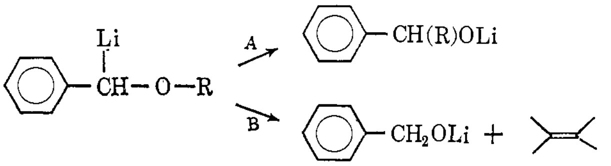
Mechanistic Aspects of the Rearrangement and Elimination Reactions of α-Metalated Benzyl Alkyl Ethers

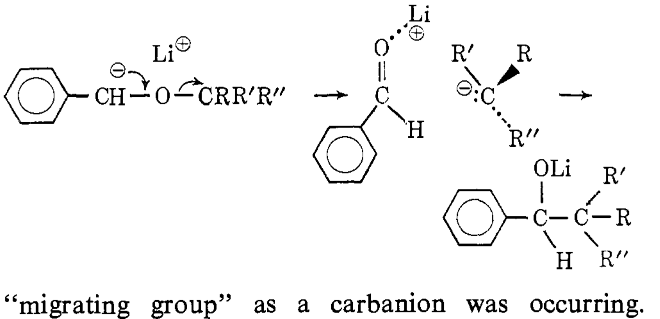
Peter T. Lansbury,[1a] V. A. Pattison,[1b] J. D. Sidler, and J. B. Bieber

Contribution from the Department of Chemistry, State University of New York at Buffalo, Buffalo, New York 14214. *Received August 2, 1965*

Abstract: The previously proposed carbanion cleavage–recombination mechanism for the Wittig rearrangement is shown to be incompatible for ethers containing *sec*-alkyl or *t*-alkyl groups. In these cases, particularly for bridgehead bicycloalkyl groups, the migration tendency has no relation to the stability of the corresponding alkyllithium compounds. It is possible to rationalize all previous and present experimental findings of this reaction by invoking a cleavage–recombination mechanism involving free-radical pairs.

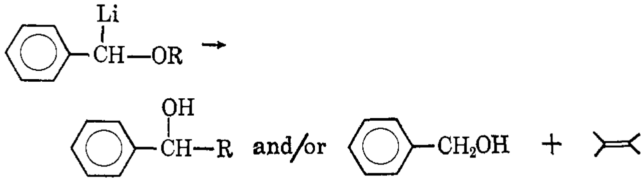
In 1942, Wittig discovered that benzyl alkyl ethers underwent metalation by alkyllithium reagents, followed by rearrangement (A) and/or elimination (B) to give phenylalkylcarbinols and benzyl alcohol plus olefin, respectively. Earlier studies on the scope and mechanism of the Wittig rearrangement, as well as other reactions of α-metalated ethers, have been summarized elsewhere.[2–5] We now wish to focus attention on pertinent data bearing on present mechanistic interpretations of the rearrangement and elimination reactions.





Schollkopf and co-workers[2] observed that partial racemization occurred in the rearrangements of optically active benzyl 2-butyl ether and benzyl 2-phenyl-2-butyl ether and they claimed that a cleavage–recombination reaction involving initial expulsion of the "migrating group" as a carbanion was occurring. Simultaneously, Lansbury and Pattison[3b] were able to detect "crossover" products during the methyllithium-induced rearrangements of benzyl ether (*i.e.*, methylphenylcarbinol), and subsequently other benzyl alkyl ethers (see below). These results also supported the cleavage–recombination mechanism; however, it was pointed out that the carbanion pathway did not explain the results observed with some benzyl *t*-alkyl ethers. The inertness of benzyl apocamphyl ether toward rearrangement, under conditions where other *t*-alkyl ethers reacted, was of some concern. Furthermore all *t*-alkyl ethers investigated gave no more than 1–2%, if any, of the elimination products. In contrast, α-metalated benzyl *n*-alkyl ethers gave predominant elimination and *sec*-alkyl ethers gave intermediate results, as shown in Table I. The results in the table raised the question of whether the elimination products might not arise from hydride transfer within the alkyllithium–benzaldehyde complex[2,3] rather than by α′,β-elimination as had been generally thought.[6] Since such a complex was thought not to form from *t*-alkyl benzyl ethers,[3] the absence of elimination products would be understandable.

Table I. Elimination–Rearrangement Ratios from Benzyl Alkyl Ethers[a]



R	% rearrangement[c]	% elimination[c]	Elim./rearr.
CH_3CH_2	45	55	1.2
n-C_4H_9	46	54	1.2
i-C_4H_9	38	62	1.6
i-C_3H_7	73	27	0.4
sec-C_4H_9	79	21	0.3
3-Methyl-2-butyl	84	16	0.2
Cyclobutyl	85	15	0.2
t-Butyl	100	0	0
t-Amyl	98	2	~0
3,7-Dimethyl-3-octyl[b]	100	0	0
α-Methylbenzyl[b]	100	0	0

[a] Unless otherwise noted, results are from the Ph.D. Thesis of V. A. Pattison, State University of New York, 1964. [b] From the Ph.D. Dissertation of J. D. Sidler, State University of New York, in preparation. [c] Based on the combined yields of the two products as 100%; actual yields were usually ≥90% when calculated from starting material consumed.

---

(1) (a) Alfred P. Sloan Foundation Fellow, 1963–1967; (b) Allied Chemical Corporation Fellow, 1962–1963.

(2) U. Schollkopf and W. Fabian, *Ann.*, **642**, 1 (1961); U. Schollkopf and H. Schafer, *ibid.*, **663**, 22 (1963).

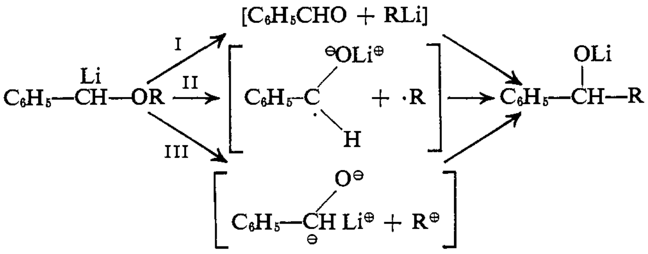
(3) P. T. Lansbury and V. A. Pattison, *J. Am. Chem. Soc.*, **84**, 4295 (1962); P. T. Lansbury and V. A. Pattison, *J. Org. Chem.*, **27**, 1933 (1962).

(4) H. E. Zimmerman in "Molecular Rearrangements," Vol. 1, P. de Mayo, Ed., Interscience Publishers, Inc., New York, N. Y., 1963.

