followed by analysis of the ^{11}B resonance spectrum showed the presence of only dimethyl alkylboronate.

The remaining portion of the hydroboration mixture was hydrolyzed and oxidized as described above and the residue was analyzed by gas–liquid partition chromatography. The results of the analysis are presented in Table II.

Determination of the Relative Acidities of the Substituted Boranes. Borane and Phenylthioborane. A relatively concentrated solution of borane in tetrahydrofuran (approximately 2 *M*) was diluted to several lower concentrations and the solutions were standardized by gas evolution measurements on hydrolysis or by titration of the boric acid formed on hydrolysis. The proton magnetic resonance spectra of these solutions were recorded, making approximately ten passes through the α- and β-hydrogen region of tetrahydrofuran with side bands being placed on each side of the multiplets. The average value for the center, most intense peak in the multiplets was determined and used to calculated the $\Delta\delta_{THF}$. The $\Delta\delta_{THF}$'s were plotted *vs.* the mole ratio of borane complex:tetrahydrofuran and the straight line was extrapolated to a 1:1 complex.

To the dilute standardized solutions of borane in tetrahydrofuran was added a slight excess of freshly distilled thiophenol. After the hydrogen evolution had ceased (approximately 10 min) the samples were sealed and the nuclear magnetic resonance spectra run immediately before extensive ether cleavage had occurred. The data were handled as described above.

Monochloro- and Dichloroborane. As preliminary experiments indicated that a relatively slow exchange of tetrahydrofuran molecules was occurring, freshly prepared monochloro- and dichloroborane solutions in pure tetrahydrofuran were prepared and used in the nuclear magnetic resonance experiments. The proton magnetic resonance spectra of the monochloroborane solution was taken at various temperature intervals from −35 to +82°. A coalescence temperature of 57° was evident (see text for discussion). The proton magnetic resonance spectra of dichloroborane displayed two sets of multiplets (see text for discussion).

Other Substituted Boranes. Tri-*n*-propylborane, di-*n*-butylboron chloride, and di-*n*-butylphenylthioborane were added to tetrahydrofuran to produce 1:1 mole ratios. The positions of the α-hydrogens of tetrahydrofuran in these mixtures were used to calculate $\Delta\delta_{THF}$. A mixture of di-*n*-butylboron chloride and tetrahydrofuran in a 0.5:1 mole ratio displayed only a single set of multiplets in the nuclear magnetic resonance spectrum.

Electron Transfer Processes. VI. Disproportionation of *o*- and *p*-Nitrotoluenes in Basic Solution[1,2]

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Abstract: A wide variety of *o*- and *p*-nitrotoluene derivatives having an acidic α-hydrogen atom spontaneously disproportionate in basic solution, forming as the reduced species the radical anion derived from the parent nitroaromatic. This process has been considered in detail for *p*-nitrotoluene and it is concluded that the rate of formation of the radical anion is limited by the rate of ionization of *p*-nitrotoluene in *t*-butyl alcohol containing potassium *t*-butoxide.

The prolonged treatment of *o*- and *p*-nitrotoluene by strong base is recognized to give rise to a complicated mixture of products in which the methyl group has been oxidized and the nitro group reduced. Perkin first noted the formation of insoluble material by the action of hot alcoholic potassium hydroxide on *p*-nitrotoluene.[3] Klinger[4] obtained red amorphous and insoluble materials from a reduction of *p*-nitrotoluene with sodium in methanol. Bender and Schultz,[5] in a reinvestigation of this work, were able to show that 4,4′-diaminostilbene could be obtained from the reduction of the amorphous product described by Klinger. Also 4,4′-diaminostilbene-2,2′-disulfonic acid was prepared *via* similar reactions starting from 4-nitrotoluene-2-sulfonic acid. Fischer and Hepp[6] were able to isolate *p,p*′-dinitrobibenzyl and *p,p*′-dinitrostilbene from the reaction of *p*-nitrotoluene with sodium methoxide in methanol. However, the major product was a compound of empirical formula C_7H_5NO. Green[7] suggested the following structure for this compound ($C_{28}H_{20}N_4O_4$).

$$p\text{-}O_2NC_6H_4CH{=}CHC_6H_4N{=}NC_6H_4CH{=}CHC_6H_4NO_2\text{-}p$$

A number of ionic and molecular processes, some with unusual novelty, have been suggested for these oxidation–reduction reactions.[7,8]

Numerous *ortho,ortho*′-disubstituted *p,p*′-dinitrobibenzyls or stilbenes have been prepared by treating the appropriate *ortho*-substituted *p*-nitrotoluene with methanolic potassium hydroxide in the presence of an oxidizing agent.[7] A procedure for preparation of *p,p*′-dinitrobibenzyl from *p*-nitrotoluene in methanolic potassium hydroxide and air has been described.[9]

o,o′-Dinitrobibenzyl has been isolated from the treatment of *o*-nitrotoluene with diphenylamide anion in liquid ammonia solution.[10] Similarly *p,p*′-dinitrobibenzyl was formed from *p*-nitrotoluene with this base or with sodamide in piperidine.[11] Another product from the action of alkali and heat upon *o*-nitrotoluene is anthranilic acid.[12]

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(1) Reactions of Resonance Stabilized Anions. XXV.

(2) This work was supported by a grant from the Petroleum Research Fund, administered by the American Chemical Society. Grateful acknowledgment to the donors of this fund is hereby made.

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(5) F. Bender and G. Schultz, *ibid.*, **19**, 3234 (1886).

(6) O. Fischer and E. Hepp, *ibid.*, **26**, 2231 (1893).

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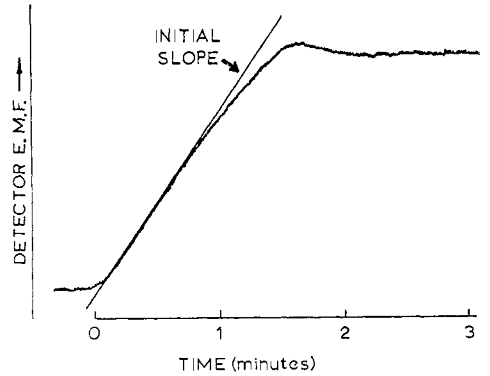

Figure 1. Typical formation of *p*-nitrotoluene radical anion (by esr spectroscopy) from *p*-nitrotoluene in *t*-butyl alcohol containing excess potassium *t*-butoxide. In this experiment formation of a precipitate occurred after 1.5 min of reaction. For initial reaction rates as a function of concentration see Table I.

Results

p-Nitrotoluene when dissolved in *t*-butyl alcohol or dimethyl sulfoxide–*t*-butyl alcohol mixtures containing potassium *t*-butoxide rapidly generates paramagnetic species.[13] The total concentration of paramagnetic molecules formed in the presence of an excess of potassium *t*-butoxide in *t*-butyl alcohol is about 0.5 mole/mole of *p*-nitrotoluene.[13] In *t*-butyl alcohol solution about 50% of the starting *p*-nitrotoluene is converted to *p,p'*-dinitrobibenzyl which has a low solubility in this solvent. *p,p'*-Dinitrobibenzyl and *p,p'*-dinitrostilbene have a greater solubility in DMSO–*t*-butyl alcohol (80:20). The paramagnetic species formed are only initially soluble in *t*-butyl alcohol, whereas they have an appreciable solubility in DMSO–*t*-butyl alcohol (80:20). Although reactions in both solvent systems follow the same general course, products and reaction kinetics are different enough to warrant consideration of each solvent system independently.

