337 (100), 208 (80). **15b** (oil): *m/e* (relative intensity) GC/MS 222 (M^+, 44), 207 (100), 194 (32), 193 934), 192 (37), 165 (5).

Reaction of 4,7-Dichloroquinoline (16) with Enolate 2. Procedure A (30-min irradiation) gave a yellow solid. Chromatography on TLC silica gel (short column, hexane–ethyl acetate eluant) produced **17** as a white solid, mp 108–110 °C (from hexane).

Reaction of 2,6-Dichloropyrazine (18) with Enolate 2. Procedure B gave a yellow oil. GC analysis indicated >99% of 2-(3,3-dimethyl-2-oxobutyl)-6-chloropyrazine (**19**). Procedure B, using 15 mol % of DTBN, gave a 90% yield of **19**, which was isolated as a light yellow oil by chromatography on a PTLC plate (40:60 CH_2Cl_2–hexane).

Reaction of 2,3-Dichloropyrazine (20) with Enolate 2. Procedure B gave a red oil which was largely 2-(3,3-dimethyl-2-oxobutyl)-3-chloropyrazine (**21**). GC analysis indicated a 71% yield. An analytical sample was isolated as a light yellow oil by preparative GC. No disubstitution product could be isolated. Repeating procedure B with 15 mol % DTBN gave a 70% yield (GC) of **21**.

Reaction of 2,3-Dichloropyrazine (20) with Diisopropyl Ketone Enolate 22. Procedure B (employing 23.0 mmol of **22**) gave a red tar containing (GC analysis) 2% of 2-(1,1,3-trimethyl-2-oxobutyl)pyrazine (**25**), 20% of 2-chloro-3-(1,1,3-trimethyl-2-oxobutyl)pyrazine (**23**) as an oil, pyrazino[2,3-*c*]-2,2,5,5-tetramethylcyclopentanone (**24**, mp 78 °C); and 5% of 2,4,4,6,8-pentamethyl-3,7-dioxononane (**26**). Repetition of procedure B with 10 mol % of DTBN present gave the following results (analysis by GC): **21**, 23%; **24**, 7%.

Reactions of 3,6-Dichloropyridazine (27) with Enolate 22. Procedures A, B, and A with 10 mol % of DTBN as inhibitor all gave the same results; a yellow oil was obtained in each case. Careful dilution of the oil with hexane and cooling below 30 °C gave an unstable white solid which could not be fully characterized but appeared to be **28**: mp 50 °C dec; ^1H NMR δ 3.0 (m, 4 H, CH_2, and CH), 1.20 (m, 12 H, CH_3). Allowing an ethereal solution of this crude product to stir with wet silica gel for 24 h gave a mixture of products isolated by PTLC (60:40 ether–hexane). These compounds were identified as 4-(1,3-dimethyl-2-oxobutyl)-6-chloro-4,5-dihydropyridazin-3-one (**29**, mp 133 °C) and 5-(1,3-dimethyl-2-oxobutyl)-6-chloro-4,5-dihydropyridazin-3-one (**30**), mp 131–133 °C.

Reactions of 2,4-Dichloropyrimidine (31) with 12a. Procedure A gave a yellow oil. Chromatography on 50 g of silica gel afforded 2-chloro-4-(α-cyanobenzyl)pyridine (**32**) as a clear oil which crystallized over a period of several days to give a white solid: 58% yield; mp 64–66 °C MS, *m/e* (relative intensity) 231 (M^+, 46), 229 (M^+, 100), 228 (97), 204 (14), 203 (18), 202 (38), 194 (30), 193 (21), 167 (17), 166 (15), 141 (17), 140 (27), 116 (32), 113 (17). Procedure B or procedure A with 10 mol % of DTBN returned starting materials.

Acknowledgment. We are grateful to Prof. Thomas M. Harris of Vanderbilt University for suggesting and helping to carry out the proton-decoupling experiments.

Registry No. **1a**, 626-05-1; **1c**, 2402-77-9; **1d**, 2457-47-8; **1e**, 624-28-2; **2**, 55440-76-1; **3b**, 84960-21-4; **3c**, 84960-22-5; **3d**, 84960-23-6; **10a**, 82545-62-8; **10b**, 84960-24-7; **11a**, 84960-25-8; **11b**, 84960-26-9; **12a**, 75782-32-0; **12b**, 84960-27-0; **13a**, 84960-28-1; **13b**, 84960-29-2; **14a** (isomer 1), 84960-30-5; **14a** (isomer 2), 84960-31-6; **14b** (isomer 1), 84960-32-7; **14b** (isomer 2), 84960-33-8; **15b**, 19395-42-7; **16**, 86-98-6; **17**, 84960-34-9; **18**, 4774-14-5; **19**, 84960-35-0; **20**, 4858-85-9; **21**, 84960-36-1; **22**, 84960-37-2; **23**, 84986-92-5; **24**, 84960-38-3; **25**, 75782-31-9; **26**, 65738-41-2; **27**, 141-30-0; **28**, 84960-39-4; **29**, 84960-40-7; **30**, 84960-41-8; **31**, 3934-20-1; **32**, 84960-42-9.

Supplementary Material Available: ^1H NMR, IR, and analytical data for all new compounds (3 pages). Ordering information is given on any current masthead page.