(5) D. J. Cram, "Fundamentals of Carbanion Chemistry," Academic Press Inc., New York, N. Y., 1965, Chapter, 6.

(6) R. L. Letsinger and D. F. Pollart, *J. Am. Chem. Soc.*, **78**, 6079 (1956).

The present paper considers previously published data as well as new information obtained in our laboratories, in an effort to rationalize all the experimental facts by a single mechanistic scheme. We propose, in the discussion which follows, that of the three cleavage–recombination mechanisms possible, the radical-pair hypothesis is most consistant with the experimental results, although not necessarily the exclusive mechanism. One is also able to rationalize the above rearrangement/elimination ratios as R changes from primary to tertiary without need to call on the hydride transfer mechanism. Additional independent evidence for the α',β-elimination is also presented.



Results and Discussion

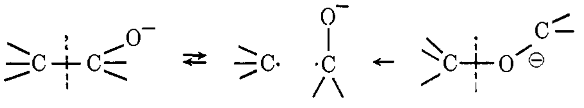
The first indication that the carbanion cleavage mechanism was inadequate came from a study of *t*-alkyl benzyl ethers,[3a] which has now been extended. As shown in Table II, when a 1-bicyclo[2.2.1]heptyl group was the migrating group (entries 4 and 5), no isomerization to alcohol occurred. We had anticipated that 1-norbornyl anions would be at least as stable as other tertiary carbanions, perhaps even more so.[7] In fact, by means of metal–halogen exchange reactions we have established that 1-norbornyllithium is decidedly more stable than other unstrained 1-bicycloalkyllithium compounds and even more stable than *sec*-butyllithium.[7] The exchange reactions between alkyl iodides and lithium reagents were run at −70° in ether–hydrocarbon mixtures and the position of equilibrium estimated by quenching with benzaldehyde and analyzing the resultant phenylcarbinols.[7] Some typical, reproducible results are shown in Table III. An interesting sidelight of these results is the first successful preparation of 1-adamantyllithium and a more efficient one for 1-bicyclo[2.2.2]octyllithium. It is likely that previous unsatisfactory efforts to make these compounds involved formation of dimeric hydrocarbon from radical coupling, the latter species arising from electron transfer of slowly formed *t*-RLi[8] with excess *t*-RI. The latter iodides can give rise to exceptionally stable tertiary free radicals.[9] The bicycloalkyllithium reagents except for 1-adamantyllithium are all more stable than *t*-butyllithium, possibly because their solvated dimeric structures are less compressed[7]; 1-norbornyllithium is additionally stabilized because the exocyclic C–Li bonding orbital has greater s character as a consequence of ring strain.[7] The above studies of relative stability of organolithium reagents suggest that *t*-alkyl benzyl ethers (and even *sec*-butyl benzyl ether) do not rearrange *via* mechanism I.

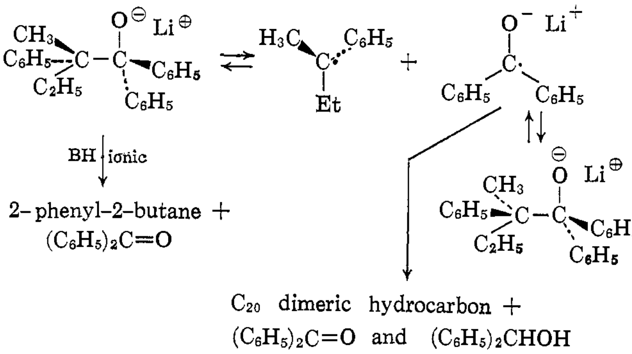
Table II. Wittig Rearrangements of Benzyl *t*-Alkyl Ethers

	R in $C_6H_5CH_2OR$	% yield of $C_6H_5CH(OH)R$
1.	*t*-butyl	51
2.	*t*-amyl	63
3.	3,7-dimethyl-3-octyl	60
4.	1-norbornyl	0
5.	1-apocamphyl	0
6.	1-adamantyl	54
7.	1-bicyclo[2.2.2]octyl	35

Mechanism III seemed to merit some consideration since bridgehead norbornyl compounds are known to be essentially inert in SN1 and SNi reactions.[10] However it did not appear that the metalated benzyloxy group constituted a satisfactory leaving group. Moreover, we have previously shown[3a] that the benzyl ethers of cyclopropylcarbinol and cyclobutanol rearrange without the characteristic cyclobutyl ⇄ cyclopropylcarbinyl interconversion that is so prevalent in carbonium ion reactions (but without analogy in either carbanion or free-radical reactions).[11]

We are thus left with the radical cleavage–recombination mechanism (II) to account for the above data with *t*-alkyl ethers, in addition to observations dealing with racemization of the migrating group[2] and "crossover" product formation.[3] Recent studies by Applequist and Kaplan[9] have shown that the bridgehead norbornyl radical is indeed more strained than acyclic *t*-alkyl radicals and other bicyclic radicals such as 1-adamantyl and 1-bicyclo[2.2.2]octyl, in contrast with alkyllithium stabilities. Thus the inertness of benzyl 1-norbornyl and 1-apocamphyl ethers is understandable. A homolytic mechanism for rearrangement finds considerable analogy in the reactions of certain metal alkoxides. Cram and co-workers[12] have demonstrated that reversible radical cleavage, not unlike the homolytic Wittig mechanism, may occur during the anionic cleavage reactions of alkali metal alkoxides, particularly lithium salts, *e.g.*





---

[7] P. T. Lansbury and J. D. Sidler, *Tetrahedron Letters*, **No. 11**, 691 (1965), and references cited therein.

[8] For a recent summary of electron-transfer reactions of RLi compounds, see R. Waack and M. A. Doran, *J. Organometal. Chem.*, **3**, 92 (1965).

[9] D. E. Applequist and L. Kaplan, *J. Am. Chem. Soc.*, **87**, 2194 (1965).

[10] D. E. Applequist and J. D. Roberts, *Chem. Rev.*, **54**, 1065 (1954).

[11] R. Breslow in "Molecular Rearrangements," Vol. 1, P. de Mayo Ed., Interscience Publishers, Inc., New York, N. Y., 1963, pp. 259–265.

[12] D. J. Cram, A. Langemann, W. Lwowski, and K. R. Kopecky, *J. Am. Chem. Soc.*, **81**, 5760 (1959).

