give the ion quadruplets, and that these then immediately decay, in a quasi-intramolecular fashion (Scheme V).

Table II. Dissolving Metal Reduction of 3-6-d_2 with Alkali Metals; Alcohol Mixtures Obtained

Run	Metal	Medium	Ratio metal/ 3-6-d_2, g-atoms/mol	Ratio proton source/3-6-d_2, mol/mol	% composition[b] of {4-1-d-6-d_2, 4-6-d_2, 4-6-d}		
					4-1-d-6-d_2[c]	4-6-d_2[d]	4-6-d[d]
27	Li	NH$_3$/THF/tert-butyl alcohol[a]	35	50	28	51	21
28	Li		35	50	28	58	14
29	Li	NH$_3$/THF/ethanol[a]	40	50	19	76	15
30	Na		20	50	36	21	43
31	K	NH$_3$/THF/tert-butyl alcohol[a]	18	50	25	52	20

[a] Runs 27–29, ca. 5.8:1:0.9; runs 30, 31, ca. 5.8:1:0.3 by volume. [b] Run 31: in addition, 3% of **4**. [c] Estimated, absolute, analytical error: 2–3%. [d] Estimated, absolute, analytical error for {4-d_2} and {4-d}: 2–3%, in the location of the label, 4-6-d_2, 4-6-d: 5–10%.

must thus be more rapid than that of $(3\text{-}6\text{-}d_2)^-\cdot\text{Li}^+$. According to Scheme V, the dimerization and the reaction with the medium should therefore be less important for $3^-\cdot\text{Li}^+$ than for $(3\text{-}6\text{-}d_2)^-\cdot\text{Li}^+$. This can be verified for the case of the dimerization and we indeed find more of the pinacols in runs with **3**. (We give this qualitative result, but do not further describe experiments with **3**, since they do not provide direct information about the reaction with the medium.)

Labeled Substrate, Lithium or Sodium or Potassium, Liquid Ammonia/THF/tert-Butyl Alcohol or Ethanol. With results for two nonacidic media, an aprotic and a protic one, in hand we can progress to liquid ammonia based, acidic media of the type most commonly used in synthetic practice.[2] For consistency, we continue to work at ca. -75 °C (in practice, reductions are carried out at ca. -75 °C or at -33 °C). The metals are added in excess to ca. 0.025 M solutions of the substrate in liquid ammonia/THF containing excess tert-butyl alcohol or ethanol (normal addition), the mixtures are stirred until the metal is consumed, and they are then hydrolyzed. Mixtures of deuterium-labeled alcohols and, in the experiments with lithium, the (labeled) pinacols are obtained. The material balances[19] are 80–90%.

Analysis, Results. The distribution of the label in the alcohol mixtures is determined as in the previous runs by combination of mass and ^{1}H NMR spectrometry. The analyses are more difficult, however, because we now find sizable amounts of the trideuterated ({4-d_3}), dideuterated ({4-d_2}), and monodeuterated alcohols ({4-d}). We have to rely on ^{1}H NMR spectrometry using Eu(fod)$_3$ shift reagent to identify both the positional isomers {4-d_2}, 4-1-d-6-d and 4-6-d_2, and the positional isomers {4-d}, 4-1-d and 4-6-d, in the presence of the trideuterated alcohol 4-1-d-6-d_2. Furthermore, geometrical isomerism can arise in the case of 4-1-d-6-d and 4-6-d: the analysis does not distinguish between geometrical isomers. A single positional isomer with two deuterium atoms, 4-6-d_2, and a single type of positional isomer with one deuterium atom, 4-6-d (we assume that we have a mixture of geometrical isomers), are found, but the analytical error is large. The data are collected in Table II.