Disproportionation of *p*-Nitrotoluene in *t*-Butyl Alcohol Solution. Reaction of 0.05 *M* *p*-nitrotoluene with 0.01 *M* potassium *t*-butoxide in the absence of oxygen gives a homogeneous blood-red solution containing an appreciable concentration of a paramagnetic substance. The esr spectrum (Figure 1 in ref 13) is consistent with the *p*-nitrotoluene radical anion ($p\text{-}CH_3C_6H_4NO_2\cdot^-$). At a concentration of 0.0025 *M* *p*-nitrotoluene (0.06 *M* potassium *t*-butoxide) a paramagnetic precipitate is formed soon after mixing and an additional strong peak with little hyperfine structure is superimposed on the spectrum of the *p*-nitrotoluene radical anion in solution. The concentration of radical anion in solution remains constant after the insoluble radical appears. After 1 hr the total concentration of unpaired spins was estimated to be 0.0016 *M*,[13] approximately 50% of the initial *p*-nitrotoluene concentration. In a more dilute solution of *p*-nitrotoluene containing excess potassium *t*-butoxide a sample sealed under vacuum gave a well-resolved spectrum which did not undergo change for at least 2 weeks. However, after 5 months a precipitate had formed and only a weak signal with no hyperfine structure remained.

In general, solutions containing an excess of *p*-nitrotoluene to base yield homogeneous solutions of the *p*-nitrotoluene radical anion, while in the presence of excess potassium *t*-butoxide a precipitate forms after a short period of time and a second esr signal is observed. The maximum concentration of radical anion in solution (the concentration at which precipitation starts) increases with an increase in the ratio $[p\text{-nitrotoluene}]_0/[B^-]$.

The initial rates of formation of *p*-nitrotoluene radical anion in homogeneous solution have been followed in a stopped-flow apparatus wherein deoxygenated solutions of potassium *t*-butoxide (0.020–0.25 *M*) and *p*-nitrotoluene (0.0025–0.1 *M*) were mixed and introduced into an esr cell approximately 5 sec after mixing. The solutions immediately developed a yellow color upon mixing, followed by the blood red coloration from 15 to 60 sec after mixing. The induction period for the development of the red color was shorter at the higher base and *p*-nitrotoluene concentrations. The induction period was also a function of the extent of deoxygenation with the red coloration produced most rapidly for the most thoroughly degassed solutions. An esr signal for very low concentrations ($\sim 1 \times 10^{-6}$ *M*) of *p*-nitrotoluene radical anion could be detected somewhat before the solutions appeared to be red. The strength of the signal increased until the reaction mixture became opaque due to precipitation. It is believed that the initial yellow color, most easily observed with incompletely deoxygenated solutions, is due to a very low concentration of the *p*-nitrobenzyl anion.

Figure 1 shows the buildup of radical anions in a typical experiment as evidenced by the intensity of the eighth peak of the first derivative esr spectrum of the *p*-nitrotoluene radical anion (Figure 1, ref 13). Plots of peak height *vs.* time were linear over the first few per cent of reaction of *p*-nitrotoluene. Since similar plots were observed for other peaks of the spectrum, it is apparent that only a single radical anion is present in solution.

Plots of the initial rates of radical production, as judged by the magnitude of the overmodulated (unresolved) signal or of the intensity of a single peak of the multiline spectrum, indicated a simple kinetic relationship. Correlation of the magnitude of the overmodulated signal with initial *p*-nitrotoluene concentration at constant concentrations of base is shown in Figure 2. The correlation at a variety of initial base concentrations but constant initial *p*-nitrotoluene concentration is given in Figure 3. These correlations clearly indicate that the initial rate of radical buildup follows the expression

$$\frac{d[p\text{-}NO_2C_6H_4CH_3\cdot^-]_0}{dt} = k[p\text{-}NO_2C_6H_4CH_3]_0[KOC(CH_3)_3]_0$$

wherein *k* is 0.017 l./mole min (from Table I) with an estimated experimental uncertainty of ±30%. The same kinetic relationship was observed at ratios of $[p\text{-}NO_2C_6H_4CH_3]_0/[B^-]$ either >1 or <1 (Table I).

In addition to *p*-nitrotoluene radical anion the spontaneous disproportionation of *p*-nitrotoluene in basic

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Monatsh., **34**, 1011 (1913); G. Look, *Ber.*, **73**, 1377 (1940); G. Del Re, *Tetrahedron*, **10**, 81 (1960).

[13] G. A. Russell and E. G. Janzen, *J. Am. Chem. Soc.*, **84**, 4153 (1962).

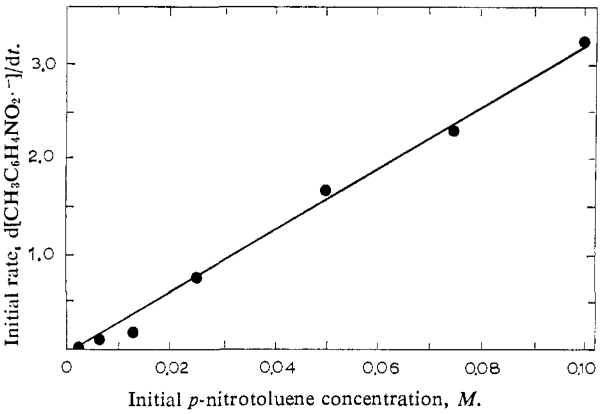

Figure 2. Initial rates of formation of *p*-nitrotoluene radical anion from solutions of *p*-nitrotoluene in *t*-butyl alcohol containing 0.2 *M* potassium *t*-butoxide. Initial rates are in *M* min^{-1} × 10^4.

t-butyl alcohol produces *p,p'*-dinitrobibenzyl. In a typical experiment a solution of potassium *t*-butoxide in *t*-butyl alcohol was added with rapid stirring to a solution of *p*-nitrotoluene in *t*-butyl alcohol. After varying lengths of time (5–30 min) a large excess of thoroughly degassed water was added in a system closed to atmospheric oxygen (see Experimental Section). The solution was subsequently treated with air or oxygen. *p*-Nitrotoluene is not converted to dimer by oxygen under the work-up procedure. *p,p'*-Dinitrobibenzyl was isolated by filtration and *p*-nitrotoluene by extraction with benzene. Similar experiments using acetic acid or dilute sulfuric acid to quench the reaction give the same products. If the initial reaction mixture is not quenched within about 30 min (room temperature) red amorphous solids are formed. After long reaction times the purity of the bibenzyl and recovered *p*-nitrotoluene decreases significantly. Some typical yields are summarized in Table II.

Table I. Spontaneous Formation of *p*-Nitrotoluene Radical Anion in *t*-Butyl Alcohol at 30°

Initial concn, *M*		— Initial rates of radical anion formn, *M* min^{-1} × 10^5 —			
p-Nitrotoluene	Potassium *t*-butoxide	Expt 1	Expt 2	Expt 3	10^2 × k_{av}[b]
0.0065	0.20	0.032	0.028	0.030	2.5
0.013	0.20	0.0514	0.073	0.057	2.3
0.025	0.20	7.40	7.40	7.40	1.5
0.050	0.20	17.4	17.2	15.9	1.7
0.075	0.20	25.4	22.8	22.2	1.6
0.100	0.20	31.7	33.2	33.2	1.6
0.025	0.025	1.16	0.935	0.970	1.6
0.025	0.044	1.45	1.45	1.45	1.3
0.025	0.088	2.90	3.63	3.92	1.6
0.025	0.131	5.65	5.80	5.80	1.8
0.025	0.175	8.40	8.70	8.85	2.0
0.025	0.250	12.1	13.8	13.0	2.0
0.025	0.020	0.734[a]			1.5
0.025	0.015	0.520[a]			1.4
0.025	0.010	0.354[a]			1.4
0.025	0.005	0.141[a]			1.2
			Av	1.7 ± 0.3[c]	

[a] Average of 4–5 experiments. [b] Initial rate/[*p*-nitrotoluene]$_0$·[KOC(CH$_3$)$_3$]$_0$, l./mole min. [c] Standard deviation.