Table III. Lithium–Halogen Exchange Reactions Involving Bridgehead Bicycloalkyl Systems

$$\mathrm{RLi} + \mathrm{R'I} \underset{}{\overset{-70^\circ}{\rightleftharpoons}} \mathrm{RI} + \mathrm{R'Li}$$

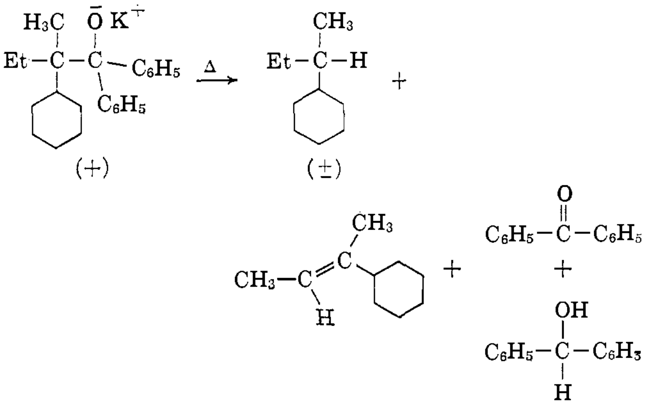
$$\downarrow \mathrm{C_6H_5CHO}$$

$$\mathrm{C_6H_5CHROH,\ C_6H_5CHR'OH}$$

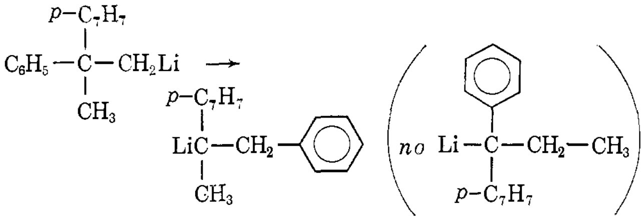
Run	RLi	RI	Phenylcarbinols[a,b]
1	*t*-Butyl	1-Norbornyl	Phenyl-1-norbornylcarbinol
2	1-Bicyclooctyl	1-Norbornyl	Phenyl-1-norbornylcarbinol
3	*t*-Butyl	1-Bicyclooctyl	Phenyl-1-bicyclooctylcarbinol
4	*sec*-Butyl	1-Norbornyl	Phenyl-*sec*-butylcarbinol (10%) Phenyl-1-norbornylcarbinol (90%)
5	*sec*-Butyl	1-Bicyclooctyl	Phenyl-*sec*-butylcarbinol
6[c]	*t*-Butyl	1-Adamantyl	Phenyl-*t*-butylcarbinol (40–60%) Phenyl-1-adamantylcarbinol (40–60%)

[a] Approximately equimolar amounts (1–2 mmoles) of reactants were used, giving 60–90% yields of phenylcarbinols after benzaldehyde quench and work-up. [b] Those carbinols not listed were formed in <1%, if at all, based on v.p.c. analysis ("Tide" on Chromosorb W column). [c] Due to the great ease of coupling between adamantyllithium and adamantyl iodide (unpublished results of J. D. Sidler) *ca.* 2 moles of *t*-butyllithium per mole of adamantyl iodide was used; however some diadamantane was still found. It is not possible to estimate accurately the stabilities of the two alkyllithiums here.

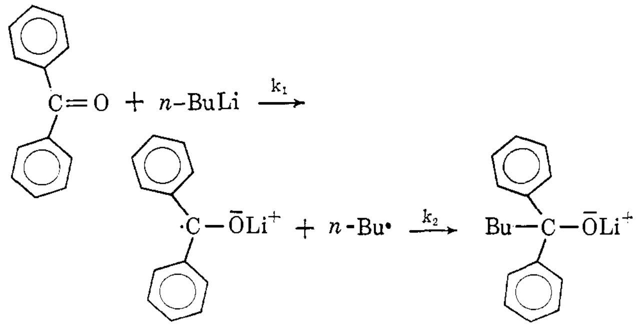
The homolytic reaction is responsible for the racemization of starting material, owing to its reversibility under the somewhat vigorous conditions (compared with Wittig rearrangements, where alkoxide cleavage does not occur[3]). Cram's study demonstrates that racemization in the solvent cage during Wittig rearrangements is not inconsistent with the free-radical hypothesis. Finally, it should be noted that 1,1-diphenyl-2-cyclohexyl-2-methyl-1-butanol underwent *only* homolytic cleavage, even as the potassium salt.[12]



The absence of the normally predominating anionic cleavage was ascribed[12] to the extreme instability of the 2-cyclohexyl-2-butyl anion (compared with 2-phenyl-2-butyl), whereas the corresponding radical would be quite stable. Such radicals are of course analogous with the migrating groups in the presently considered Wittig rearrangements. It is also interesting to consider the mechanistic significance of migratory aptitudes in the Wittig rearrangement.[4,5] Wittig postulated an intramolecular carbanion mechanism (without cleavage) to explain the relative rearrangement rates of a series of 9-fluorenyl ethers (allyl, benzyl > CH_3, C_2H_5, *p*-$NO_2C_6H_5$ > C_6H_5). However, in unambiguous 1,2-carbanion rearrangements it has been shown that phenyl migration occurs with the complete exclusion of methyl, possibly *via* a "phenanion" intermediate.[13] Even in the simple carbanion cleavage mechanism (without considering bridged anions), one would have expected phenyllithium to be ejected at least as readily as ethyllithium, based on their stabilities obtained from exchange reactions. Thus Wittig's data favor the homolytic mechanism even more than the carbanion one, especially since the relative rates are explainable in terms of the appropriate bond dissociation energies ($C_6H_5H > CH_3H > C_2H_5H > (CH_3)_2CHH > (CH_3)_3CH >$ allyl-H $\sim C_6H_5CH_2H$).[14] Thus the fastest rate occurs in the ether where C–O homolysis would give the most stable carbon radical (see below, however, for evidence that the metalation rate is important).



Radical pairs, such as those proposed in mechanism II, have been detected using electron spin resonance spectroscopy by Russell and co-workers during the addition of *n*-butyllithium to benzophenone and fluorenone.[15] Unfortunately we were unable to observe e.s.r. signals during Wittig rearrangements of a variety



---

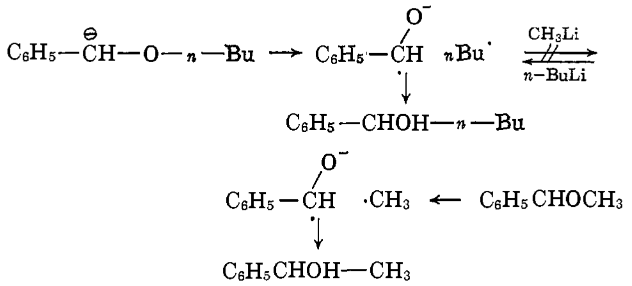
[13] H. E. Zimmerman and A. Zweig, *J. Am. Chem. Soc.*, **83**, 1196 (1961).