Carbanion Photochemistry. 7. The $S_{RN}1$ vs. S_{ET} Photoarylation of Triphenylmethyl Anion[1]

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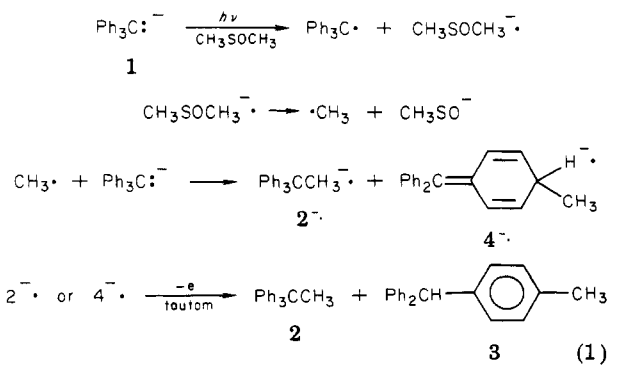
Received July 13, 1982

Irradiation of (triphenylmethyl)lithium in tetrahydrofuran containing bromobenzene, iodobenzene, or diphenyl sulfoxide produced three major products: tetraphenylmethane (TPM), biphenylyldiphenylmethane (BDM), and 2-(triphenylmethyl)tetrahydrofuran (TTF). The product composition was a function of anion and acceptor concentration and reflected the competition among solvent, triphenylmethyl anion, and triphenylmethyl radical. Product composition studies thus provide detailed information about the key steps in the mechanism.

Carbon–carbon bond-forming reactions that proceed via a preliminary electron-transfer step are now recognized as being an extremely important class of reactions, both synthetically and mechanistically. We have been particularly interested in that subset of these reactions which proceed through the intervention of a photochemically excited resonance-stabilized carbanion. Irradiation of triphenylmethyl ("trityl") anion (**1**) in dimethyl sulfoxide leads to efficient formation of two primary products, 1,1,1-triphenylethane (**2**) and *p*-tolyldiphenylmethane (**3**), through a mechanism involving initial electron transfer (see Scheme I).[2] Although this mechanism involves steps that are also involved in the radical chain mechanism known as the $S_{RN}1$ mechanism,[3] it differs in three important respects. First, no chain mechanism is observed. Second,

Scheme I



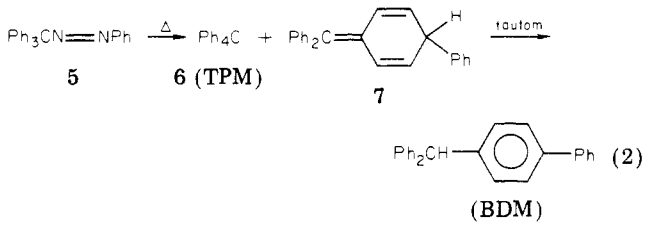
(1) For our previous paper, see: Tolbert, L. M.; Siddiqui, S. *J. Am. Chem. Soc.* **1982**, *104*, 4273.
(2) Tolbert, L. M. *J. Am. Chem. Soc.* **1980**, *102*, 6808.

0022-3263/83/1948-1185$01.50/0

no radical–radical recombination products are observed. Third, products of "abnormal" regiochemistry result, that is, alkylation of a site other than that bearing the formal negative charge. This is in contrast to the $S_{RN}1$ arylation of enolates. For these reasons, we felt that an understanding of the basis for these differences would be provided by investigating the case in which the electron acceptor is the same, i.e., the photoarylation of triphenylmethyl anion by aryl halides.

Background

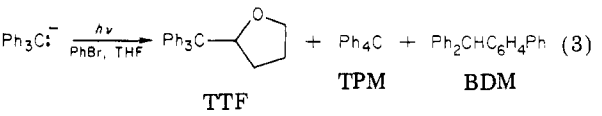
We have attributed the formation of para-alkylated products from trityl anion photomethylation to the intervention of the delocalized radical anion $4^{-}\cdot$, which partially compensates for the loss of aromaticity through a substantially lower energy for the π^* orbital containing the odd electron.[2] That is, while reaction of methyl radical with trityl anion produces both α and para products in an approximately 3:1 ratio, reaction of methyl radical with the trityl radical produces exclusively the α product 1,1,1-triphenylethane. Since phenyl radical and trityl radical combine to give para and α products[4] (see eq 2),



the demand for the more aromatic α intermediate is less, presumably because of steric factors. We might expect radical anion stabilization of an intermediate of type **7** to provide even further impetus for formation of the abnormal para product. In the course of other investigations, we made the somewhat startling observation that even when a more stable radical anion intermediate is available, radicals tend to attack the more basic carbanion center.[5] In fact the presence of the para-methylated product in the photomethylation may reflect the greater electron density in the ring carbons of the triphenylmethyl anion,[6] although some contribution of steric hindrance at the α position from the contact ion pair may contribute. At these concentrations, triphenylmethyllithium will still exist predominantly as the solvent-separated species. In any event, we anticipated that when alternative regiochemistries are finely balanced, as is the case for phenyl, radical anion stabilities could be the overriding factor.

