Transition-State Polarization in Cleavage of C–C Bonds in Radical Anions

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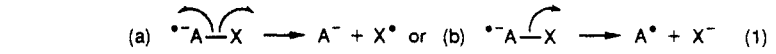
The substituent effect on the rate of C–C bond cleavage in radical anions of 1-(4-nitrophenyl)-2-(substituted-phenyl)-1,1,2,2-tetraethylethanes has been explored. The data provide evidence for two distinctive modes of bond scission. One mode is characterized by a significant negative charge transfer across the scissile bond in the transition state. Such polarization of the transition state is in contradiction to the prediction based on the fragments' stability. The second mode, dominant in cases where the charge shift leads to negative charge accumulation on an already electron-rich fragment, involves a σ^* radical anion. Both modes point to a general kinetic preference for a cleavage of radical anions that allows for charge delocalization across the scissile bond.

Radical anions often undergo facile fragmentation to an anion and a radical.[2] Such reactions have been observed during the reductive cleavage of carbon–halogen,[2a,b] carbon–oxygen,[2c-e] and carbon–sulfur[2f,g] bonds. Recently, it has been shown[3,4] that radical anions can also undergo *unimolecular*[5] scission of relatively nonpolar C–C bonds with activation energies much smaller than that observed for the corresponding homolytic processes.[6] The mechanistic aspects of such reactions attract considerable attention[7] due to their importance in synthesis[8,9] ($S_{RN}1$ reactions) and potential application in depolymerization of macromolecules.

Most frequently, the unpaired electron in the initially formed radical anion resides in a π-type orbital localized on one side of the scissile bond. The fragmentation reaction is accompanied by the redistribution of electron density leading ultimately to apportionment of electrons to the two forming fragments. In order to understand the mechanism of bond activation available via such one-electron reduction, the details of the redistribution of electron density have to be determined.

Formally, two modes of electron apportionment may be considered:



The first process corresponds to homolysis, the second is equivalent to heterolysis. To express this mechanistic duality, we have proposed[6] to call such processes *mesolytic*. Thus, unimolecular fragmentations of radical cations is termed *catiomesolytic*, and the unimolecular cleavage of the radical anions—the subject of this paper—is named *aniomesolytic*.[6] The term "mesolytic" also applies to formal one-electron or three-electron bonds, wherein spin delocalization is not limited to π-systems.

In general, the dissociating radical anions can be divided into two structural groups.[10,11] In the first group, the bond to be broken is orthogonal to the π-system bearing the unpaired electron. Such a situation—found, for example, in aryl halides—does not allow for any significant orbital overlap between the π-network and the σ^* of the scissile bond. The transition state for cleavage of such radical anions must include a large intramolecular $\pi \rightarrow \sigma^*$ electron-transfer component. In the other group—for instance benzylic halides—not only is direct overlap between the orbitals of interest possible, but such overlap should increase as the reaction progresses toward a resonance-stabilized anion or radical. The facility with which the redistribution of the electron density takes place should also depend on preexisting polarization of the scissile bond and—especially for reactions with late transition states—on the relative thermodynamic stability of products from the alternative modes of electron apportionment.

From the point of view of the initial spin delocalization, the vast majority of aniomesolytic reactions result in departure[12] of a negatively charged fragment, i.e. the leaving group is an anion and not a radical (eq 1b). In all such cases, the electron apportionment is consistent with the polarization of the scissile bond, and reflects the lowest energy distribution of electrons between fragments. Recently, it has been postulated[13] that the fragmentation process is controlled by factors other than product stability, and a mode of cleavage requiring a charge transfer across the scissile bond is kinetically preferred.[14]

An appropriate experimental test for the above postulate must involve a system where such a charge shift is contrary to that based on thermodynamic stability of the fragments. Any preexisting polarization within the scissile bond should be minimized. Also, atoms with lone electron pairs should not be part of the breaking bond to avoid any complicating three-electron interactions. In contrast to theoretical[7]

(1) On leave from the Technical University of Łódź (Poland).