[14] E. W. R. Steacie, "Atomic and Free Radical Reactions," Vol. 1, 2nd Ed., Reinhold Publishing Corp., New York, N. Y., 1954, p. 95.

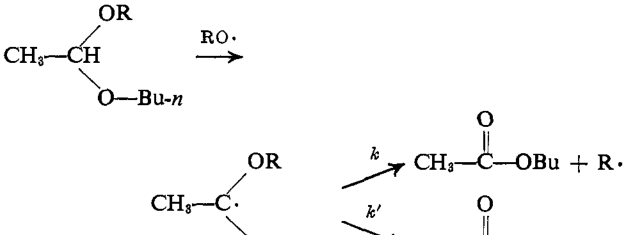
[15] G. A. Russell, E. G. Janzen, and E. T. Strom, *J. Am. Chem. Soc.*, **86**, 1807 (1964).

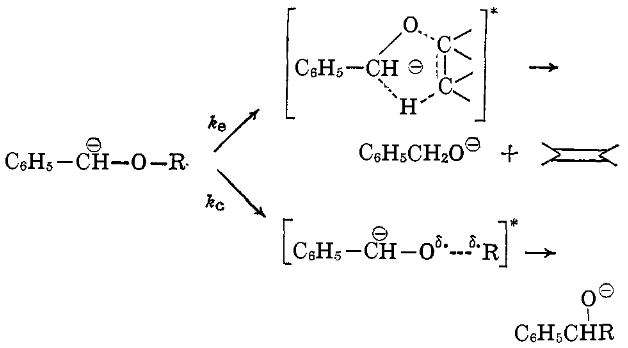
of *sec*-alkyl and *t*-alkyl benzyl ethers,[16] perhaps because benzaldehyde radical anions undergo recombination with alkyl radicals much more rapidly than occurs with the more stable benzophenone and fluorenone ketyls.[17] Even if one were to observe e.s.r. signals during rearrangement of a benzhydryl ether (where benzophenone ketyls might arise), it would not be clear if the radicals arose from initial homolysis (II) or from electron transfer after carbanion cleavage[15] (I).

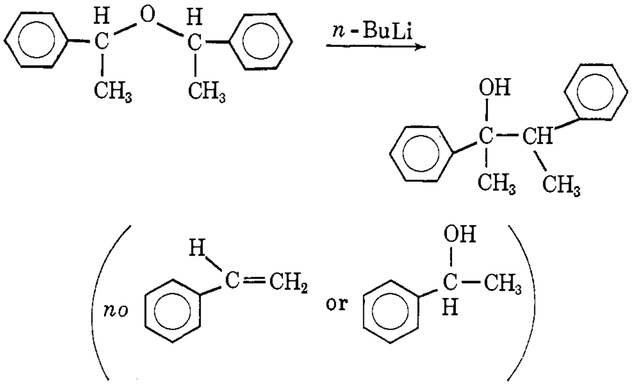
Crossover product formation in Wittig rearrangements[3] is explainable by assuming electron transfer from the metalating base to the cleavage alkyl radical. Consistent with this reasoning are the observations that *ca.* 7% *n*-butylphenylcarbinol is formed in the *n*-butyllithium-induced rearrangement of benzyl methyl ether but *no* methylphenylcarbinol is formed when *n*-butyl benzyl ether is rearranged by using methyllithium under comparable experimental conditions. The tendency for electron transfer from butyl anion to methyl radical is in line with the known relative stabilities of these radicals (*n*-butyl > methyl) and anions (methyl > *n*-butyl).



If we now assume that the radical pair cleavage–recombination mechanism is correct, at least for *sec*-alkyl and *t*-alkyl ethers,[18] then it remains to explain the great differences in the ratios of elimination to rearrangement products for the various ethers (see Table I). It is likely that the rate of cleavage of the metalated ether, k_c, is greater for *t*-alkyl ethers than *n*-alkyl ethers on the basis of the respective O–R bond strengths. An analogy is found in Huyser's work on reactions of mixed acetals with peroxides.[19] It was found that in intramolecular competitive carbon–oxygen bond homolyses of the type shown above, the ease of cleavage was benzyl, allyl > *t*-R > *sec*-R > *n*-R, in accord with the stabilities of the respective radicals. On the other hand, the α',β-elimination rate, k_e, is probably insensitive to the nature of the alkyl group but may depend on conformational effects in the transition state, among other factors. If we note that conformational strain is comparable in the transition states for elimination of the *t*-butyl and isobutyl ethers (*i.e.*, k_e similar for both) and that k_c should be greater in the former ether, it is understandable that 60% of the products from benzyl isobutyl ether are derived from elimination ($k_e \sim k_c$) whereas essentially none are from benzyl *t*-butyl ether ($k_c >> k_e$). According to these ideas we would expect no elimination products from rearrangement of α-methylbenzyl ether, in which homolytic cleavage would produce the highly stabilized α-methylbenzyl radical. In actuality, this ether slowly rearranged to the expected alcohol (mixture of *erythro* and *threo* racemates) with no evidence (v.p.c.) for either styrene or α-phenylethanol formation.







The noticeably slow reaction rate, as judged from extensive recovery of ether and lack of characteristic intense color formation during reaction with metalating base, may result from a greatly reduced metalation rate which could now be the rate-determining step in the sequence (metalation by *n*-butyllithium has been shown to be fast compared with the actual rearrangement of certain benzyl ethers in tetrahydrofuran[2a]). Among possible factors responsible for the lowered metalation rate are inductive effects of the α-methyl group, steric hindrance to approach of the metalating base (*e.g.*, benzyl *t*-butyl ether reacts more slowly than the methyl ether, in accord with the "six number"[20] of 9 for the former and 0 for the latter), and the conformational preference about the phenyl–methylene bond. In α-methylbenzyl ether, the preferred conformation places

---

(16) Unpublished experiments with Dr. M. T. Jones.