Results: Preparative Irradiations

When 0.1 M solutions of triphenylmethyllithium in tetrahydrofuran containing equimolar concentrations of bromobenzene were irradiated with visible light, the two hydrocarbon producdts tetraphenylmethane (TPM) and biphenylyldiphenylmethane (BDM) were formed in a 1:2 ratio and in 10% overall yield. The major product, produced in 30% yield, proved to be 2-(triphenylmethyl)-tetrahydrofuran (TTF) (see eq 3). The major product



clearly involves hydrogen abstraction from tetrahydrofuran by phenyl radical and is in marked contrast to the complete absence of hydrogen abstraction when dimethyl sulfoxide is the solvent. Benzene, the byproduct of this reaction, could also be detected in amounts commensurate with TTF formation. Finally, an additional product (<5%) with gas chromatographic retention time similar to TTF was not isolated, but NMR analysis of crude mixtures indicated this to be an additional solvent adduct, apparently the *p*-triphenylmethyl product.

Confirmation of the structure of TTF was determined by spectral analysis and established by independent synthesis. Thus addition of tritylllithium to a tetrahydrofuran solution of 2-chlorotetrahydrofuran,[7] obtained from free radical chlorination of tetrahydrofuran, yielded a single adduct in low yield. This product was identical in all respects with that obtained from the photochemical synthesis (see eq 3).

BDM and TPM were also produced when triphenylmethyl anion was irradiated with bromobenzene in the presence of liquid ammonia. Thus a 30-mL solution of 1.6 mmol of triphenylmethyl anion generated from triphenylmethane and 1.6 mmol of lithium amide in liquid ammonia produced BDM and TPM in overall 15.3% yield and a ratio of 1.86 after 7 min of irradiation. In contrast, a similarly prepared solution allowed to stand for 30 min without irradiation produced the same products in 6.7% yield but 0.52 ratio. Finally, a control experiment in which the base concentration was doubled produced both products in 23% yield and 0.36 ratio.

Discussion: Mechanism of Triphenylmethyl Anion Arylation

The varying yields of BDM and TPM produced in liquid ammonia in the irradiated and unirradiated experiments are in accord with a competitive photostimulated $S_{RN}1$ mechanism and a ground-state benzyne mechanism. The benzyne mechanism favors TPM formation, presumably because of a kinetic preference for arylation of the site of greater electron density by the electrophilic benzyne molecule. Because of the complications induced by the presence of the competing benzyne reaction, our purposes appeared to be better served by examining the reaction in tetrahydrofuran.

The results from the preparative irradiation of trityl anion in tetrahydrofuran are consistent with carbon–carbon bond formation via an $S_{RN}1$ mechanism. In particular, the formation of BDM in a 3:1 ratio over TPM clearly reflects the intervention of a radical anion intermediate. Thus by analogy with the mechanistic steps outlined by Russell, Kornblum, and Bunnett,[3] we propose the following mechanistic scheme shown in Scheme II, which also takes into account solvent incorporation.

There are two possible modes of product formation. The first involves combination of phenyl radical with triphenylmethyl anion. The second involves combination of phenyl radical with triphenylmethyl radical. This mode is a chain-termination step and diverts the process into an S_{ET} pathway.[8] That product formation does not proceed

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(4) Bentrude, W. G.; Fu, J.-J. L. *J. Am. Chem. Soc.* **1972**, *94*, 7710.

(5) (a) Tolbert, L. M. *J. Am. Chem. Soc.* **1980**, *102*, 3531. (b) Tolbert, L. M.; Siddiqui, S. *Tetrahedron* **1982**, *38*, 1079.

(6) House, H. O.; Weeks, P. D. *J. Am. Chem. Soc.* **1975**, *97*, 2785.

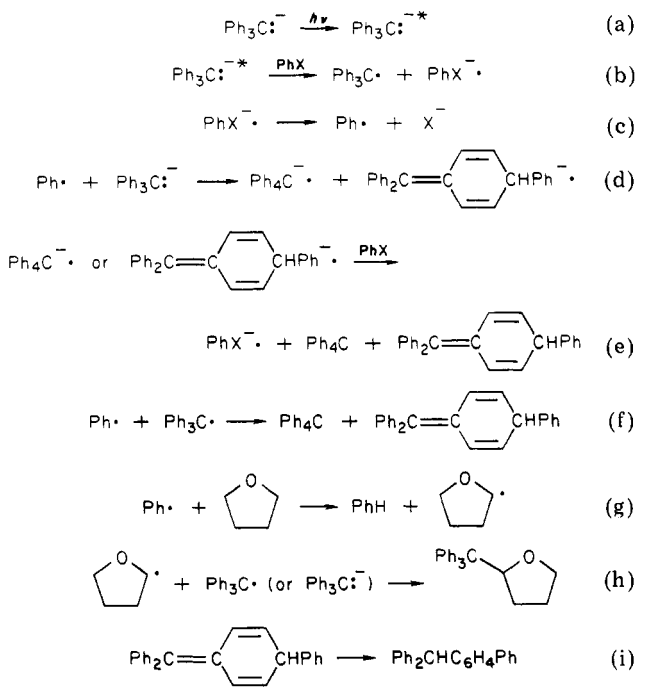
(7) Hort, J.; Kratochvil, M. *Collect. Czech. Chem. Commun.* **1962**, *27*, 52.