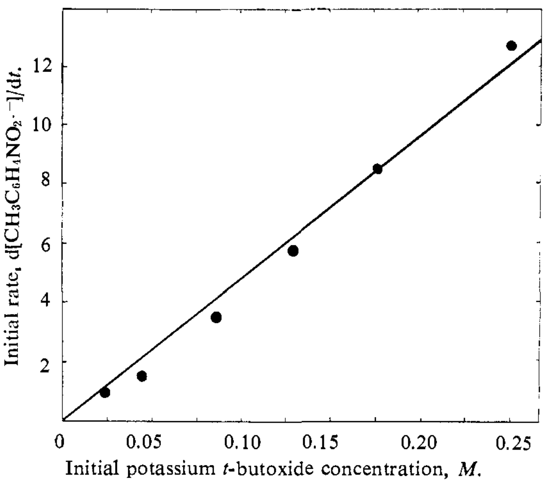

Figure 3. Initial rates of formation of *p*-nitrotoluene radical anion from 0.025 *M* *p*-nitrotoluene in *t*-butyl alcohol solution containing potassium *t*-butoxide. Initial rates in *M* min^{-1} × 10^5.

The data of Table II, together with the measurement of total paramagnetic species formed after a 1-hr reaction period,[13] are consistent with the following stoichiometry for the disproportionation.

$$4CH_3C_6H_4NO_2 \xrightarrow{B^-} 2CH_3C_6H_4NO_2\cdot^- + p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p$$

This equation suggests that it should be possible to increase the yield of *p,p'*-dinitrobibenzyl by the addition of nitrobenzene to act as an electron acceptor.[14]

Table II. Spontaneous Dimerization of *p*-Nitrotoluene in *t*-Butyl Alcohol Containing Potassium *t*-Butoxide at 25°[a]

Reaction time, min	Yield of *p,p'*-dinitrobibenzyl (mp, °C)[b,c]	Recovered *p*-nitrotoluene[b,d]	Benzene-insoluble materials[b]
5	21 (176–180)	69	0
10	37 (170–175)[e]	56	0.4
20	41 (170–175)	51	1.5
30	47 (165–175)	*f*	+
60	57 (170–172)	*f*	++

[a] 0.01 *M* *p*-nitrotoluene, 0.21 *M* potassium *t*-butoxide. [b] Per cent, based on starting *p*-nitrotoluene. [c] Melting point of pure *p,p'*-dinitrobibenzyl, 178–181°. [d] Melting point of recovered material, 49–51°; lit. 50.5–51°. [e] Melting point 179–181° after recrystallization from benzene. [f] Not measured.

Moreover, in the presence of excess nitrobenzene the esr signal formed from *p*-nitrotoluene in base should be due to nitrobenzene radical anion. Both of these possibilities have been realized. The hyperfine spectrum obtained from *p*-nitrotoluene in *t*-butyl alcohol containing potassium *t*-butoxide and excess nitrobenzene is due to nitrobenzene radical anion and not to the *p*-nitrotoluene radical anion. The yield of *p,p'*-dinitrobibenzyl from 0.10 *M* *p*-nitrotoluene and 0.30 *M* potassium *t*-butoxide in *t*-butyl alcohol containing 0.12 *M* nitrobenzene is 67% after a 15-min

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(14) Experiments performed by Mr. G. Kuehn, National Science Foundation Undergraduate Research Participant, summer 1962. It is of interest to note that the yield of dimerization products from 2-methoxy-4-nitrotoluene in the presence of oxygen is improved by the use of electron acceptors such as *p*-benzoquinone: G. R. Treves, *J. Am. Chem. Soc.*, 70, 875 (1948).

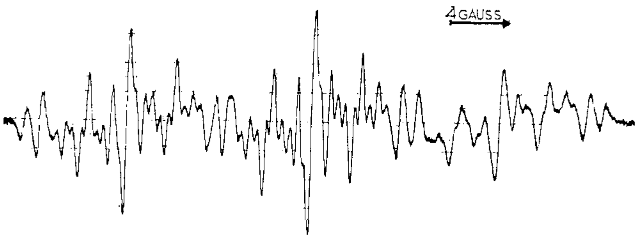

Figure 4. Esr spectrum of *p*-nitroethylbenzene radical anion in *t*-butyl alcohol containing potassium *t*-butoxide: $a^N = 12.85$, $a_{CH_2}{}^H = 2.84$, $a_{ortho}{}^H = 3.18$, $a_{meta}{}^H = 1.1$ gauss.

reaction time (compare with Table II). However the amount of benzene-insoluble materials also increases when nitrobenzene is present. Under the same reaction conditions with *o*-nitrotoluene (0.12 *M* nitrobenzene), *o,o'*-dinitrobibenzyl was isolated after a 15-min reaction period in 15% yield.[14]

Spontaneous Disproportionation of *p*-Nitroethylbenzene in *t*-Butyl Alcohol Solution. *p*-Nitroethylbenzene produced the *p*-nitroethylbenzene radical anion in the presence of potassium *t*-butoxide in *t*-butyl alcohol solution. Figure 4 shows a typical spectrum observed from a solution 0.01 *M* in *p*-nitroethylbenzene and 0.05 *M* in potassium *t*-butoxide. The formation of *p*-nitroethylbenzene radical anion was followed by esr and the initial rate of radical production was measured as a function of base concentration for a solution originally 0.025 *M* in *p*-nitroethylbenzene. The results are plotted in Figure 5. Again the rate of radical anion formation is first order in the concentration of potassium *t*-butoxide, and by analogy to the kinetics observed for *p*-nitrotoluene it has been assumed that the reaction is also first order in *p*-nitroethylbenzene concentration. With this assumption the data of Figure 5 yield a rate constant of 0.014 l./mole min.

p-Nitroethylbenzene also underwent spontaneous dimerization in *t*-butyl alcohol, although to a small extent. 2,3-Bis(*p*-nitrophenyl)butane was isolated in a 3% yield from 0.1 *M* *p*-nitroethylbenzene, 0.3 *M* potassium *t*-butoxide, and 0.12 *M* nitrobenzene in *t*-butyl alcohol after a 15-min reaction period. Longer reaction times gave the same yield of dimer but more insoluble unidentified products.

From *p*-nitrocumene under similar conditions only unreacted starting material was recovered, and an esr signal was not observed.

Spontaneous Disproportionation of *p*-Nitrotoluene in Dimethyl Sulfoxide–*t*-Butyl Alcohol Solution. In DMSO–*t*-butyl alcohol (80:20) the disproportionation reaction of *p*-nitrotoluene is very rapid. The *p*-nitrotoluene radical anion is initially formed, but shortly thereafter other radical anions are formed, particularly at high *p*-nitrotoluene or base concentrations. Figure 6 shows a typical esr spectrum of the *p*-nitrotoluene radical anion initially formed in DMSO (80%) from a solution 0.005 *M* in *p*-nitrotoluene and 0.007 *M* in potassium *t*-butoxide. After 12 min the spectrum clearly showed the presence of a second radical anion with a smaller total line width which caused interferences in the center of the spectrum but not at the wings. The same spectrum of two radicals was obtained initially if *p,p'*-dinitrostilbene was purposely added to the solution of *p*-nitrotoluene. Since a spectrum almost identical with the one obtained from the second radical is obtained from electrolytic reduction of *p,p'*-dinitrostilbene in DMSO solutions at low potentials,[15] it is concluded that the second radical is the *p,p'*-dinitrostilbene radical anion.

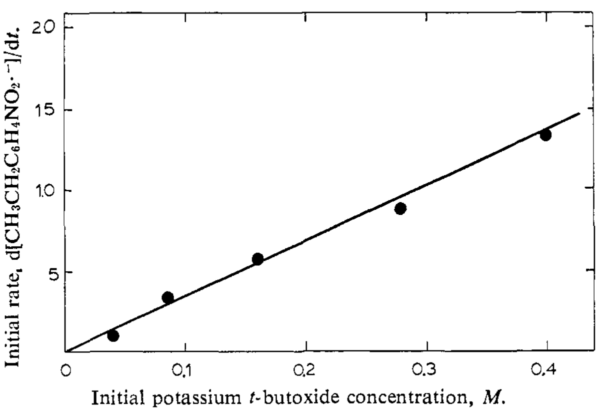

Figure 5. Spontaneous disproportionation of 0.025 *M* *p*-nitroethylbenzene in *t*-butyl alcohol. Each point is the average of 3–4 experiments. Initial rate in *M* min^{-1} × 10^6.