We interpret as follows. The ketyl ion pairs $[(3\text{-}6\text{-}d_2)^-\cdot \text{M}^+]_1$, and perhaps the ion quadruplets $[(3\text{-}6\text{-}d_2)^-\cdot\text{M}^+]_2$, are protonated in part by the proton source. House's general mechanism then continues to operate. These sequences lead to 4-6-d_2. The reactions with the THF and the liquid ammonia probably also occur and also lead to 4-6-d_2. Disproportionation and dimerization within the ion quadruplets persist. Disproportionation and subsequent protonations lead to 4-1-d-6-d_2 and the monodeuterated ketone 3-6-d. The latter is reduced in turn, but House's general mechanism appears to be dominant at this stage: it leads to 4-6-d, while disproportionation should give at least some 4-1-d-6-d and, eventually, perhaps some 4-1-d. Only 4-6-d is found, although the analytical error is large. That disproportionation and dimerization are indeed jointly blocked at this stage, in accord with Scheme V, can be checked in the experiments with lithium. Only the tetradeuterated pinacols 5-6-d_2-6'-d_2 (purity:[8b] ≥95% of 5-6-d_2-6'-d_2)

are formed![19] Also, the ratio 5-6-d_2-6'-d_2/4-1-d-6-d_2 is found to be of the same magnitude as in the experiments in the nonacidic liquid ammonia/THF medium. That House's mechanism is dominant at this stage, via protonation of the ketyl ion pairs $[(3\text{-}6\text{-}d)^-\cdot\text{M}^+]_1$, must be due to a slow liberation of the precursor (3-6-d) through protonation of the enolate. The data also show that, within the analytical error, the entire set of parallel and consecutive reactions takes place without loss of the deuterium label to the acidic, protic medium (cf. ref 10)!

Concluding Remarks

Experiments in which the substrates and/or the temperature are varied confirm that the disproportionation of saturated alkali metal ketyls generated under the usual experimental conditions is a general phenomenon; these studies will be reported at a later date. The usual experimental procedure is to add the metal to a solution containing the substrate and the proton source, usually a relatively weak and often a sterically hindered one, in order to minimize the reaction of the metal with the proton source, hence the term "dissolving metal reduction". These conditions tend to favor the association of the ketyls, and therefore, in terms of Scheme V, disproportionation, dimerization, and the reaction with nonacidic solvent molecules. We are now trying to find conditions which exclude association. House's mechanism, through protonation of the nascent ketyl ion pairs, should then operate exclusively, and alcohols would probably be the only products. The stereochemical course of such reductions could then be investigated. We think it likely that disproportionation has intervened to some extent in all previous studies.

Experimental Section

1. Apparatus. The reactions with the alkali metals were carried out in Schlenk tubes[16] under argon, with magnetic stirring using a Teflon-coated bar. Extracts were concentrated by distilling off the solvents through an efficient glass spiral column. A small short-path distillation apparatus was used for distillations. Gas chromatography (GC) was performed on a Perkin-Elmer 881 instrument using regular Carbowax 20M15 columns.

2. Spectrometry. NMR spectra (NMR) were measured in CDCl$_3$ on a Fourier transform Bruker HX90 instrument and are given in parts per million (δ) downfield from Me$_4$Si as an internal standard; the multiplicities of the signals (s for singlet, m for multiplet) and the number of protons are given in brackets. Tris(1,1,1,2,2,3,3-heptafluoro-7,7-dimethyl-4,6-octadionato-d_{10})europium (111) (Eu(fod)$_3$) was used as shift reagent. Mass spectra (MS) were determined on an Atlas CH4 instrument (ca. 70eV). The molecular ions (M$^+\cdot$) and fragments (m/e) with intensities down to 12–15% of the base peak are listed; the relative intensities are given in brackets. ESR spectra (ESR) were measured on a Varian E9 instrument using 100-kHz field modulation.

3. Alkali Metals. Alkali metals with the following specifications were used: lithium (Metallgesellschaft), 99.4–99.8% Li, 0.1–0.5% Na, 0.08% K, 0.01% Fe; sodium (Degussa), ca. 99.6% Na, ca. 0.04–0.06% Ca; potassium (Fluka) 98% K, 0.4% Ca, Na.

4. Solvents. THF was distilled from LiAlH$_4$ and stored over Na wire. Ammonia was distilled from NaNH$_2$ into the reaction vessel.

It was necessary to add ca. 1 vol of THF per ca. 5.8 vol of liquid ammonia to obtain homogenous[20] ca. 0.028 M solutions of 3-6-d_2 at ca. −75 °C. This ca. 5.8:1 mixture was used throughout.