(2) Recent references for radical anion fragmentation in solution: (a) Andrieux, C. P.; Gallardo, I.; Saveant, J.-M.; Su, K.-B. *J. Am. Chem. Soc.* **1986**, *108*, 638 and references therein. (b) Meot-Ner (Mautner), M.; Neta, P.; Norris, R. K.; Wilson, K. *J. Phys. Chem.* **1986**, *90*, 168 and references therein. (c) Koppang, M.; Woolsey, N. F.; Bartak, D. E. *J. Am. Chem. Soc.* **1984**, *106*, 2799. (d) Patel, K. M.; Baltisberger, R. J.; Stenberg, V. I.; Woolsey, N. F. *J. Org. Chem.* **1982**, *47*, 4250. (e) Dewald, R. R.; Conlon, N. J.; Song, W. M. *J. Org. Chem.* **1989**, *54*, 261. (f) Beak, P.; Sullivan, T. A. *J. Am. Chem. Soc.* **1982**, *104*, 4450. (g) Saeva, F. D. *Tetrahedron* **1986**, *42*, 6132.

(3) Walsh, T. D. *J. Am. Chem. Soc.* **1987**, *109*, 1511.

(4) Maslak, P.; Narvaez, J. N. *J. Chem. Soc., Chem. Comm.* **1989**, 138.

(5) The reductive cleavage of C–C bonds may involve dianions: (a) Legendijk, A.; Szwarc, M. *J. Am. Chem. Soc.* **1971**, *93*, 5359. (b) Walsh, T. D.; Megremis, T. L. *J. Am. Chem. Soc.* **1981**, *103*, 3897. (c) Grovenstein, E., Jr.; Bhatti, A. M.; Quest, D. E.; Sengupta, D.; VanDerveer, D. *J. Am. Chem. Soc.* **1983**, *105*, 6290 and references therein. (d) Staley, S. W. In *Selective Organic Transformations*; Thyagarajan, B. S. Ed.; Wiley Interscience: New York, 1972; Vol. 2, p 309.

(6) Maslak, P.; Narvaez, J. N. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 283.

(7) For theoretical treatment of the cleavage reaction, see: (a) Canadell, E.; Karafiloglou, P.; Salem, L. *J. Am. Chem. Soc.* **1980**, *102*, 855. (b) Bigot, B.; Roux, D.; Salem, L. *J. Am. Chem. Soc.* **1981**, *103*, 5271. (c) Villar, H.; Castro, E. A.; Rossi, R. A. *Can. J. Chem.* **1982**, *60*, 1525. (d) Clark, T. *J. Chem. Soc., Chem. Comm.* **1984**, 93.

(8) (a) Kornblum, N. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 734. (b) Bunnett, J. *Acc. Chem. Res.* **1978**, *11*, 413. (c) Julliard, M.; Chanon, M. *Chem. Rev.* **1983**, *83*, 425.

(9) See for example: (a) Maercker, A. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 972. (b) See also: refs 2 and 5.

(10) Dressler, R.; Allan, M.; Haselbach, E. *Chimia* **1985**, *39*, 385.

(11) Symons, M. C. R.; Bowman, W. R. *J. Chem. Soc., Perkin Trans. 2* **1988**, 584.

(12) The leaving group is defined as a fragment forming from that part of the initial radical ion which has the smaller (usually negligible) spin density.

(13) Maslak, P.; Guthrie, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 2628 and 2637.

(14) For operational convenience this postulate has been formulated as the preference for spin regioconservation (ref 13).