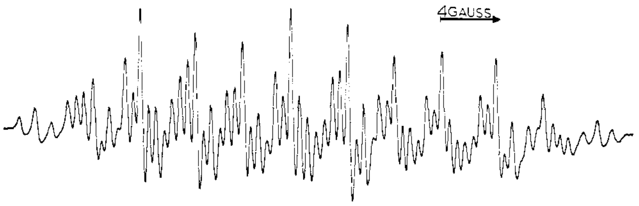

Figure 6. Esr spectrum of *p*-nitrotoluene radical anion in dimethyl sulfoxide–*t*-butyl alcohol (80:20) containing potassium *t*-butoxide; $a^N = 10.55$, $a_{CH_3}{}^H = 3.81$, $a_{ortho}{}^H = 3.40$, $a_{meta}{}^H = 1.11$ gauss.

The addition of *p,p'*-dinitrobenzyl had little effect upon the spectrum of *p*-nitrotoluene radical anion. In DMSO (80%) the bibenzyl, stilbene, and radical anions were soluble and no precipitation occurred.

Rates of formation of *p*-nitrotoluene radical anion were followed by measuring the steady-state concentration of the radical anion formed in a 2.5-sec period between mixing solutions of *p*-nitrotoluene and potassium *t*-butoxide. Figure 7 shows a typical flow experiment including the buildup of radicals in the cavity after the flow was halted. Table III lists the initial rates of radical production as measured by the amount of radical anion formed during the flow time.

The rate of formation of *p*-nitrotoluene radical anion is no longer first order in the concentration of base. In fact, now the rate is independent of base above a concentration of potassium *t*-butoxide of 0.03 *M* ([*p*-nitrotoluene]$_0$ = 0.005 *M*). The rate profile is given in Figure 8. It would appear that in DMSO (80%) a reversible ionization occurs whose equilibrium is essentially completely to the right at concentrations of potassium *t*-butoxide greater than 0.03 *M*.

$$p\text{-}NO_2C_6H_4CH_3 + (CH_3)_3CO^- \rightleftharpoons p\text{-}NO_2C_6H_4CH_2^- + (CH_3)_3COH$$

The kinetic dependence on *p*-nitrotoluene is best described as a second-order relationship ($[KOC(CH_3)_3]_0$ = 0.035 *M*), at least up to *p*-nitrotoluene concentrations of 0.006 *M* (Figure 9). We thus conclude that in

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(15) Experiments performed by J. L. Gerlock.

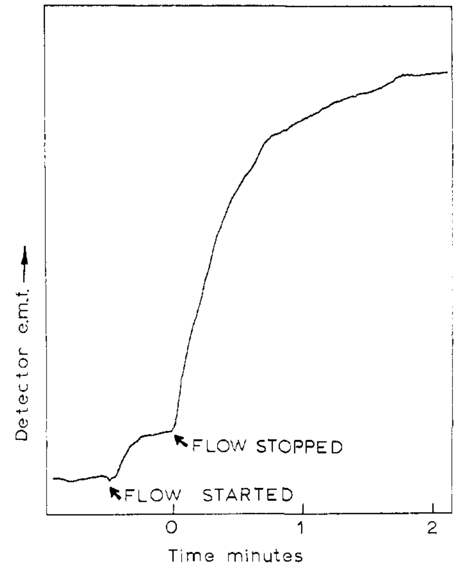


Figure 7. A typical buildup of *p*-nitrotoluene radical anion in a stopped-flow experiment involving a solution 0.004 *M* in *p*-nitrotoluene and 0.08 *M* in potassium *t*-butoxide in DMSO-*t*-butyl alcohol (50:50) at 30°. When flow started the esr cell was filled with solvent. The mixed solution entered the esr cell a few seconds after mixing. With a 2.5-sec flow time approximately 1% of the initial *p*-nitrotoluene is converted to the radical anion.

DMSO (80%) the kinetic expression for the initial rate of formation of *p*-nitrotoluene radical anion is empirically

$$\frac{d[p\text{-CH}_3\text{C}_6\text{H}_4\text{NO}_2\cdot^-]_0}{dt} = k[p\text{-CH}_3\text{C}_6\text{H}_4\text{NO}_2]_0^2[\text{B}^-]/(k' + [\text{B}^-])$$

with $k' \ll 0.03\ M$.

Spontaneous dimerization of *p*-nitrotoluene also takes place in DMSO solutions. However the yields of pure *p,p'*-dinitrobibenzyl are low and the amounts of insoluble unidentified materials are high.

Table III. Formation of *p*-Nitrotoluene Radical Anion at 30° in Dimethyl Sulfoxide-*t*-Butyl Alcohol (80:20)

$[p\text{-CH}_3\text{C}_6\text{H}_4\text{NO}_2]_0$[a]	$[\text{KOC(CH}_3)_3]$[a]	$[p\text{-CH}_3\text{C}_6\text{H}_4\text{NO}_2\cdot^-]$[a,b]
0.001	0.035	$3.1 \pm 0.3 \times 10^{-6}$
0.002	0.035	$7.3 \pm 0.3 \times 10^{-6}$
0.004	0.035	2.3×10^{-5}
0.005	0.035	3.7×10^{-5}[c]
0.006	0.035	$4.4 \pm 0.6 \times 10^{-5}$
0.008	0.035	$7.0 \pm 0.5 \times 10^{-5}$
0.010	0.035	1.1×10^{-4}
0.005	0.007	$1.3 \pm 0.2 \times 10^{-5}$
0.005	0.014	$2.1 \pm 0.3 \times 10^{-5}$
0.005	0.028	$3.63 \pm 0.2 \times 10^{-5}$
0.005	0.042	$3.8 \pm 0.2 \times 10^{-5}$
0.005	0.056	$3.7 \pm 0.5 \times 10^{-5}$
0.005	0.070	$4.0 \pm 0.04 \times 10^{-5}$
0.10	0.10	*d*

[a] Moles/liter. [b] Formed during a flow time of 2.5 sec. [c] Interpolated from Figure 9. [d] *p,p'*-Dinitrostilbene radical anion formed during flow period.

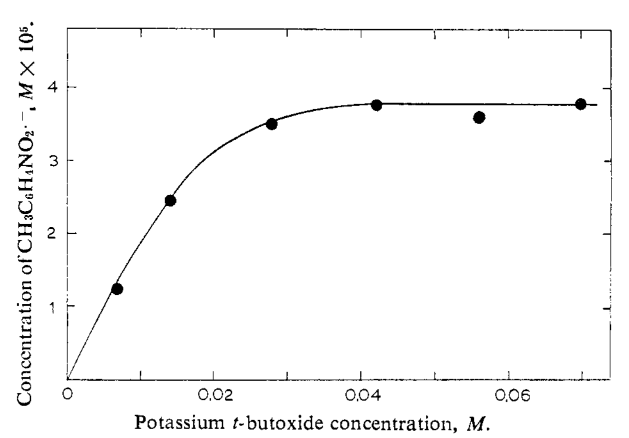


Figure 8. Spontaneous formation of *p*-nitrotoluene radical anion during a 2.5-sec reaction period of 0.005 *M* *p*-nitrotoluene in DMSO-*t*-butyl alcohol (80:20). Each point represents the average of 2-4 experiments.