5. Substrate. 2,2-Dimethylcyclohexanone (3) was made by methylation of cyclohexanone with methyl chloride and KOH[17] on a pilot plant scale. A fraction obtained by fractionation using a Sulzer column, bp 73 °C (30 mm), containing ca. 95% of 3 and ca. 5% of the 2,6-dimethylcyclohexanones (6) was converted into the corresponding, fully deuterated mixture of 3-6-d_2 (purity:[8a] ≥98%) and 6-1-d-6-d (purity:[8a] ≥98%) using a standard exchange technique,[18] followed by washing with water, drying (MgSO$_4$), and distillation. This sample was used in all experiments. The presence of 6-1-d-6-d does not affect our results and conclusions in any way.

6. Runs in THF (Runs 1-10). Experiments were carried out with 1-3 mmol of substrate. Lithium rods were hammered flat (1-2 mm) and a single piece was cut to the desired weight. The strip was weighed in the air and then etched to brilliance in methanol and rinsed and cut into pieces (ca. 5 × 3 mm) in THF. The THF-wet pieces were dropped into stirred, cooled (ca. −75 °C) ca. 0.26-0.028 M solutions of 3-6-d_2 in THF. Vigorous stirring at ca. −75 °C for 70-420 min gave homogenous,[20] colorless solutions. Stirring was discontinued, a layer of pentane was added on top of the THF solutions, and the mixture was cooled to ca. −75 °C. The remaining lithium, now floating on the pentane layer, was removed, and water was added with renewed stirring. The phases were separated and the aqueous phase was extracted with ether. The combined organic phases were dried (MgSO$_4$) and concentrated. The concentrate was analyzed by GC and distilled and sublimed. Fraction I, bp ca. 65 °C (12 mm), contained the (liquid) alcohols and ketones. Fraction II, subliming (0.01 mm) at ca. 160 °C (bath temperature), contained the crystalline pinacols as a ca. 1:2 mixture, mp 92-94 °C (uncorrected). The stereochemistries of the pinacols were not assigned.

7. Runs in Liquid Ammonia/THF (Runs 11-26). Experiments were carried out with 1-3 mmol of substrate. Single pieces of the alkali metals were cut to the desired weight; lithium and sodium were weighed in the air, potassium in ligroin. **Normal addition.** The weighed pieces were added to stirred, cooled (ca. −75 °C) ca. 0.028-0.0028 M solutions of 3-6-d_2 in liquid ammonia/THF. Initially, the stirred, dissolving metal pieces left a blue trail of dissolved, quickly reacting metal. For 2-3 min the solutions stayed clear, then a colorless precipitate was formed. Finally, on complete "dissolution" of the metal pieces, dark-blue, opaque mixtures were obtained (provided the metal had been added in excess). **Inverse addition.** The metals were first dissolved in the liquid ammonia/THF medium. To the resulting dark-blue, opaque mixtures the substrate was then added in a small amount of THF, either at once (rapid inverse addition) or dropwise (slow inverse addition). The overall ratio substrate/solvent mixture was the same as that in the runs involving normal addition. After stirring the blue mixtures at ca. −75 °C for 5-270 min, excess solid NH$_4$Cl was added with stirring to consume excess metal (the blue color immediately disappeared), ether was added, and the ammonia was evaporated. The NH$_4$Cl presumably liberates the alcohols and ketones into the organic phase. Subsequent workup was done as described in section 6.

8. Runs in Liquid Ammonia/THF Containing *tert*-Butyl Alcohol or Ethanol (runs 27-31). Experiments were carried out with 1-5 mmol of substrate. The procedure corresponded to that described in section 7, for normal addition, except that *tert*-butyl alcohol or ethanol was initially added to the liquid ammonia/THF medium, and that the mixtures were stirred until the blue color had disappeared (4-5 h).

9. Analyses. Analytical samples of the ketones, alcohols, and pinacols (unlabeled compounds, uniformly labeled compounds, or mixtures of differently labeled compounds) were purified by GC; purity ≥ 98%. In the GC analyses, corrections for response factors were made. In the determination of the distribution of the deuterium label in the ketones and alcohols, the M$^+$· peaks were used for evaluation; for mixtures, corrections for the normal isotopic peaks were made. In the case of the pinacols, the (M/2)$^+$· peak was used for evaluation.

10. Authentic, Pure Samples. Pure samples of 4-6-d_2 and 4-1-d-6-d_2 for spectral comparison were made by LiAlH$_4$ and LiAlD$_4$ reduction, respectively, using standard techniques.