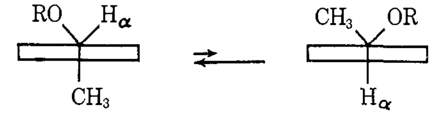
(17) Professor Glen Russell has informed us that benzaldehyde and *n*-butyllithium in fact do not give detectable concentrations of radicals under conditions where benzophenone did, in line with the insufficient lifetimes of the expected radicals ($k_2 >> k_1$).

(18) The anion mechanism quite possibly may still hold for *n*-alkyl benzyl ether rearrangements as one extreme in a spectrum of mechanisms. It should also be noted that the rearrangement of the cyclopropylcarbinyl group *without ring opening* (ref. 3a) is consistent with the homolytic mechanism (*cf.* E. S. Huyser and J. D. Taliaferro, *J. Org. Chem.*, **28**, 3442 (1963), as well as the previously postulated carbanion one.

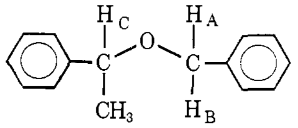
(19) E. S. Huyser and D. T. Wang, *ibid.*, **29**, 2720 (1964).

(20) M. S. Newman, "Steric Effects in Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 4.

H_α in a position unfavorable for benzylic resonance stabilization in the transition state for metalation.

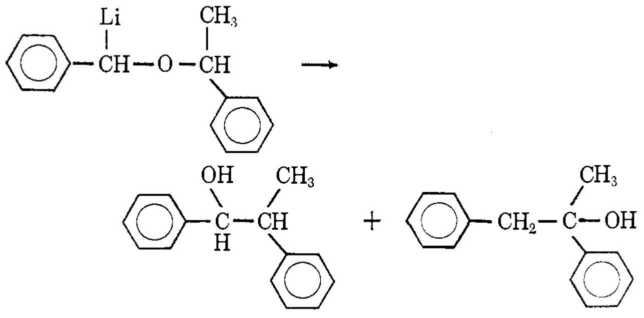


On the other hand, in benzyl alkyl ethers one α-H is stereoelectronically well situated for metalation, as indicated by the magnetic nonequivalence of the methylene protons.[21] An indication of these conformational preferences is available from the high-resolution n.m.r. spectrum of α-methylbenzyl benzyl ether which shows that the line width of the H_c signal (quartet) is less than that of a peak in the AB quartet of the methylene group.

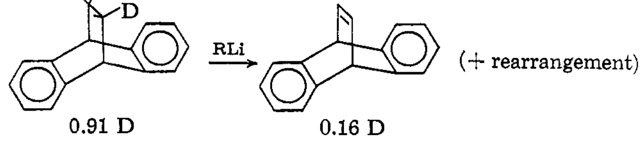


proton	$\Delta\nu_{1/2}$ c.p.s.
H_A H_B	1.1
H_C	0.95
CH_3	0.74

This is because long-range coupling of benzylic protons with aromatic ortho- and parahydrogens is greatest when the former C–H bond lies perpendicular to the plane of the ring.[22] We would expect this ether to metalate faster at the methylene group than at H_c and, as expected, the Wittig rearrangement produces mainly 1,2-diphenyl-1-propanol (*erythro* and *threo*) and little 1,2-diphenyl-2-propanol. Moreover the rate was qualitatively comparable to other benzyl ethers.



As discussed above, it is unnecessary to invoke other mechanistic explanations (such as hydride transfer) for the elimination reaction. Indeed confirmatory evidence for the α',β-elimination mechanism[6] comes from a study of the ether derived from *cis*-3-deuteriodibenzobicyclo[2.2.2]octadien-2-ol.[23] The olefin derived from reaction of the above deuterated ether with methyllithium contained only 17% of its original deuterium,[24] whereas if cleavage to RLi–benzaldehyde complex had occurred and then hydride were transferred, the major product (~80%) should have been deuterated dibenzobicyclo[2.2.2]octadiene, assuming $k_H/k_D \sim 5$.



It was thought that the ratio of butenes resulting from elimination in *sec*-butyl benzyl ether might also be indicative of a *cis* elimination proceeding through a five-membered transition state, because the results closely resembled those from Cope pyrolysis of *sec*-butyldimethylamine oxide.[25] In both cases, 1-butene was twice as abundant as 2-butenes (about 60–80% *trans*). However, the butenes produced from the reduction of benzophenone to benzhydrol by *sec*-butyllithium, an unambiguous hydride transfer of the type being considered above, had a similar isomer distribution so that no conclusions were derivable from these data.

In summary, we feel that the free-radical cleavage–recombination mechanism[26] adequately explains the experimental results of many Wittig rearrangements of ethers although we do not claim that this is the exclusive pathway, nor can these conclusions be applied to rearrangements carried out under grossly different conditions (*e.g.*, in liquid ammonia or hydroxylic solvents or by varying the cation[12]).[4,5]

Experimetal Section[27]

Benzyl 1-Norbornyl Ether. 1-Norbornanol was prepared by Baeyer–Villiger oxidation[28] of phenyl 1-norbornyl ketone followed by ester saponification and had m.p. 145–150° (sealed tube) (lit.[29] m.p. 151–154° (sealed tube)). *Anal.* Calcd. for $C_2H_{12}O$: C, 74.95; H, 10.78. Found: C, 75.14; H, 10.66.

Benzyl norbornyl ether was prepared from the potassium salt of 1-norbornanol and benzyl chloride in dimethylformamide, according to the procedure of Lansbury and Pattison.[3b] The product showed no O–H absorption in the infrared spectrum but had bands at 8.78 (C–O stretch), 13.68 and 14.4 μ (aromatic proton bending vibrations). *Anal.* Calcd. for $C_{14}H_{18}O$: C, 83.12; H, 8.97. Found: C, 82.97; H, 8.79.

Phenyl-1-norbornylcarbinol. 1-Norbornyllithium was prepared according to Bixler and Niemann[30] from 1-chloronorbornane and lithium sand, then treated with excess benzaldehyde. Dilute acid hydrolysis and work-up gave the crystalline alcohol, m.p. 96° (from petroleum ether), in 69–83% yield. The infrared spectrum (Nujol mull) showed O–H stretching at 2.96, C–O stretching at 9.8 and

---

[21] G. M. Whitesides, D. Holtz, and J. D. Roberts, *J. Am. Chem. Soc.*, **86**, 2628 (1964).