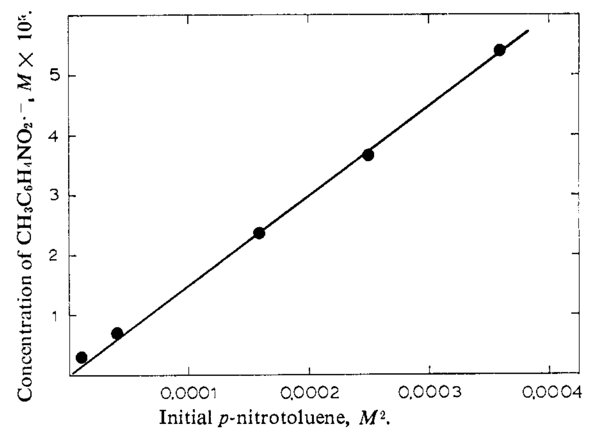


Figure 9. Formation of *p*-nitrotoluene radical anion during 2.5 sec in DMSO-*t*-butyl alcohol (80:20) containing 0.03 *M* potassium *t*-butoxide.

The formation of *p,p'*-dinitrostilbene radical anion in DMSO (80%) but not in *t*-butyl alcohol solution is apparently connected with the fact that *p,p'*-dinitrobibenzyl is soluble in DMSO (80%) but not in *t*-butyl alcohol. In DMSO (80%) the following reactions can occur.

$$p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_6\text{H}_4\text{NO}_2\text{-}p \xrightarrow{2\text{B}^-} \underset{\mathbf{1}}{[p\text{-NO}_2\text{C}_6\text{H}_4\text{CHCHC}_6\text{H}_4\text{NO}_2\text{-}p]^{2-}}$$

$$\mathbf{1} + p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_3 \longrightarrow \underset{\mathbf{2}}{[p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}{=}\text{CHC}_6\text{H}_4\text{NO}_2\text{-}p]\cdot^-} + p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_3\cdot^-$$

$$\mathbf{2} + p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_3 \rightleftarrows p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}{=}\text{CHC}_6\text{H}_4\text{NO}_2\text{-}p + p\text{-NO}_2\text{C}_6\text{H}_4\text{CH}_3\cdot^-$$

Formation of Radical Anions from Other Nitroaromatics. A wide variety of *o*- and *p*-nitrotoluene derivatives form the corresponding radical anions in *t*-butyl alcohol or DMSO-*t*-butyl alcohol (80:20) solution containing excess potassium *t*-butoxide. Esr spectra of *p*-nitrotoluene, *o*-nitrotoluene, *p*-nitroethylbenzene, and *p*-nitrocumene in DMSO-*t*-butyl alcohol (80:20) are very similar to spectra obtained by electrolytic reduction of the nitro compounds in acetonitrile.[15] Other radicals are also produced from *p*-nitroethylbenzene and *p*-nitrocumene depending on the concentrations used.

A number of highly acidic *p*-nitrotoluene derivatives fail to produce radical anions in the presence of either deficient or excess base. Among compounds in this category are 2,4,6-trinitrotoluene, bis(2,4-dinitrophenyl)methane, and *p*-nitrophenylacetonitrile. In excess base it might have been expected that these compounds would be converted to their anions so rapidly that electron transfer could not be observed. However, the absence of electron transfer in the presence of deficient base clearly shows that the nitroaromatic nucleus is incapable of oxidizing these polynitro-stabilized anions. Results for 2,4-dinitrotoluene are particularly interesting because here electron transfer can be observed in deficient base but not in excess base.

Discussion

The formation of radical anions from *p*-nitrotoluene and *p*-nitroethylbenzene in *t*-butyl alcohol containing potassium *t*-butoxide may be a process whose rate is limited by the ionization of the benzylic protons. It does not appear possible to rationalize the kinetics

$$p\text{-}CH_3C_6H_4NO_2 + (CH_3)_3CO^- \xrightarrow[k_i]{\text{slow}} p\text{-}NO_2C_6H_4CH_2^- \xrightarrow{\text{fast}} \longrightarrow$$
$$p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p + 2\,p\text{-}CH_3C_6H_4NO_2\cdot^-$$

observed in *t*-butyl alcohol if an appreciable fraction ($>\sim 20\%$) of the *p*-nitrobenzyl anions is reprotonated except if this reprotonation itself leads to the bibenzyl.[13] There is apparently a low steady-state concentration of *p*-nitrobenzyl anions (yellow)[16] that is much below the equilibrium concentration of the anion. Using the stoichiometry given above and assuming that each ionization step yields one molecule of the radical anion, k_i is found to be not less than 3×10^{-4} and 2×10^{-4} l./mole sec for *p*-nitrotoluene and *p*-nitroethylbenzene, respectively. *p*-Nitrocumene is ionized very slowly under these reaction conditions ($k_i < 1 \times 10^{-5}$). It is possible that at much higher base concentrations than employed herein the rate of ionization will no longer be limiting.

It is our conclusion that the major difference between the disproportionation reaction of *p*-nitrotoluene in *t*-butyl alcohol and DMSO (80%) is simply a change in the rate-controlling step from one of ionization (*t*-butyl alcohol) to one of charge-transfer complex formation or electron transfer (DMSO).

$$p\text{-}NO_2C_6H_4CH_3 + (CH_3)_3CO^- \underset{\text{fast}}{\overset{K_e}{\rightleftarrows}} p\text{-}NO_2C_6H_4CH_2^- + (CH_3)_3COH$$

The observed kinetic expression can be fairly well rationalized by assuming that in DMSO–*t*-butyl alcohol (80:20) the rate of the reaction is controlled by the rate of the following reaction.

$$p\text{-}NO_2C_6H_4CH_2^- + p\text{-}NO_2C_6H_4CH_3 \xrightarrow{k_2} \text{paramagnetic and other products}$$

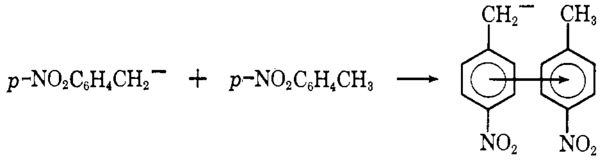
It follows that the sum of the initial concentrations of *p*-nitrotoluene and *p*-nitrobenzyl anion immediately after preparation of the solution ($[RH]_0 + [R^-]_0$) is equal to the total amount of *p*-nitrotoluene added ($[RH]_t$). When $[B^-] \gg [RH]_t$ and $[HB] = C$, $[R^-]_0 = K_e[RH]_0[B^-]$ and $[RH]_0 = [RH_t] - K_e[RH]_0[B]$. Rearranging yields, $[RH]_0 = [RH]_t/((1 + K_e)[B^-])$. The value of $[R^-]_0$ can now be evaluated as $[R^-]_0 = K_e[RH]_t[B^-]/(1 + K_e[B^-])$ and the initial rate of reaction leading to paramagnetic products given as

$$\frac{d[RH^-]_0}{dt} = \frac{k_2K_e[RH]_t^2[B^-]}{1 + K_e[B^-]}$$

This expression predicts the observed second-order dependence on $[RH]_t$ and predicts the general shape of the rate profile as the concentration of base is increased. However, the kinetic dependence observed does not require that a molecule of *p*-nitrotoluene is uniquely involved in the slow reaction with the anion. Any species whose concentration is first order in $[RH]_t$ will suffice, including a second *p*-nitrobenzyl anion.

The evidence required to describe completely the reaction leading to the bibenzyl and *p*-nitrotoluene radical anion in the absence of oxygen, and to the bibenzyl and *p*-nitrobenzoic acid in the presence of oxygen,[17] cannot be provided by esr spectroscopy alone. Ultraviolet absorption spectroscopy does indicate the formation of other intermediates which are partially responsible for the red color of *p*-nitrotoluene in basic solution, including an absorption bond at 557 mμ assigned to a charge-transfer complex.[16b] Electrolytic reduction of *p*-nitrotoluene produces a red solution containing the radical anion. However, it is difficult to obtain comparable ultraviolet and esr spectra under the same reaction conditions. Moreover, the solubility problem in ultraviolet transparent solvents is an additional complicating feature.