11. Spectra. 3: NMR δ 1.13 (s, 6), 1.5-2.0 (m, 6), 2.2-2.6 (m, 2); MS M$^+$· 126 (26), *m/e* 83 (15), 82 (100), 69 (40), 56 (43), 55 (46), 42 (15), 41 (46).

3-6-d (purity:[8a] ≥98%): NMR δ 1.13 (s, 6), 1.5-2.0 (m, 6), 2.2-2.6

(m, 1); MS M$^+$·127 (25), *m/e* 82 (100), 69 (41), 56 (49), 55 (35), 43 (11), 42 (21), 41 (41).

3-6-d_2 (purity:[8a] ≥98%): NMR δ 1.13 (s, 6), 1.5-2.0 (m, 6); MS M$^+$· 128 (27), *m/e* 82 (100), 70 (15), 69 (43), 57 (17), 56 (44), 55 (29), 43 (13), 42 (19), 41 (38).

4: NMR δ 0.89 (s, 3), 0.99 (s, 3), 1.1-1.9 (m, 9), 3.1-3.5 (m, 1); MS M$^+$· 128 (9), *m/e* 95 (43), 82 (100), 69 (41), 67 (26), 57 (47), 56 (29), 55 (29).

4-6-d_2 (purity:[8a] ≥98%): NMR δ 0.89 (s, 3), 0.99 (s, 3), 1.1-1.9 (m,7), 3.32 (s, broadened, 1); MS M$^+$· 130 (14), *m/e* 97 (38), 83 (24), 82 (100), 69 (54), 68 (17), 67 (15), 58 (40), 57 (22), 56 (38), 55 (18).

4-1-d-6-d_2 (purity:[8a] ≥98%): NMR δ 0.89 (s, 3), 0.99 (s, 3), 1.1-1.9 (m, 7); MS M$^+$· 131 (26), *m/e* 113 (17), 98 (45), 97 (16), 84 (17), 83 (72), 82 (100), 70 (28), 69 (66), 68 (20), 67 (13), 59 (35), 58 (22), 57 (24), 56 (53), 55 (19).

5a: NMR δ 1.12 (s, 6), 1.25 (s, 6), 1.3-2.2 (m, 18); MS M$^+$· 254 (2), *m/e* 127 (100), 110 (43), 109 (84), 95 (18), 83 (24), 82 (59), 69 (34), 67 (29), 59 (30), 56 (18), 55 (49).

5b: NMR δ 1.17 (s, 6), 1.24 (s, 6), 1.3-2.2 (m, 18); MS very similar to that of **5a**.

5-d_2-6'-d_2 (a) (purity:[8b] ≥95%): NMR δ 1.12 (s, 6), 1.25 (s, 6), 1.3-1.9 (m, 14); MS M$^+$· 258 (2), *m/e* 129 (100), 112 (36), 111 (61), 97 (12), 85 (13), 82 (59), 70 (16), 69 (46), 67 (14), 59 (35), 57 (21), 56 (34), 55 (21).

5-d_2-6'-d_2 (b) (purity:[8b] ≥95%): NMR δ 1.16 (s, 6), 1.23 (s, 6), 1.3-1.9 (m, 14); MS very similar to that of **5-d_2-6'-d_2** (a).

12. ESR Experiments. (a) A solution of lithium in liquid ammonia/THF was prepared in a Schlenk tube as described in section 7 and a fraction was transferred at ca. −75 °C into a sealed-on ESR tube. **1** in a small amount of THF was added with a syringe to the solution in the ESR tube until the blue color had disappeared. The light red-brown solution so obtained was frozen to ca. 77 K and then exhibited an ESR spectrum which was identical with that previously observed[6] for frozen THF solutions containing [1$^-$·Li$^+$]$_2$. (b) **3** in a small amount of THF was added at ca. −75 °C to the lithium solution until the blue color had disappeared. The colorless solution so obtained was frozen to ca. 77 K and then did not exhibit an ESR signal. (c) **3** in a small amount of THF was added at ca. −75 °C to the lithium solution, but not enough to consume all the lithium. The blue solution so obtained was frozen to ca. 77 K and then only exhibited the central ESR signal due to solvated electrons. Subsequent addition of **1** in a small amount of THF to this solution at ca. −75 °C gave a light red-brown solution which, frozen to ca. 77 K, again exhibited the spectrum of [1$^-$·Li$^+$]$_2$. (d) **3** in a small amount of THF was added at ca. −75 °C to a solution of 1$^-$·Li$^+$ prepared as in a. On complete mixing and subsequent freezing to ca. 77 K, no ESR signal was observed. On gradual mixing and intermittent freezing the signals due to [1$^-$·Li$^+$]$_2$ gradually disappeared.