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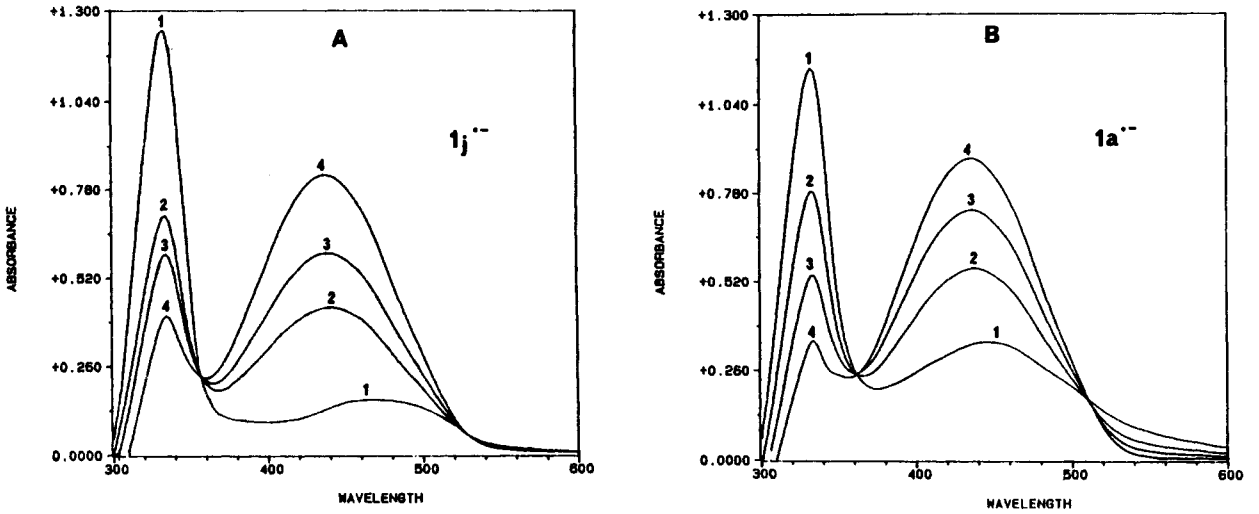


Figure 1. The visible spectra obtained by reduction of **1j** (A) and **1a** (B) with the same amount of Li^+ $TTNB^{\bullet-}$ in Me_2SO at ca. 27 °C. Spectrum 1 (A) is essentially that of pure $\mathbf{1j}^{\bullet-}$ (ca. 0.15 mM). Spectra 4 (A and B) are identical with one obtained for the independently generated $\mathbf{2}^-$. The intermediate scans were taken at arbitrarily selected times to illustrate presence of isosbestic points. Spectra 4 (A and B) were taken after the reaction was essentially complete (i.e. no significant change in the spectra was observed).

calculations, experimental considerations limit such investigation to probing the electron distribution of only three states, the starting radical anion, the transition state, and the products. This investigation attempts to evaluate the charge delocalization accompanying the reaction progress from the starting radical anion to the transition state by probing substituent effects on the fragmentation rate.[15]

An experimental situation satisfying the above requirements has been found[4] in the irreversible unimolecular cleavage of largely nonpolar C–C bonds in radical anions of 1-(4-nitrophenyl)-2-(substituted-phenyl)-1,1,2,2-tetraethylethanes, **1a–m**. This bis-benzylic system yields a resonance-stabilized benzylic anion and benzylic radical upon cleavage of the central C–C bond. Substituent effects on radical[16,17] and anion[18] stability in such conjugated systems have been explored extensively providing a sound data base for our investigation. Importantly, as indicated by molecular mechanics calculations and results of X-ray and NMR analysis,[19,20] the radical anion precursors exist predominantly in a conformation allowing for direct overlap between the scissile bond and the π-system. This conformation should not be affected by one-electron reduction.

The cleavage reaction is estimated to be endergonic and should possess a late transition state (see below). For all compounds in the series, the most stable fragments are the *p*-nitrobenzyl anion and para-substituted benzyl radical. The reverse mode of electron apportionment would require a substantial amount of energy. Even in the most favorable case of $\mathbf{1a}^{\bullet-}$, this energy gap[21] would amount to ca. 10 kcal/mol. Thus, little charge transfer across the scissile bond would be expected in the transition state if it were to reflect the distribution of electron density of the most stable products.

Results and Discussion

The radical anions of **1a–m** were generated by electron transfer from lithium 2,4,6-tri-*tert*-butylnitrobenzenide[13,22] (Li^+ $TTNB^{\bullet-}$) and sodium or potassium 1-(*N*,*N*-dimethylamino)naphthalenide[23] (Na^+ or K^+ $DMAN^{\bullet-}$). The electron transfer from these reducing agents to **1** was complete upon mixing, as expected from reduction potentials[24] and confirmed by ESR spectra. In Me_2SO, ESR spectra for all compounds displayed indistinguishable 27-peak patterns with coupling constants very similar to that observed for the *p*-*tert*-butylnitrobenzene radical anion (see Experimental Section). This observation indicates that the unpaired electron is initially highly localized in the nitrophenyl moiety as required for unambiguous interpretation of substituent effects.