The initial reaction of the *p*-nitrobenzyl anion seems most likely to be a bimolecular one with either (a) an un-ionized molecule of *p*-nitrotoluene, (b) a molecule of the *aci* form of *p*-nitrotoluene,[13,18] or (c) a second *p*-nitrobenzyl anion. Since ultraviolet spectra consistent with a charge-transfer complex have been presented,[17] we will assume that this intermediate (**3**) is rapidly formed. Moreover, the kinetics observed in DMSO solution are consistent with this approach.



3

Intermediate **3** could be converted to the bibenzyl by two distinct reaction routes: (A) loss of a proton[19] and two electrons *without separation of the two p-nitrotoluene residues;* (B) complete electron transfer to yield a *p*-nitrobenzyl radical and a *p*-nitrotoluene radical anion.

The occurrence of electron transfer to yield the *p*-nitrobenzyl radical is consistent with all results pre-

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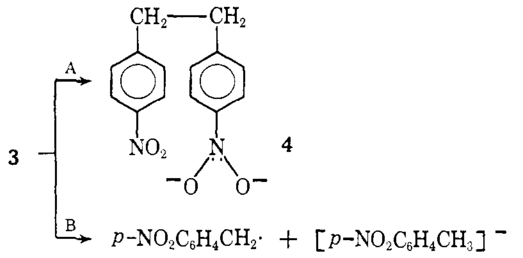
(16) (a) J. D. Margerum, *J. Am. Chem. Soc.*, **87**, 3772 (1965); (b) J. M. Miller and H. Pobiner, *Anal. Chem.*, **36**, 238 (1964).

(17) (a) G. A. Russell and A. J. Moye, Preprints of Papers, Division of Petroleum Chemistry, American Chemical Society, Vol. 5, No. 2-C, April 1960, p C-25; (b) G. A. Russell, A. J. Moye, E. G. Janzen, S. Mak, and E. R. Talaty, *J. Org. Chem.*, **31**, 137 (1966).

(18) G. A. Russell and E. G. Janzen, Preprints of Papers, Division of Petroleum Chemistry, American Chemical Society, Vol. 7, No. 4-C, Sept 1962, p C-81.

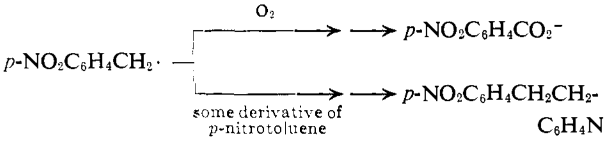
(19) The intermediate thus formed (**4**) would be identical with the intermediate formed by the loss of a proton from the product of initial coupling between the *p*-nitrobenzyl anion and the *aci* form of *p*-nitrotoluene, or from the coupling of two *p*-nitrobenzyl anions.



$$3 \xrightarrow{B} p\text{-}NO_2C_6H_4CH_2\cdot + [p\text{-}NO_2C_6H_4CH_3]^-$$

sented herein. Furthermore, it allows for the production of nitroaromatic radical anions without the concurrent formation of the carbon–carbon coupled product, for example, from *p*-nitrocumene in DMSO (80%) solution.

The formation of the bibenzyl from *p*-nitrobenzyl radical in the presence of oxygen presents a problem. It can be shown that the bibenzyl cannot be formed by coupling of *p*-nitrobenzyl radicals in the presence of oxygen.[16b,20] This conclusion originally led us to discard schemes leading to the bibenzyl that involved the *p*-nitrobenzyl radical.[13,18] However, the experiments in the presence of oxygen are still very suggestive of a *p*-nitrobenzyl radical intermediate.[16,18] As the oxygen pressure is increased, a larger fraction of the *p*-nitrotoluene is converted to *p*-nitrobenzoic acid, a logical oxidation product of the *p*-nitrobenzyl radical. As the concentration of *p*-nitrotoluene is increased (at constant oxygen concentration), a larger percentage of the *p*-nitrotoluene is converted to the bibenzyl. It appears that there may be a competition for the *p*-nitrobenzyl radical.



$$p\text{-}NO_2C_6H_4CH_2\cdot \left\{ \begin{array}{l} \xrightarrow{O_2} \longrightarrow p\text{-}NO_2C_6H_4CO_2^- \\ \xrightarrow[\text{some derivative of } p\text{-nitrotoluene}]{} \longrightarrow p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p \end{array} \right.$$

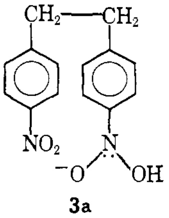
The possible trapping agents for the *p*-nitrobenzyl radical that could lead to the bibenzyl are (a) the radical itself, (b) *p*-nitrotoluene, (c) the *aci* form of *p*-nitrotoluene, and (d) the *p*-nitrobenzyl anion. We have excluded the radical; no reasonable mechanism appears possible for un-ionized *p*-nitrotoluene; the *aci* form is undoubtedly present at an extremely low concentration because of its acidity.

Can the *p*-nitrobenzyl anion be an effective trap for the *p*-nitrobenzyl radical? A reaction leading to the radical anion of the bibenzyl appears feasible.[21]

$$p\text{-}NO_2C_6H_4CH_2\cdot + p\text{-}NO_2C_6H_4CH_2^- \longrightarrow [p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p]\cdot^- \xrightarrow{p\text{-}CH_3C_6H_4NO_2} p\text{-}CH_3C_6H_4NO_2\cdot^- + p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p$$

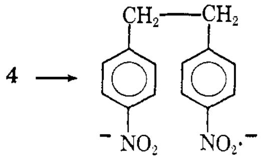
However, if this reaction occurs it must be extremely rapid and capable of competing with the reaction of oxygen with the *p*-nitrobenzyl radical, a process with a rate constant of about 1 × 10^7 l./mole sec.[20,22]

Final proof of this coupling mechanism could possibly be provided by the detection of certain cross-reaction products. However, we have been unable to detect significant amounts of the coupling product from the disproportionation reaction of *p*-nitrotoluene in the presence of high concentrations of other nitro-substituted carbanions, such as the 2-nitro-2-propyl anion or bis(2,4-dinitrophenyl)methide ion. This forces us to still give serious consideration to routes to the bibenzyl directly from intermediate **3** or its isomer **3a**.

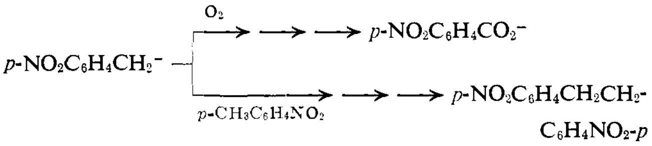


3a

Intermediate **4**, formed by ionization of **3** or **3a**, would be expected to dissociate rapidly into two *p*-nitrobenzyl anions. However, intermediate **4** should also rapidly undergo intramolecular electron transfer with great rapidity to yield **5** which could transfer two electrons to two molecules of *p*-nitrotoluene to yield the final reaction products. Intermediate **5** could react with oxygen in a cage process to yield the bibenzyl and one molecule of O_2^{2-}, the observed stoichiometry of the oxygen coupling reaction.[16,23] This leads us to suggest that the observed oxidation products of *p*-nitrotoluene in basic solution may be determined by the competition of oxygen and *p*-nitrotoluene (or possibly its *aci* form) for the *p*-nitrobenzyl anion.



5



$$p\text{-}NO_2C_6H_4CH_2^- \left\{ \begin{array}{l} \xrightarrow{O_2} \longrightarrow \longrightarrow p\text{-}NO_2C_6H_4CO_2^- \\ \xrightarrow[p\text{-}CH_3C_6H_4NO_2]{} \longrightarrow \longrightarrow p\text{-}NO_2C_6H_4CH_2CH_2C_6H_4NO_2\text{-}p \end{array} \right.$$

Intermediates of type **3** may lead only to the bibenzyl for *p*-nitrotoluene, but may give the benzyl-type radical and the nitroaromatic radical anion for *p*-nitroethylbenzene and *p*-nitrocumene.