Table I. Yields[a] of Phenylated Products

entry[b]		starting materials [BuLi]	starting materials [PhX]	% conversion	products, % TPM	BDM	TTF	BDM/TPM[c]
BuLi, 15 min	1 (2)	0.04	0.04	3[d]	11.5	28.8	47.5	2.51
	2 (4)	0.03	0.04	3[d]	10.4	24.0	48.6	2.32
	3 (1)	0.02	0.04	3[d]	8.4	21.2	53.3	2.51
	4 (1)	0.02	0.05	3[d]	10.0	23.1	62.2	2.31
PhBr, 15 min	5 (1)	0.04	0.09	3[d]	14.3	32.8	36.9	2.29
	6 (1)	0.04	0.22	3[d]	17.3	36.7	30.7	2.12
	7 (1)	0.04	0.42	3[d]	21.2	36.6	29.3	1.72
PhBr, 5 min	8 (4)	0.04	0.04	1.4	9.3	31.1	56.8	3.34
PhI, 5 min	9 (4)	0.04	0.04	2.3	11.1	33.9	51.3	3.05
	10 (2)	0.04	0.09	3.3	12.7	34.9	40.7	2.75
	11 (2)	0.04	0.22	5.0	12.4	34.4	41.8	2.77
	12 (2)	0.04	0.42	5.2	13.2	32.8	49.0	2.50
Ph_2SO, 15 min	13 (3)	0.04	0.04	0.7	4.2	15.5	77.6	3.73
	14 (3)	0.04	0.09	0.5	4.8	17.4	75.8	3.62
	15 (1)	0.04	0.22	0.6	5.3	18.3	74.5	3.49
	16 (1)	0.04	0.43	0.8	8.6	25.7	65.7	3.00

[a] All entries are subject to a ±10% relative error. [b] Numbers in parentheses represent number of runs. [c] ±14% relative error. [d] Estimated.

Scheme II



via the second mode to a major extent is indicated by the ratio of BDM to TPM, which provides a "fingerprint" of mechanism. Thus independent generation of phenyl radical in the presence of triphenylmethyl radical generated via thermal decomposition of (phenylazo)triphenylmethane (PAT) leads to a BDM/TPM ratio of 1.0,[4] in contrast to the observed ratio of 2.9. Even assuming TPM is formed exclusively via the radical–radical pathway, this S_{ET} pathway cannot account for more than 50% of the mechanism.

Additional information is provided by the presence of the trityl adduct TTF. Presumably the yield of this product is dependent upon the relative rate of reaction of phenyl radical with trityl anion (or radical) and with tetrahydrofuran. Thus we would expect increased yields of TPM and BDM in the presence of larger trityl anion or trityl radical concentrations. Under the preparative conditions described here, the solvent adduct is present in slightly higher amounts due to the much larger concentration of THF relative to triphenylmethyl anion. A careful analysis of the product composition as a function of anion concentration, acceptor concentration, and leaving group should provide detailed information about the competition between product-forming steps outlined above. Our results are outlined below.

Results

A. Anion Concentration Studies. Solutions of triphenylmethyl anion generated from triphenylmethane and varying amounts of butyllithium were treated with a constant amount of bromobenzene and subjected to visible light irradiation using a merry-go-round apparatus. The irradiation was carried out to ca. 5% conversion, and the products were analyzed by gas chromatography using independently prepared materials for comparison of retention times. The products are reported as percentages of products rather than absolute yields and entered in Table I as entries 1–4. Significantly, the yield of solvent adduct increased from 46% to 62% of the product mixture as anion concentration decreased by a factor of 3. The ratio of BDM to TPM, however, increased slightly from 2.4 ± 0.1.

B. Bromobenzene Studies. Solutions of triphenylmethyl anion were prepared as above by treating 1.6 mmol of triphenylmethane in 35 mL of tetrahydrofuran with 1.6 mmol of butyllithium. Amounts of bromobenzene varying from 1 to 10 equiv were added, and the solutions were irradiated as above. Analysis by gas chromatography yielded the values entered in Table I as entries 5–8. Both a *decrease* in TTF and in the BDM/TPM ratio were noted as bromobenzene concentration increased.

C. Iodobenzene Studies. With iodobenzene as the electron acceptor, the experiments in part B were repeated. Two solutions with 1 equiv each of bromobenzene served as standards. Again, irradiations were carried out to low conversion. The results of increasing iodobenzene concentration are listed as entries 9–12. Entry 13 is the control experiment with bromobenzene. Three features of these data are significant. First, the competition between solvent adduct and BDM + TPM formation was of the same magnitude as those for bromobenzene. Second, the BDM/TPM ratio was much less subject to acceptor concentration. Third, the reaction was twice as efficient with iodobenzene as with bromobenzene.

D. Diphenyl Sulfoxide Studies. The experiments in part B were repeated with diphenyl sulfoxide instead of

(8) Russell, G. A.; Jawdosuik, M.; Makosza, M. *J. Am. Chem. Soc.* **1979**, *101*, 2355.