References and Notes

(1) (a) Dedicated to Professor G. Wittig on the occasion of his 80th birthday; (b) Firmenich SA; (c) Université de Genève.
(2) Review: H. O. House, "Modern Synthetic Reactions", 2nd ed, W. A. Benjamin, Menlo Park, Calif., 1972, Chapter 3.
(3) We use the term dimerization for the reaction, ketyl → pinacolates, and the term association for the reaction, or the sequence of reactions, ketyl ion pair → ketyl ion quadruplet and/or ketyl ion quadruplet → higher ion clusters, cf. ref 7.
(4) The following related results have been reported. Reaction between aldehydes or ketones, an alkali metal (lithium or sodium), and trimethylsilyl chloride, brings about reductive coupling-cum-trimethylsilylation, and reductive disproportionation-cum-trimethylsilylation: K. Rühlmann, A. Sitzki, and C. Michael, *Chem. Ber.*, **101**, 285 (1968); see also V. Rautenstrauch, *Synthesis*, 787 (1975), erratum 285 (1976), and references cited in each. Disproportionation at the level of the ketyl or aldehyde analogue was proposed as a possible mechanism. The extrapolation to the conditions of the dissolving metal reduction was not made.
(5) We use this term phenomenologically for two different overall reactions, (1) the reaction of the ketyl radical derived from 1$^-$·Li$^+$ to give ketone and

alcohol, and (2) the reaction of the ketyls (3-6-d_2)⁻·M⁺ to give enolate and alcoholate, since both reactions resemble radical disproportionations. Mechanistically, the latter involve transfer of a hydrogen atom from one radical to another. In radical anion chemistry, the term usually denotes the transfer of an electron from one radical anion to another. Either type of process may be involved in both our reactions; see ref 6 and the mechanistic discussion.

(6) V. Rautenstrauch and M. Geoffroy, *J. Am. Chem. Soc.*, **98**, 5035 (1976).

(7) For clarity we initially leave open the degree of association of the ketyls and then write 1⁻·Li⁺, (3-6-d_2)⁻·Li⁺. The association phenomena are introduced subsequently, and we then write [1⁻·Li⁺]₁, [(3-6-d_2)⁻·Li⁺]₁ for the ion pairs, and [1⁻·Li⁺]₂, [(3-6-d_2)⁻·Li⁺]₂ for the ion quadruplets.

(8) Analysis by low resolution mass spectrometry (see the Experimental Section). Estimated, absolute, analytical error: (a) 2–3%; (b) ca. 5%.

(9) The prefix c- is used to designate the conjugate base (enolate, alcoholate, dialcoholate) of a given substrate and the prefix r- is used to designate the radical derived from a given substrate by hydrogen or deuterium atom abstraction.

(10) In principle, it would be more correct to leave open the possible mechanisms [a deuterium atom abstraction and a reduction (as formulated, Scheme II), or the corresponding dedeuteronation (leading to c-(3-6-d)⁻Li⁺ and the O-deuterated ketyl radical corresponding to (3-6-d_2)⁻·Li⁺) and a

reduction (of the ketyl radical)] at this stage, and to formulate instead a purely kinetic scheme (corresponding to Scheme I) which is essentially the same for both mechanisms. We nevertheless introduce the more likely mechanism[11] explicitly at this stage, for the following reasons (and for clarity and brevity): (1) the underlying kinetic scheme is subsequently excluded experimentally; the dedeuteronation mode is (2) unfavorable (estimated pK_a values) and is (3) subsequently excluded experimentally (independently from (1): disproportionation is found to occur without loss of the deuterium label to protic, acidic media).

(11) Analogy: J. E. Bennett, B. Mile, and A. Thomas, *J. Chem. Soc. A*, 298 (1968).

(12) Estimated, absolute, analytical error: (a) 0.2; (b) 0.1.

(13) Below ca. 0.038 M, the reaction does not start.

(14) Reference 6 and literature cited therein.