Other Examples of Spontaneous Disproportionation. The spontaneous disproportionation of *p*-nitrotoluene and its derivatives in basic solution is not an isolated phenomenon. It can be expected in basic solution whenever hydrogen atoms are α to an easily reducible group (π) that also promotes the acidity of the hydrogen atoms.

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(20) G. A. Russell and R. C. Williamson, *J. Am. Chem. Soc.*, **86**, 2357 (1964).

(21) In the oxidation experiments the yield of acid increases at very low base concentrations.[16]

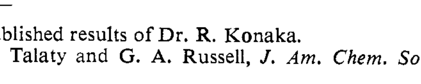
(22) It has been reported that phenyl radicals and phenyllithium react in ether solution to yield ultimately the biphenyl and lithium metal: E. E. van Tamelen, J. H. Brauman, and L. E. Ellis, *J. Am. Chem. Soc.*, **87**, 4964 (1965). Moreover, the trapping of the phenyl radical occurs so readily that the ether is not attacked to form benzene. It appears that radicals and anions may react very rapidly in those cases where the resulting radical anion has appreciable stability, and that such reactions may be extremely important for the formation of carbon–carbon bonds in the oxidation of carbanionic species.

(23) The oxidation of the potassium salt of nitrobenzene ($C_6H_5NO_2\cdot^-K^+$) in tetrahydrofuran or DMSO solution has a stoichiometry of 1 mole of oxygen/mole of radical anion to yield superoxide (KO_2): unpublished results with Dr. A. G. Bemis. Presumably the oxidations of *p*-nitrotoluene radical anion and the *p*,*p*′-dinitrobibenzyl radical anion would have similar stoichiometries. The stoichiometry observed in the oxidative coupling reaction is thus most consistent with the intervention of **5** as an intermediate.

$$\pi\text{-CH}< \xrightarrow{B^-} >\text{CH-}\pi\ ^-$$

Other examples of π in addition to the *p*-nitrophenyl group are the *p*-azophenyl (*p*-$C_6H_5N_2C_6H_4$) and *p*-benzoylphenyl groups. A wide variety of heteroaromatic systems such as 1-methyltetrazine, 8-methylisoalloxazines, or 3-methyl-4-nitropyridine N-oxide have been observed to undergo the disproportionation.[24] Conjugated diketone systems readily undergo the disproportionation in both the alkylanthraquinone system and in the aliphatic α-diketones.[25] Of the aforementioned compounds only 3-methyl-4-nitropyridine N-oxide,[26] 2-methyl-9,10-anthraquinone,[27] and lumiflavin or riboflavin[28] are recognized to yield spontaneously the dimeric product (π–CH_2CH_2–π), or in some cases the unsaturated dimer (π–CH=CH–π) upon treatment with base in the absence of oxygen.

The only completely aliphatic examples of π–CH< of which we are aware wherein disproportionation by electron transfer can be readily detected by esr spectroscopy are the conjugated diketones.[25] A process of this type is undoubtedly involved in certain reactions of the nitroalkanes in basic solution, but we have been unable to detect by esr the expected radical anions of the type $>CHNO_2\cdot^-$ even though such radical anions are known to have some stability in aqueous solution.[29] However, certain aspects of the oxidation of 2-nitropropane in basic solution are particularly consistent with reactions of the type suggested to occur with *p*-nitrotoluene.[30] In water (hydroxide ion in excess of 2-nitropropane) or at lower base to 2-nitropropane ratios in nonaqueous solvents,[31] a rapid long kinetic chain oxidation yielding acetone and nitrite ion occurs spontaneously. This chain reaction has been formulated to involve the 2-nitro-2-propyl radical.[30,31] At still higher pH in water, or in the presence of an excess of alkoxide ion in nonaqueous solvents,[31] the oxidation no longer occurs spontaneously at an appreciable rate, suggesting the un-ionized 2-nitropropane, or its *aci* form, or some derivative thereof, is required for the initiation step. It is particularly pertinent that under these conditions oxidation to acetone and nitrite ion can be catalyzed by the addition of a good electron acceptor, such as nitrobenzene, particularly in the presence of light. The situation appears very similar to the detection of radical anions from 2,4-dinitrotoluene in the presence of a deficient quantity of alkoxide ion but not in the presence of a slight excess of alkoxide ion, and would appear to involve electron transfer from an anion to an un-ionized electron acceptor, *e.g.*



$$\pi\text{-}\overset{|}{\underset{|}{C}}{:}^- + H\overset{|}{\underset{|}{C}}\text{-}\pi \longrightarrow \pi\text{-}\overset{|}{\underset{|}{C}} + H\overset{|}{\underset{|}{C}}\text{-}\pi\ ^-$$

Experimental Section

Flow Experiments. Measurements of rates of free-radical formation were obtained by the use of a flow system[31] installed in the cavity of a Varian 4500 epr spectrometer. Solutions of *p*-nitrotoluene and potassium *t*-butoxide were degassed in separate bulbs with prepurified nitrogen previously passed through a solution of benzophenone ketyl in xylene. Preliminary experiments were performed with solutions degassed by freezing (acetone–Dry Ice) and thawing under vacuum. Deoxygenation by bubbling dry nitrogen through the solutions before and during the experiments gave the same results and was the method used for all experiments reported herein.

Solutions of *p*-nitrotoluene in *t*-butyl alcohol were prepared prior to use since *p*-nitrotoluene dissolves slowly in *t*-butyl alcohol. Solutions of potassium *t*-butoxide in *t*-butyl alcohol or in DMSO–*t*-butyl alcohol (80:20) were prepared by diluting a concentrated solution of potassium *t*-butoxide (1 *M*) prepared from commercial potassium *t*-butoxide and *t*-butyl alcohol. Solutions of potassium *t*-butoxide in DMSO–*t*-butyl alcohol (80:20) were not stable over a period of days.

In *t*-butyl alcohol a free-radical signal could not be detected during flows of about 5 sec but always appeared shortly after stopping the flow. In dimethyl sulfoxide solutions radicals formed during flow. At the concentrations and flow rates (~2.5 sec) reported herein, a rapid increase (at least tenfold) in concentration of radical was observed when the flow was stopped, indicating that only a small fraction of the reaction had taken place before the solutions passed through the cavity. In a number of experiments not reported at high concentrations and slow flow rates this was not the case. At high base concentration in *t*-butyl alcohol and to a lesser extent in DMSO the higher viscosity of the base solution caused slower flow rates.

The increase in signal intensity was followed by either scanning repeatedly up- and downfield through the signal or by recording the increase in intensity at the field required for resonance. The former method gave better results. The intensity of the first derivative spectrum was assumed proportional to the concentration of the radical present in solution. Calibration was by means of solutions of known concentrations of diphenylpicrylhydrazyl in ethanol. This technique may involve considerable absolute error in the rate constants derived. However, on a relative basis, such as is required for establishing kinetic order, the data have an experimental uncertainty of only a few per cent at most.

Isolation of *p,p'*-Dinitrobibenzyl. A 150-ml solution of *p*-nitrotoluene in *t*-butyl alcohol was degassed by the freeze–thaw method in a 1-l. flask. Attached by a ground-glass joint was a smaller flask containing potassium *t*-butoxide in 25 ml of degassed *t*-butyl alcohol. When thoroughly deoxygenated, the solutions were mixed by inverting the smaller flask. Stirring was by means of a Teflon-covered magnet. The flasks were kept under partial vacuum (vapor pressure of *t*-butyl alcohol) during the complete experiment. Almost immediately after mixing the solution turned pale yellow-green, orange after 0.5 min, and slowly clear bright red after 1 min. After 1.4 min the solution became turbid, and shortly after a solid formed in solution. The amount of this precipitate increased with time. At the time of quenching the experiment approximately 500 ml of deoxygenated water was rapidly added by opening a stopcock to a flask of water under atmospheric pressure. The *t*-butyl alcohol solution and water formed an emulsion. Precipitation of yellow *p,p'*-dinitrobibenzyl occurred when air or oxygen was bubbled through the solution and could be removed by filtration. *p*-Nitrotoluene remained in solution but could be recovered by extraction with benzene. The dimer was purified by recrystallization from boiling benzene. Red side products formed after extended periods of reaction were insoluble in hot benzene. Identification of reaction products was by means of infrared comparisons and mixture melting point.