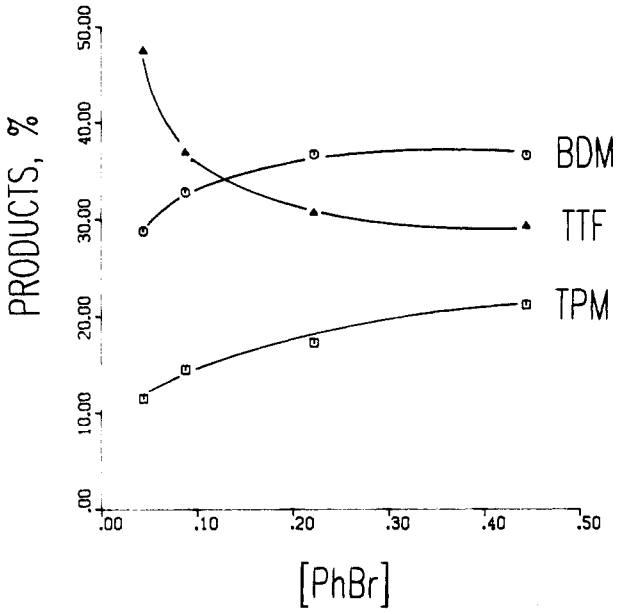


Figure 1. Effect of bromobenzene concentration.

bromobenzene. An additional tube containing 1.6 mmol of bromobenzene served as a control. The product distributions as a function of acceptor concentration are listed in Table I. Overall, conversions are much lower, the yield of TTF relatively higher, and the BDM/TPM ratio the highest of the four sets of conditions. Significantly, the amount of dibenzothiophene (see below) was in all cases negligible.

Discussion

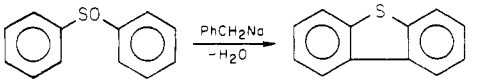
Competitive Product Formation and Identity of Product-Forming Steps. Variation of the concentrations of the species present in solution during irradiation of triphenylmethyllithium has a pronounced effect on the product distribution, which can be seen graphically for the bromobenzene case illustrated in Figure 1. This indicates that different mechanistic pathways are competing. Careful analysis of this product distribution, therefore, allows a delineation of the importance of the various pathways that are either chain-carrying or chain-terminating steps in the $S_{RN}1$ reaction.

The effect of diminishing anion concentration of part A in increasing TTF formation clearly reflects the competition for phenyl radical between triphenylmethyl anion and tetrahydrofuran (steps d and g, respectively). That is, the trityl radical concentration at fixed bromobenzene concentration depends only upon light intensity. As triphenylmethyl anion concentration diminishes, solvent becomes more competitive and TTF increases. The fact that the BDM/TPM ratio remains relatively constant indicates that the radical anion mechanism accounts for the major part of the reaction pathway. That is, if step f accounted for an appreciable fraction of the product, as triphenylmethyl anion concentration decreased, the radical–radical (S_{ET}) pathway should account for a larger share of the products, which should be reflected in a BDM/TPM ratio approaching that obtained from (phenylazo)triphenylmethane decomposition, i.e., 1.0.

The effect of increasing bromobenzene concentration is an interesting one. The decrease in TTF yields and BDM/TPM ratio apparently reflect the same phenomenon. That is, increasing the bromobenzene concentration increases the number of photoexcited carbanions that are intercepted and thus increases the steady-state concentration of trityl radical. At higher trityl radical concentrations, the number of phenyl radicals that react by a radical–radical mechanism (step f) is increased, thus decreasing the number that are intercepted by THF and increasing the relative TPM yield.

The effect of iodobenzene in increasing product yield without altering the product ratios substantially is in accord with the onset of a chain mechanism. Thus product radical anion is able to transfer electrons more efficiently to iodobenzene (step e). As a results, phenyl radicals are produced in higher concentration, giving more efficient product formation. Furthermore, since this increase in unaccompanied by higher trityl radical concentrations, less of the reaction proceeds via a radical–radical mechanism and the BDM/TPM is even higher than with bromobenzene. In support of this conclusion, we note that solutions of trityl anion in the presence of iodobenzene rapidly turned blue in room light, indicating the formation of the biphenylyldiphenylmethyl anion. Such solutions were difficult to prepare without some initial conversion to products, although irradiations were carried out to an extent so as to overcome any errors introduced by prior reaction. An alternative explanation involves electron transfer to iodobenzene at longer distances so that radical–radical cage products are less important.

The relatively high amount of solvent adduct and high BDM/TPM ratios produced when diphenyl sulfoxide is the electron acceptor reflect the rather poor electron-accepting ability of diphenyl sulfoxide. Alternatively, the phenylsulfenate anion may be such a poor leaving group that back electron transfer becomes competitive. In any event, a significant steady-state concentration of trityl radicals is never attained, and the BDM/TPM ratio reaches its highest value, reflecting nearly total reaction via the radical anion pathway. Since the radical–radical pathway does not compete, significantly more solvent adduct is obtained through hydrogen-atom abstraction by phenyl radical. The lack of dibenzothiophene provides evidence that steps leading to benzyne are *not* involved, since proton abstraction from diphenyl sulfoxide would lead not to dibenzothiophene via the known dehydrative cyclization of eq 4.[9] The generation of phenyl radicals



(4)

from diphenyl sulfoxide is in contrast to Bunnett's results, which probably result from two-electron reduction in the heterogeneous reduction conditions employed by Bunnett.[10]

With all three electron acceptors, increasing the acceptor concentration increases the steady-state concentration of trityl radicals and the percentage of the reaction pathway going via the S_{ET} mechanism. As a consequence, TTF production and the BDM/TPM ratios decrease. Thus the production of TTF provides an index of the fraction of the reaction pathway going via radical–anion recombination. A scatter plot of BDM/TPM ratio vs. TTF yield, despite experimental errors due to taking ratios of experimental variables, is remarkably linear, even though quite different electron acceptors are used (see Figure 2). Thus we have a "left group effect",[11] which merely reflects the leaving group ability.