[22] S. Sternhell, *Rev. Pure Appl. Chem.*, **14**, 15 (1964); H. Rottendorf and S. Sternhell, *Australian J. Chem.*, **17**, 1315 (1964).

[23] We thank Professor S. J. Cristol for unpublished results on the synthesis of this compound.

[24] The α',β-mechanism predicts total loss of D; however, minor side reactions such as α-elimination followed by carbene rearrangement or *trans*-β-elimination could account for the residual deuterium. In fact the occurrence of some *trans*-β-elimination is indicated from the Wittig rearrangement of *trans*-3-deuteriodibenzobicyclo[2.2.2]octadien-2-ol. In this reaction the recovered dibenzobicyclo[2.2.2]octatriene-2-*d* contained *ca.* 16% less deuterium than the starting ether.

[25] A. C. Cope, N. A. LeBel, H. H. Lee, and W. R. Moore, *J. Am. Chem. Soc.*, **79**, 4720 (1957).

[26] A similar interpretation has recently been proposed for the Meisenheimer rearrangement of amine oxides to hydroxylamines: U. Schollkopf, M. Patsch, and H. Schafer, *Tetrahedron Letters*, **No. 36**, 2515 (1964).

[27] Melting points and boiling points are uncorrected. Infrared spectra were obtained on a Beckman IR5-A spectrometer and n.m.r. spectra on the Varian A-60 spectrometer in deuteriochloroform, unless otherwise stated, with tetramethylsilane as internal standard. Gas-liquid partition chromatography analyses were made on an F and M Model 300 instrument using helium as carrier gas. Elemental analyses were by Dr. A. Bernhardt, Mulheim, Germany, except those for deuterium (by Mr. J. Nemeth, Urban, Ill.). All alumina used for column chromatography was Merck chromatography grade aluminum oxide. The petroleum ether used was the 30–60° boiling range fraction.

[28] M. F. Hawthorne, W. D. Emmons, and K. S. McCallum, *J. Am. Chem. Soc.*, **80**, 6393 (1958).

[29] W. Whelan, Jr., Ph.D. Thesis, Columbia University, 1952.

[30] R. L. Bixler and C. Niemann, *J. Org. Chem.*, **23**, 742 (1958).

10, and aromatic hydrogen out-of-plane bending at 14.25 μ. *Anal.* Calcd. for $C_{14}H_{18}O$: C, 83.12; H, 8.97. Found: C, 82.98; H, 8.84.

1-Norbornyl Phenyl Ketone. 1-Norbornylphenylcarbinol was oxidized with chromium trioxide–acetic acid using the procedure of Pattison[31] for the oxidation of 1-apocamphylphenylcarbinol to give 80% yield of 1-norbornyl phenyl ketone, b.p. 103.5–104° (0.3 mm.), which solidified to a low-melting solid, m.p. 35°. Over-all yields from 1-chloronorbornane to 1-norbornyl phenyl ketone were 50%. The infrared spectrum (neat) was free of O–H absorption (2.8–3.1-μ region) and exhibited carbonyl stretching at 6.0 and aromatic protons at 14.15 and 14.95 μ. *Anal.* Calcd. for $C_{14}H_{16}O$: C, 83.96; H, 8.05. Found: C, 84.05; H, 8.01.

Benzyl 1-Bicyclo[2.2.2]octyl Ether. 1-Bromobicyclo[2.2.2]octane was prepared by the method of Whelan.[29] To prepare the ether, 2.5 g. (0.05 mole) of 50% sodium hydride (Nujol dispersion) was dissolved in 150 ml. of benzyl alcohol and the solution was stirred until gas evolution ceased. At this time 9.71 g. (0.051 mole) of 1-bromobicyclo[2.2.2]octane and 17.0 g. (0.10 mole) of silver nitrate were added. The mixture was stirred for 17 hr. at room temperature, for 3 hr. at 50°, and then filtered and diluted to *ca.* 500 ml. with ether. The ether solution was washed with water (two 100-ml. portions) and saturated sodium chloride solution (two 100-ml. portions), then dried over sodium sulfate before distillation of the solvent. The benzyl alcohol was removed *in vacuo* (50 mm.) and the residue was chromatographed over alumina. Elution with 10% ether–90% petroleum ether afforded 2.51 g. (23%) of the desired ether, whose infrared spectrum (neat) was free of O—H and >C═O absorption, showing C—O stretching at 9.05 and aromatic C—H bending at 13.65 and 14.4 μ. *Anal.* Calcd. for $C_{15}H_{20}O$: C, 83.31; H, 9.29. Found: C, 83.15; H, 9.26.

Preparation of 1-Bicyclo[2.2.2]octylphenylcarbinol. 1-Bicyclo[2.2.2]octyllithium prepared in cyclohexane from the corresponding chloride (5.5 mmoles) and excess lithium sand according to the method of Sayigh[32] was treated with benzaldehyde (5.5 mmoles) to give the desired carbinol after work-up as above for the norbornylcarbinol. The alcohol exhibited identical v.p.c. behavior as that obtained from rearrangement of benzyl 1-bicyclo[2.2.2]octyl ether and the infrared spectra (partly crystallized on a salt plate) of the two carbinols were identical. The major bands in the infrared spectrum were O–H stretching at 2.94, C–O stretching at 9.66 and 9.83, and out-of-plane bending of aromatic protons at 14.05 and 14.3 μ. The analytical sample had m.p. 107–109° (petroleum ether). *Anal.* Calcd. for $C_{15}H_{20}O$: C, 83.31; H, 9.29. Found: C, 83.17; H, 9.30.

General Procedure for Wittig Rearrangements. The rearrangements discussed in this paper were carried out according to previously published techniques[3] except where noted otherwise. The substrate ether, dissolved in tetrahydrofuran, was treated with *ca.* 5 molar equiv. of methyllithium in diethyl ether solvent (final solvent composition usually *ca.* 1:1 tetrahydrofuran–ether) for periods of 1–2 days. Hydrolysis was followed by v.p.c. analysis[3] of product mixtures using appropriate authentic samples.

The reaction mixture containing benzyl 1-norbornyl ether (1.02 g., 5 mmoles) and excess methyllithium in tetrahydrofuran–ether was decomposed with 1.5 ml. of deuterium oxide before conventional hydrolysis and work-up. Chromatography over alumina gave 0.47 g. of recovered ether whose n.m.r. spectrum showed only *ca.* one benzylic proton. In addition, 0.31 g. of 1-norbornanol was obtained, apparently from α-elimination,[33] and a small amount of unidentified material, probably from the latter reaction. Vapor phase chromatographic analysis of the crude hydrolysis product revealed that phenyl-1-norbornylcarbinol, norbornane, and stilbene were not present in detectable amounts (*i.e.*, ≥0.5%).