Reaction of *p*-Nitrotoluene with Base in the Presence of the 2-Nitro-2-propyl Anions.[32] Potassium (7.8 g, 0.2 g-atom) was dissolved in 175 ml of *t*-butyl alcohol with stirring at 60–70° while a stream of deoxygenated, anhydrous nitrogen passed through the solution. A solution of 13.8 g (0.1 mole) of *p*-nitrotoluene in 20 ml of *t*-butyl alcohol was deoxygenated with nitrogen and added to the potassium *t*-butoxide solution at 25° without exposure to air. After a 35-min reaction period the resulting solution was poured into 350 ml of an ice–water slurry acidified with 7 ml of concentrated sulfuric acid. The yellow precipitate thus formed was filtered and

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(24) Unpublished results of Dr. R. Konaka.

(25) E. R. Talaty and G. A. Russell, *J. Am. Chem. Soc.*, **87**, 4867 (1965).

(26) E. C. Taylor and J. S. Driscoll, *J. Org. Chem.*, **26**, 3796 (1961).

(27) German Patent No. 199,756 (1908); *Chem. Zentr.*, 1908 [II], 460 (1908); R. Scholl and H.-D. Wallenstein, *Ber.*, **69**, 503 (1936).

(28) P. Hemmerick, B. Prijs, and H. Erlenmeyer, *Helv. Chim. Acta*, **43**, 2164 (1959).

(29) L. H. Piette, P. Ludwig, and R. N. Adams, *J. Am. Chem. Soc.*, **83**, 3909 (1961); **84**, 4212 (1962).

(30) G. A. Russell, *ibid.*, **76**, 1595 (1954).

(31) G. A. Russell, E. G. Janzen, A. G. Bemis, E. J. Geels, A. J. Moye, S. Mak, and E. T. Strom, "Selective Oxidation Processes," Advances in Chemistry Series, No. 51, American Chemical Society, Washington, D. C., 1965, p 112.

(32) Experiments performed by Dr. G. J. Mikol.

extracted (Soxhlet) for 12 hr with 300 ml of acetone. The acetone was evaporated and the solid residue slurried and filtered from 75 ml of carbon tetrachloride to yield 7.5 g (55%) of *p,p'*-dinitrobibenzyl.

The reaction was repeated using 27.3 g of potassium metal and 550 ml of *t*-butyl alcohol. 2-Nitropropane (15 ml, 0.5 mole) was added, followed (15 min) by 13.8 g (0.1 mole) of *p*-nitrotoluene in 25 ml of *t*-butyl alcohol. After 35 min *p,p'*-dinitrobibenzyl was isolated, as described previously, in yields of 59 and 57% in two reactions. From the green filtrate from the initial filtration of *p,p'*-dinitrobibenzyl, 2-nitroso-2-nitropropane, mp 71–73°, slowly precipitated. Extraction of the green filtrate with five 100-ml portions of chloroform yielded 4.15 g of a residue not vaporized at 25° and 10 mm. A portion of the residue was dissolved in ethyl acetate and analyzed by gas–liquid partition chromatography. 1-(4-Nitrophenyl)-2-methyl-2-nitropropane was identified with the pure material on a 2-m 3% SE-30 silicone rubber–Chromosorb P column at 172°. The total yield of the coupled product was 0.6–0.7%, based on *p*-nitrotoluene. Extraction of the entire solid residue with carbon tetrachloride left 0.24 g (0.56%, based on 2-nitropropane) of 2,3-dimethyl-2,3-dinitrobutane, mp 212–214°. Repetition of the whole procedure omitting the *p*-nitrotoluene yielded 0.02 g (0.04%) of 2,3-dimethyl-2,3-dinitrobutane. The coupled products formed in the mixed reaction were at least 28.4 mmoles of *p,p'*-dinitrobibenzyl, at least 1.36 mmoles of 2,3-dimethyl-2,3-dinitrobutane, and not more than 0.7 mmole of *p*-NO$_2$-C$_6$H$_4$CH$_2$C(CH$_3$)$_2$NO$_2$.

Modification of Reaction Rates by Complex Formation. II. Inhibition of the Rate of Alkaline Hydrolysis of Methyl *trans*-Cinnamate by Some Heterocyclic Compounds[1]

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Abstract: The rate of alkaline hydrolysis of methyl *trans*-cinnamate is decreased in the presence of several imidazole and purine compounds. This effect is ascribed to formation of one or more complexes between the ester substrate and the heterocyclic ligand, the complexed form of the ester being much less susceptible to attack by hydroxide than is the free ester. Apparent stability constants, based on an assumed 1:1 stoichiometry, were evaluated by the solubility, spectral, and kinetic techniques; these comparative measurements provided information bearing on the actual stoichiometric relationships. Many of the ligands appear to form 1:1 complexes, but some systems are more complicated. The apparent stability constants (at 25° in aqueous solution) ranged from 1.0 M^{-1} for the imidazole complex to 36 M^{-1} for caffeine (which, however, does not form only a 1:1 complex). Xanthines were the strongest complexers of methyl cinnamate, with the purines, as well as simple imidazole compounds, being less effective. Conversion of the neutral theophylline molecule (stability constant 24 M^{-1}) to its anion reduced its effectiveness (anion stability constant 12 M^{-1}); this was attributed to extensive solvation of the anion. Possible complications in catalytic studies may arise when unsuspected complexing occurs to cause concurrent inhibition.

The concept of complex formation as a rate-mediating phenomenon is a familiar one in studies of enzyme-catalyzed reactions, and an adequate understanding of the mechanisms of enzymatic reactions will require that the complex formation aspect be understood far better than it is at present. Both the reactivity and the specificity behavior of enzymes as catalysts appear to be closely related to their capabilities for intermolecular and intramolecular binding interactions. In studies of the high catalytic efficiency of enzymes successful use has been made of relatively simple nonenzymatic model systems as aids in locating and elucidating possible mechanistic pathways. The associated problem of enzyme specificity behavior may similarly be attacked, and this paper presents results of studies planned to provide information on the modification of reaction rates by complex formation in homogeneous, nonenzymatic systems. The point of view tentatively adopted is that specificity patterns may reflect a more active process than simply a suitable juxtaposition of labile and catalytic functions in the enzyme–substrate complex; rather it is supposed that specificity can also be the manifestation of interactions that cause or prevent necessary combinations of groups in space.[1] Thus rate inhibitions caused by complex formation may be as meaningful for this aspect of model studies as are rate enhancements, and the systems to be described here all demonstrate inhibitory effects.

The term "complex" has been assigned many meanings. In this paper it signifies a stoichiometric product formed in a very facile equilibrium process by interaction between two or more species, the product not being susceptible to description in conventional bond symbolism. The existence of such complex species is inferred from nonadditive behavior in the physical and chemical properties of solutions of the interacting species and sometimes from the appearance of insoluble complexes. Hydrogen bonding, charge-transfer processes, dispersion forces, electrostatic interactions, etc., are responsible for the existence of complex species; solvent orientation effects may also be important.

An earlier communication[1] reported that the rate of alkaline hydrolysis of methyl *trans*-cinnamate[2] is decreased in the presence of imidazole. This observation seemed remarkable in view of the well-known catalytic properties of imidazole,[3,4] and the investiga-

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(1) For the first paper in this series see K. A. Connors and J. A. Mollica, Jr., *J. Am. Chem. Soc.*, **87**, 123 (1965).

(2) Throughout this paper the *trans* isomer is to be understood when methyl cinnamate is specified.