(9) (a) Fuchs, K. *Monatsh. Chem.* **1929**, *53*, 438–44. (b) Chaix, M.; Kelner, J. *C. R. Hebd. Seances Acad. Sci.* **1932**, *194*, 1837–9.
(10) Rossi, R. A.; Bunnett, J. F. *J. Am. Chem. Soc.* **1974**, *96*, 112.
(11) Tremelling, M. J.; Bunnett, J. F. *J. Am. Chem. Soc.* **1980**, *102*, 7375.

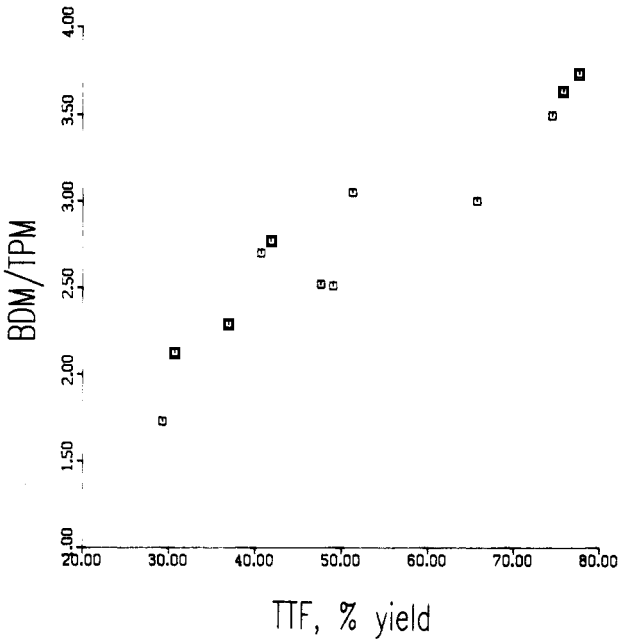


Figure 2.

Conclusions

The reaction of radicals with enolates and other carbanions stabilized by strongly electron-withdrawing groups generally yields exclusively the product of C-alkylation or -arylation, reflecting attack at the more basic center. With resonance-stabilized carbanions, in which the ambident nature of the nucleophiles provides two sites for radical attack, both possible products are produced. In the absence of steric effects, the major product reflects a kinetic preference for the most basic site of the carbanion. When such a kinetic preference is countered by steric or other effects, as is apparently the case for the reaction of trityl anion with phenyl radical, the stability of the radical anion may become a factor. As we have pointed out, however, such a product redistribution may have nothing to do with radical anion stability but may simply reflect the distribution of charge into the rings of trityl anion due to electron–electron repulsion.[6]

Differentiation between $S_{RN}1$, S_{ET}, S_NAr, and S_N2 mechanisms has depended almost entirely on kinetic arguments. We have now presented evidence that allows distinction between $S_{RN}1$ and S_{ET} mechanisms based upon product distributions and allows some generalizations to be made. First, for the $S_{RN}1$ chain mechanism, the S_{ET} pathway provides chain-termination steps. Second, in the absence of chain steps, the S_{ET} pathway will become significant when decomposition of the radical anion of aryl halide (step c of Scheme II or its equivalent) occurs before solvent-cage escape. Moreover, since addition of radicals to anions is remarkably selective,[5,12] and therefore controlled by activation energies, the diffusion-controlled radical–radical process (S_{ET} mechanism) can become important at high radical concentration. In the case of the trityl anion, in principle, it is possible to select among possible products by a choice of reaction conditions that favors radical–radical reaction, radical–anion reaction, or the benzyne intermediate. We expect that further examples of varying site selectivity will become available.

Experimental Section

Analyses. Triphenylmethane, 2-(triphenylmethyl)tetrahydrofuran (TTF), tetraphenylmethane (TPM), and biphenylyldiphenylmethane (BDM) were analyzed on a Varian Model 3700 gas chromatograph (FID) with either OV-101 on Partisorb (Whatman) or 5% OV-17 on Chromasorb GAWDCS columns and a Hewlett-Packard Model 3390A integrator. Retention times were compared with those of authentic samples.

Elemental analyses were performed by Galbraith Microanalytical Laboratories of Knoxville, TN.

Materials. Tetrahydrofuran was freshly distilled from benzophenone sodium ketyl under argon. Triphenylmethane and tetraphenylmethane were obtained from Aldrich Chemical Co. and used without purification. Biphenylyldiphenylmethane was prepared in these laboratories.[5a]

Manipulations. All preparations were carried out under argon that has been dried and deoxygenated by using an Ace-Burlitch inert-atmosphere systems. All glassware was dried at 140 °C for at least 4 h and then purged three times with argon followed by evacuation to <1.0 torr. Solid materials were introduced prior to purging, while liquids were added via syringe. Solutions of triphenylmethyl anion prepared in this manner were stable for several days.