Using the same conditions as above, benzyl 1-bicyclo[2.2.2]-octyl ether gave 36% of bicyclooctylphenylcarbinol and small amounts of 1-bicyclooctanol, recovered ether, and unidentified product.

1-Bicyclo[2.2.1]heptyl Iodide. This iodide was synthesized by the reaction of 1-norbornyllithium, prepared as above,[27] with an equimolar quantity of iodine dissolved in ether at 0°. After hydrolysis, the ether layer was washed with aqueous sodium thiosulfate, water, and salt solution. After drying over sodium sulfate and removal of solvent at atmospheric pressure through a 10-in. helices-packed column, the residue was fractionated at reduced pressure, giving 65% (7.19 g.) of bicycloheptyl iodide, b.p. 75° (10 mm.). *Anal.* Calcd. for $C_7H_{11}I$: C, 37.86; H, 4.99. Found: C, 37.84; H, 5.02.

1-Bicyclo[2.2.2]octyl Iodide. This iodide was prepared from 1-hydroxymethylnorbornane[32] (3.5 g.), hydriodic acid (37.8 g. of 49% HI), and zinc iodide (31.2 g.) by heating at 90–110° for 22 hr., similar to Sayigh's procedure for making the corresponding chloride and bromide.[32] The product was extracted by petroleum ether, washed, and dried over sodium sulfate. After solvent distillation the residue was chromatographed over alumina with petroleum ether as eluent (to remove traces of alcohol) and finally the product was distilled over a short path, b.p. 65° (1.5 mm.), yield 2.9 g. (45%). The simple infrared spectrum (neat) had strong bands at 10.36, 12.4, and 15.6 μ. *Anal.* Calcd. for $C_8H_{13}I$: C, 40.70; H, 5.55. Found: C, 40.77; H, 5.52.

General Procedure for Lithium–Iodide Exchange Reactions. In typical exchange reactions, equimolar amounts (usually 1–2 mmoles) of alkyllithium reagent and alkyl iodide were reacted at −70° in 1:2 ether–petroleum ether (total volume *ca.* 5 ml.) for 3–5 min. in nitrogen-flushed flasks equipped with magnetic stirrers and rubber-capped side arms for hypodermic injection of reagents. The exchange mixtures were then quenched at −70° with excess benzaldehyde and worked up as described previously.[7,34] In experiments where 1-bicyclo[2.2.2]octyllithium was the initial lithium alkyl, it was itself generated from *t*-butyllithium (Lithium Corporation of America) and bicyclooctyl iodide, since this exchange was shown to go entirely to the bicyclic lithium reagent (Table III, run 3). This mode of generating this reagent was vastly superior to the direct synthesis from the halide and lithium metal, which gives mainly coupling product.

The exchange results are given in Table III of the discussion. Yields of carbinol(s) were generally 60–90%, based on available alkyllithium. However, when 1-adamantyl iodide was exchanged with 1 mole of *t*-butyllithium, the yield of alcohols (after benzaldehyde quenching) was quite low (*ca.* 30–35%) because of the facile coupling of 1-adamantyllithium with initially present 1-adamantyl iodide to give 1,1′-diadamantane.

Benzyl Ether of *cis*-3-Deuteriodibenzobicyclo[2.2.2]octadien-2-ol. The procedure of Cristol and co-workers[23] was used. Ten grams (49 mmoles) of dibenzobicyclo[2.2.2]octatriene and 0.84 g. (20 mmoles) of lithium aluminum deuteride in 100 ml. of ether were stirred at reflux under nitrogen while 5.0 ml. of boron trifluoride etherate, dissolved in ether, was added gradually. After 24 hr. of reflux, the reaction mixture was hydrolyzed with sodium hydroxide and hydrogen peroxide. From an ether extract of the product, evaporation and chromatography over alumina using chloroform as eluent afforded the alcohol in 56% yield, m.p. 147–148° (from ether) (lit.[20] m.p. 147–148°).

The ether was prepared from equimolar amounts of the alcohol and sodium hydride (50% in Nujol) in refluxing toluene followed by the addition of benzyl chloride after H_2 evolution had ceased. After refluxing overnight, the mixture was poured into ice water and extracted into ether. The ether solution was dried over magnesium sulfate, then evaporated, yielding 46% of the desired ether, m.p. 112.5–113.5° (ether–petroleum ether). *Anal.* Calcd. for $C_{23}H_{20}O$: C, 88.42; H, 6.45. Found: C, 88.4; H, 6.41.

Rearrangement of the Benzyl Ether of *cis*-3-Deuteriodibenzobicyclo[2.2.2]octadien-2-ol. Three grams (9.6 mmoles) of the above ether was dissolved in 10 ml. of tetrahydrofuran and cooled to −70°. Twenty milliliters (15.2 mmoles) of methyllithium in tetrahydrofuran was added and the reaction was allowed to warm to 0° for 23 hr. Hydrolysis and work-up in the usual manner,[3] followed by alumina chromatography, gave 0.215 g. (11%) of pure dibenzobicyclo[2.2.2]octatriene, m.p. 114.5–115.5°, by elution with petroleum ether. The major product was the rearranged alcohol and it was eluted subsequently with benzene–petroleum ether. The recovered olefin contained 0.156 D/molecule, corresponding to 17% retention of deuterium.

Rearrangement of Di(α-methylbenzyl) Ether. To 1.49 g. (0.0066 mole) of di(α-methylbenzyl) ether in 52 ml. of THF, 13.8 ml. of 2.4 *N* *n*-butyllithium in hexane (0.033 mole) was added and the reaction was stirred for 27.5 hr. After typical work-up the ether solution was concentrated by distillation (to reduce possibility of losing any methylphenylcarbinol or styrene which may have been present)

---

(31) V. A. Pattison, Ph.D. Thesis, State University of New York at Buffalo, 1963.

(32) A. Sayigh, Ph.D. Thesis, Columbia University, 1952.

(33) Similarly *ca.* 32% of 1-apocamphanol was obtained from reaction of 1-apocamphyl benzyl ether with methyllithium in THF and no 1-apocamphylphenylcarbinol was formed (ref. 3a).