(15) Analogy: G. P. Laroff and H. Fischer, *Helv. Chim. Acta*, **56**, 2011 (1973).

(16) U. Schöllkopf, "Houben-Weyl", Vol. XIII/1, Georg Thieme Verlag, Stuttgart, 1970, Chapters 1 and 3.

(17) W. C. Meuly, West Germany Patent 1 244 784 (1968).

(18) A. F. Thomas, "Deuterium Labeling in Organic Chemistry", Appleton-Century-Crofts, New York, N.Y., 1971, p 168.

(19) Data not included in the table.

(20) As judged from visual examination.

Syntheses of Mono-, Bis-, and Tris(diisopropylamino)triphenylcyclopropenium Ions. Cyclopropenyl Analogues of Triphenylmethane Dyes

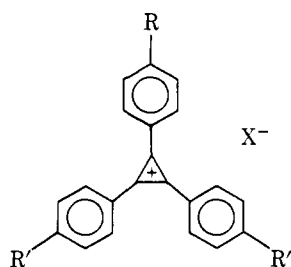## Koichi Komatsu, Robert West,* and David Stanislawski

Contribution from the Department of Chemistry, University of Wisconsin, Madison, Wisconsin 53706. Received April 14, 1976

Abstract: Mono-, bis-, and tris(p-N,N-diisopropylamino)triphenylcyclopropenium ions have been synthesized as their perchlorate or tetrafluoroborate salts (**4–6**) by reacting N,N-diisopropylaniline with the appropriate chlorocyclopropenium ion, (Ph$_n$C$_3$Cl$_{3-n}$⁺, n = 0–2). These substances are bright yellow dyes which absorb at much shorter wavelengths than the corresponding triphenylmethane dyes (λ_{max} **4**, 411 nm; **5**, 438; **6**, 447). Measurements of the pK_R⁺ values, ¹³C chemical shifts, and reduction potentials reveal that these ions are much more stabilized than the triarylmethyl analogues, in agreement with results of Hückel MO calculations.

The triphenylmethane dyes, consisting of triphenylmethyl cations substituted with strongly electron-donating amino groups, are a well-known and important class of synthetic coloring matters.[1] Two of the most useful are malachite green (**1**) and crystal violet (**2**), in which triarylmethyl cations contain two and three p-dimethylamino groups, respectively. In an early theoretical paper Dewar used simple Hückel molecular orbital theory to calculate the wavelengths of the lowest energy electronic absorption band for these and other basic dyes, with remarkable success.[2]

The series of triarylcyclopropenium ions with p-dialkylamino substituents (**4–6**) can be considered as analogues of the triphenylmethane dyes, in which the central carbon atom is replaced by a three-membered ring, giving a larger and more nearly planar[3] conjugated system. Therefore it seemed quite interesting to prepare this series of compounds and compare their properties with those of the classical triphenylmethane dyes.

Syntheses of p-Amino-Substituted Triphenylcyclopropenium Ions (4–6). The syntheses of triphenylcyclopropenium ions with mono-[4a] and bis(dimethylamino)[4b] substituents have been reported previously. However, the methods used in these syntheses are not applicable for the entire series of cations with one to three p-dialkylamino substituents. We found that these species were prepared in a simple and straightforward manner starting from the trichlorocyclopropenium ion, C$_3$Cl$_3$⁺.[5]

	R	R'	R''	X
3	H	H	H	ClO$_4$
4	i-Pr$_2$N	H	H	ClO$_4$
5	i-Pr$_2$N	i-Pr$_2$N	H	ClO$_4$
6	i-Pr$_2$N	i-Pr$_2$N	i-Pr$_2$N	BF$_4$

For the synthesis of the mono- or bisamino compounds, 1 or 2 molar equiv of N,N-diisopropylaniline was allowed to react with diphenylchlorocyclopropenium or phenyldichlorocyclopropenium ions which had been prepared in situ from C$_3$Cl$_3$⁺AlCl$_4$⁻ and 2 or 1 molar equiv of benzene in chloroform. After hydrolysis, the crude chloride salts of the corresponding triarylcyclopropenium ions were converted to and analyzed as the perchlorate salts (**4** and **5**).

The use of AlCl$_3$ for the generation of chlorocyclopropenium ions is known to have wide applicability.[6] However, we found