Bromobenzene and Triphenylmethyl Anion Concentration Studies. A 3.52-g portion of triphenylmethane was dissolved in 315 mL of tetrahydrofuran in a degassed flask containing argon. Eitht 35-mL aliquots (1.60 mmol, 1.00 equiv) were then transferred into the degassed reaction tubes via syringe. Aliquots of 1.00, 0.75, 0.50, and 0.35 mL (1.00, 0.75, 0.50, and 0.35 equiv) of *n*-butyllithium were added to tubes 1–4, respectively; tubes 5–8 received 1.00 mL each of *n*-butyllithium. The ruby-red solutions were allowed to stand for 40 min. Bromobenzene (0.17 mL, 1.00 equiv) was added to tubes 1–5, and then 0.34, 0.84, and 1.7 mL (2, 5, and 10 equiv) were added successively to tubes 6–8. All tubes were irradiated in the merry-go-round apparatus for 15 min with a 450-W Hanovia lamp filtered with 0.1 M K_2CrO_4. Each tube was subsequently quenched with 10 μL of distilled water, and the products were analyzed by gas chromatography.

Iodobenzene Concentration Studies. Two reaction sets of eight tubes were prepared and analyzed analogously to those described above. Tubes 1–4 contained 0.18, 0.36, 0.90, and 1.80 mL (1, 2, 5, 10 equiv) of iodobenzene. Tube 5 contained 1 equiv of iodobenzene, while tubes 6, 7, and 8 contained 1.1 and 5 equiv of bromobenzene, respectively, to serve as controls. Each tube contained 0.440 g of triphenylmethane and 1.00 mL (1.00 equiv) of *n*-butyllithium. Each set was irradiated for 5 min.

Diphenyl Sulfoxide Concentration Studies. Two duplicate reactions composed this set. Triphenylmethane (3.52 g) was dissolved in 45 mL of THF. A 5-mL portion of this solution was added via syringe to each of the eight reaction tubes; 27, 24, 15, and 0 mL of THF were added to tubes 1–4, respectively. *n*-Butyllithium (1.00 mL) was added to each tube, and the solutions were allowed to stand for 50 min. A 12.6-g portion of diphenyl sulfoxide was dissolved in 120 mL of THF, and then 3.1, 6.1, 15.3, and 31.0 mL (1.00, 2.00, 5.00, and 10.00 equiv) were added to tubes 1–4, respectively. The tubes were irradiated as before for 15 min and then quenched with 10 μL of water. The products were analyzed by gas chromatography.

Preparative Irradiation of Triphenylmethyl Anion. A. In Tetrahydrofuran. Triphenylmethane, 1.24 g (5.1 mmol) was dissolved in 25 mL of THF; 2.9 mL (6.1 mmol) of *n*-butyllithium and 0.69 mL (6.5 mmol) of bromobenzene were added as described previously, and the mixture was irradiated for 60 min, until the deep red color had become light orange. Gas chromatographic analysis of the photolysate indicated the presence of 65.5% triphenylmethane, 19.4% TTF, 3.0% TPM, 4.6% BDM, and 15.2% benzene (0.775 mmol using toluene as internal standard). The THF was evaporated, and the resultant oil was extracted in ether, dried, and concentrated. A 1.15-g portion of the residue was subjected to chromatography on a 100 × 3 cm column of Grade 62 silica gel (W. R. Grace), eluting with 1000 mL of hexane followed by 880 mL of 10:90 hexane–ether, 1750 mL of 20:80 hexane–ether, 1500 mL of 50:50 hexane–ether, 1500 mL of ether, and finally 1500 mL of methanol. The fractions collected yielded the following: fr 1 (500 mL), 0; 2–3 (100 mL), 216 mg of triphenylmethane; 4 (330 mL), 161 mg of triphenylmethane and 39.4 mg of BDM; 5–10 (150 mL), 150 mg of TTF; 11–12 (1500 mL), 42.5 mg of triphenylmethane; 13–14 (1750 mL), 0; and 15 (1500 mL), 18.0 mg of triphenylmethane and 57.0 mg of TPM. The

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2-(triphenylmethyl)tetrahydrofuran (TTF) was recrystallized from methanol to give colorless prisms; mp 102 °C.

The spectral data for TTF were as follows: ^{1}H NMR ($CDCl_3$) δ 0.2-2.2 (4 H, m), 3.60 (2 H, d of d, J = 7.8, 5.4 Hz), 5.50 (1 H, d of d, J = 6.0, 7.8 Hz), 7.36 (5 H, m); MS m/e 243, 59. Anal. Calcd for $C_{23}H_{22}O$: C, 87.85; H, 7.06. Found: C, 87.68; H, 7.06.

The remaining residue 0.477 g, was allowed to dissolve in ether methanol, and O_2 was bubbled through the solution for ca. 2 h to oxidize residual triarylmethanes. After solvent removal, the residue was triturated with ether. The undissolved material was identified as tetraphenylmethane by mass spectral analysis: m/e 320, 243, 166, 89.