(34) P. T. Lansbury, V. A. Pattison, W. A. Clement, and J. D. Sidler, *J. Am. Chem. Soc.*, **86**, 2247 (1964).

and analyzed using a F & M Model 720 gas chromatograph with an 8-ft., 20% SE-52 column. No methylphenylcarbinol could be detected. It was possible using this instrument and column to separate methylphenylcarbinol from any other components if it had been present. The material from the rearrangement was then chromatographed over 40 g. of alumina. Petroleum ether and 10% ether–90% petroleum ether eluted 0.757 g. (51%) of recovered ether while 30% ether–70% petroleum ether and 40% ether–60% petroleum ether eluted 0.579 g. (39%) of 2,3-diphenyl-2-butanol. The first cut of the above alcohol solidified and was recrystallized once from petroleum ether to give material, m.p. 72.0–75.5° (lit.[35] for the higher melting isomer, m.p. 83.5–84.5°).

A sample of this recrystallized material was purified by preparative v.p.c. Its n.m.r. spectrum (CCl_4) was in complete accord with the structure for the expected rearrangement product: multiplet at 7.22 (aromatic protons, area 10), quartet at 3.04 (J = 7.0 c.p.s., benzylic proton. area 1), singlet at 1.48 (hydroxyl proton, area 1), singlet at 1.27 (methyl protons, area 3), and doublet at 1.06 p.p.m. (J = 7.0 c.p.s., methyl protons split by the benzylic proton, area 3).

Rearrangement of Benzyl α-Methylbenzyl Ether. In the usual manner 2.29 g. (0.01 mole) of benzyl α-methylbenzyl ether[21] dissolved in 40 ml. of THF was treated with 31 ml. of 1.6 N methyllithium in ether (0.05 mole). After 1 hr. the reaction was quenched by addition of 2 g. of deuterium oxide. The reaction was extracted with ether and washed with water. The residue left after evaporation of the solvent, which had been dried over sodium sulfate, was chromatographed over 43 g. of alumina. Petroleum ether and 10% ether–90% petroleum ether eluted 1.46 g. (64%) of the starting ether while 30% ether–70% petroleum ether and 40% ether–60% petroleum ether eluted 0.55 g. (24%) of the isomeric alcohols from rearrangement.

Of the alcohols isolated 0.55 g. (19%) was 1,2-diphenyl-2-propanol[36] while the remaining 81% was essentially a 50:50 mixture of *erythro-* and *threo*-1,2-diphenyl-1-propanol. These components were verified by having infrared spectra and v.p.c. behavior identical with those of authentic samples. The amounts of the various isomers were determined by comparison with known mixtures of the authentic samples. This indicates a 4:1 preference for metalation at the unsubstituted benzylic position.

If metalation is relatively fast compared to rearrangement one would expect to have metalated ether present in the reaction mixture when it was quenched with deuterium oxide. This would lead to incorporation of deuterium into the benzylic position of the recovered ether. Thus the recovered ether was subjected to n.m.r. analysis. Within the limits of error, integration of the signal from the benzylic protons (compared to the aromatic protons as an internal standard) indicated *no* deuterium in the benzylic position of the recovered ether.

Acknowledgments. We are grateful to the U. S. Army Research Office (Durham) for generous support of these investigations. We also appreciate a gift of 1-adamantanol from Professor Paul von R. Schleyer.

---

(35) W. R. Brasen, S. W. Kantor, P. S. Skell, and C. R. Hauser, *J. Am. Chem. Soc.*, **79**, 397 (1957).

(36) F. A. Elhafez and D. J. Cram, *ibid.*, **75**, 339 (1953).

The Michael Reaction in Nonalkaline Media. IV. Kinetics and Mechanisms of the Reactions in the Nitroform–Methyl Acrylate System

Lloyd A. Kaplan and Donald J. Glover

Contribution from The Organic Chemistry Division, U. S. Naval Ordnance Laboratory, Silver Spring, Maryland 20910. *Received August 16, 1965*

Abstract: The kinetics of the addition of nitroform to methyl acrylate to form methyl 4,4,4-trinitrobutyrate and methyl 4,4-dinitro-2-hydroxybutyrate in 50% dioxane have been studied in the presence of perchloric acid and in acetic acid–acetate buffers. The reaction forming methyl 4,4,4-trinitrobutyrate was found to be subject to general acid catalysis. In acetic acid–acetate buffers the mechanism involves a rapid and reversible addition of trinitromethide ion to the double bond of methyl acrylate followed by a rate-determining protonation of the resulting carbanion intermediate to form methyl 4,4,4-trinitrobutyrate. In perchloric acid solutions, the rate of protonation gradually increases as the acidity of the medium increases until the formation of the intermediate carbanion becomes rate determining. The reaction forming methyl 4,4-dinitro-2-hydroxybutyrate was found to compete for the intermediate carbanion with the protonation of this intermediate to methyl 4,4,4-trinitrobutyrate. The rate of formation of the α-hydroxy ester is kinetically first order in the intermediate carbanion and inversely proportional to the acidity. From the kinetic data and the results of synthetic scale experiments in dioxane–H_2O^{18}, a mechanism for the formation of this product from the intermediate carbanion is suggested.

Previous communications in this series[1,2] have shown that the addition of nitroform to methyl acrylate produced a number of products in addition to the expected Michael adduct, methyl 4,4,4-trinitrobutyrate (MeTNB). The yields of the various products appeared to be dependent upon the acidity and solvent composition of the reaction medium. In a recent report,[3] the reaction sequence for this complex system was elucidated. In an aqueous dioxane–acetic acid–acetate buffer, the reaction proceeded as in Scheme I. The primary products of this reaction are methyl 4,4,4-trinitrobutyrate, (MeTNB) and a nitrite elimination product, methyl 4,4-dinitro-2-hydroxybutyrate (DNS). Depending upon the specific reaction conditions, each of these primary reaction products can undergo further reaction. Methyl 4,4,4-trinitrobutyrate loses the elements of nitrous acid to form methyl 4,4-dinitro-2-butenoate (DNU), and DNS acts as the addend in a Michael addition to a second mole of

---

(1) L. A. Kaplan and M. J. Kamlet, *J. Org. Chem.*, **27**, 780 (1962).

(2) M. J. Kamlet and L. A. Kaplan, *ibid.*, **28**, 2128 (1963).

(3) L. A. Kaplan, *ibid.*, **29**, 2256 (1964).