B. In Liquid Ammonia. Solutions of triphenylmethyllithium in liquid ammonia were prepared by condensing 30 mL of ammonia into a cylindrical irradiation vessel containing 0.390 g (1.60 mmol) of triphenylmethane that had been degassed and filled with argon. A 1.0-mL solution of 1.6 M n-butyllithium was introduced and the resulting red solution allowed to equilibrate for 1 h. Bromobenzene (0.168 g, 1.60 mmol) was added, the solution irradiated or allowed to stand, and the resulting blue solution quenched by addition of solid ammonium chloride. The evaporated residue was taken up in ether and washed with water. Triphenylethylene and (4-biphenylyl)diphenylmethanol were added as internal standards, and the product mixture was quantitated by gas chromatography. The yields of products were as follows.

Run 1 (30-min irradiation): triphenylmethane, 250.2 mg; TPM, 11.3 mg (6.2%); BDM, 11.6 mg (6.4%).

Run 2 (15-min irradiation): triphenylmethane, 269 mg; TPM, 7.54 mg (4.8%); BDM, 9.85 mg (6.3%).

Run 3 (7-min irradiation): triphenylmethane, 320 mg; TPM, 4.9 mg (5.3%); BDM, 9.15 mg (10.0%).

Run 4 (no irradiation): triphenylmethane, 305 mg; TPM, 4.66 mg (4.4%); BDM, 2.52 mg (2.3%).

Run 5 (no irradiation, 2.0 mL (3.2 mmol) of n-butyllithium): triphenylmethane, 140 mg; TPM, 53.1 mg (16.6%); BDM, 19.0 mg (6.0%).

Preparative Thermolysis of (Phenylazo)triphenylmethane (PAT) in Tetrahydrofuran. A 173-mg (0.500 mmol) portion of PAT was dissolved in 50 mL of THF and the mixture refluxed for 2 h. Gas chromatographic analysis indicated the presence of triphenylmethane (5%), TTF (32%), TPM (8%), and BDM (7%) as well as various unidentified less volatile products. The residue was chromatographed on a 20 × 20 × 0.2 cm silica gel plate developed twice with 5:95 ether-hexane. The isolated yields were as follows: triphenylmethane, 12 mg; TTF, 64 mg; TPM, 23 mg; BDM, 19 mg.

2-Chlorotetrahydrofuran. This was prepared by the method of Kratochivil and Hort.[7] Dried THF (82 mL, 1.0 mol) was placed in a low-temperature irradiation vessel with evacuation jacket mounted in a Dewar containing dry ice and saturated $CaCl_2$ both maintained at −48 °C. Chlorine gas was introduced, and the mixture was irradiated for 50 min. The mixture was distilled under reduced pressure; a fraction boiling at 25–37 °C (21 mmHg) contained 2-chlorotetrahydrofuran along with other chlorinated THF products. This fraction was redistilled on a Vigreux column, and two fractions (40–55 °C, 55–80 °C at 47 mmHg) were collected in a chilled receiving flask. Both fractions containing ca. 80% 2-chlorotetrahydrofuran along with dichlorinated impurities were used without further purification.

2-(Triphenylmethyl)-2,3,4,5-tetrahydrofuran (TTF). Trityl anion was generated with 2.44 g (10 mmol) of triphenylmethane and 6.5 mL (10 mmol) of n-butyllithium in 50 mL of THF. A 1.5-mL portion of 2-chlorotetrahydrofuran (fraction 2) was added, causing loss of color. After ether extraction, the oil was dissolved in hexane and chromatographed on a column of silica gel with 5:95 ethyl acetate-hexane as eluent. The yield of 2-(triphenylmethyl)tetrahydrofuran was 0.144 g (5.0%). This material had spectral properties (NMR, IR, MS) and melting point identical with those of the photochemical material.

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Registry No. 1, 40006-86-8; (triphenylmethyl)lithium, 733-90-4; bromobenzene, 108-86-1; iodobenzene, 591-50-4; diphenyl sulfoxide, 945-51-7; 2-chlorotetrahydrofuran, 13369-70-5; triphenylmethyl radical, 2216-49-1; TPM, 630-76-2; BDM, 745-36-8; TTF, 85004-92-8; PAT, 981-18-0; THF, 109-99-9.

Combining Enzymatic and Chemical Steps in the Synthesis of Biochemically Valuable Compounds: Isotopically Chiral Methyl Acetate

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An inexpensive, practical route for preparing isotopically chiral methyl acetic acid by using a combination of chemical and enzymatic steps is described. Chirality is introduced by the stereoselective exchange of the *pro-R* α-protons of [2-^{3}H]cyclohexanone catalyzed by the enzyme acetoacetate decarboxylase (AAD), while chemical steps allow the subsequent preparation of chiral acetate in 70% overall yield. Malates prepared from (*R*)-acetates retained 66% of their tritium label when incubated with fumarase, while those from (*S*)-acetates retained 35%.

Enzymes are becoming increasingly popular as synthetic tools, especially when they are used to synthesize chiral molecules.[1] However, the remarkable stereospecificity of enzymes is often not sufficient to overcome two serious limitations to their use as organic catalysts: the small quantity of material that can normally be prepared enzymatically and the narrow range of substrates accepted by most enzymes.

Recently, we needed to prepare large quantities of chiral methyl groups for enzymatic studies. Of the methods that were available in the literature, none of the purely chemical or purely enzymatic routes seemed well adapted to this goal. The purely chemical routes rely on chemical resolutions to obtain optical purity,[2-4] although in one case a

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