The ESR signal for all radical anions decayed in unimolecular fashion. Linear first-order plots were obtained for up to 4 half-lives. No other ESR active species were observed during the decays. The most extensive kinetic data were obtained in Me_2SO for the Li^+ salts of the radical anions of **1a–m**. Under similar conditions Na^+ $\mathbf{1j}^{\bullet-}$ and K^+ $\mathbf{1j}^{\bullet-}$ yielded ESR spectra and rates of decay identical with that observed for the Li^+ salt. It can be, therefore, safely assumed that only free ions are present in this solvent. The kinetic data are collected in Table I.

Under conditions similar to kinetic studies, the radical anions of **1a–m** were converted to the 3-(4′-nitrophenyl)-pentyl anion ($\mathbf{2}^-$) and to the corresponding X-substituted benzyl radicals as predicted by thermodynamic considerations[25,26] (see above). The anion could be directly ob-

(15) Hammett, L. P. *J. Am. Chem. Soc.* **1937**, *56*, 96.
(16) Dust, J. M.; Arnold, D. R. *J. Am. Chem. Soc.* **1983**, *105*, 1221 and 6531.
(17) Creary, X.; Mehrsheikh-Mohammadi, M. E.; McDonald, S. *J. Org. Chem.* **1987**, *52*, 3254.
(18) For a compilation of σ values see: Exner, O. In *Correlation Analysis in Chemistry*; Chapman, N. B., Shorter, J. Eds.; Plenum Press: New York, 1978.
(19) Krat, G.; Beckhaus, H.-D.; Lindner, H. J.; Rüchardt, C. *Chem. Ber.* **1983**, *116*, 3235.
(20) Maslak, P.; Narvaez, J. N.; Parvez, M., in preparation.
(21) We are indebted to Dr. D. D. M. Wayner for measurements of redox potentials of cumyl radicals (for the technique see: Wayner, D. D. M.; McPhee, D. J.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 132). The reduction potential of *p*-cyanocumyl radical was measured as −1.05 vs SCE. The corresponding *p*-nitro radical is reduced at ca. −0.61 V vs SCE (ref 6).
(22) Guthrie, R. D.; Hartmann, C.; Neill, R.; Nutter, D. E. *J. Org. Chem.* **1987**, *52*, 736.
(23) Bank, S.; Platz, M. *Tetrahedron Lett.* **1973**, *23*, 2097.
(24) The reduction potential of TTNB in CH_3CN is −1.50 V (Geske, D. H.; Ragle, J. L.; Bambenek, M. A.; Balch, A. L. *J. Am. Chem. Soc.* **1964**, *86*, 987). The reduction potential of DMAN in DMF is −2.58 V (Zweig, A.; Maurer, A. H.; Roberts, B. G. *J. Org. Chem.* **1967**, *32*, 1322). The reduction potential of 4-nitrotoluene in CH_3CN is −1.20 V (ref 27). All potentials were measured vs SCE.
(25) The detailed product studies and attempts to trap the primary products[26] will be described elsewhere.

Table I. Kinetic Data[a] for Unimolecular Fragmentation of Li^+ $1^{\bullet-}$

compd	X	10^3 k, s^{-1}	σ^- or σ^h	$\sigma^{\bullet}_C$[i]	$\sigma^{\bullet}_A$[j]
a	*p*-CN	23.41	0.95[d]	0.46	0.040
b	*p*-CF_3	9.33	0.74	0.08	−0.009
c	*p*-CH_3CO	9.29	0.84	(0.54)[b]	0.060
d	*p*-$NMe_3^+I^-$	3.98	0.64[e]	(0.0)[f]	(0.0)[f]
e	*m*-CF_3	2.32	0.46	−0.07	−0.017
f	*m*-CN	1.79	0.62	−0.12	−0.026
g	*p*-Cl	1.28	0.24	0.12	0.011
h	*m*-F	1.25	0.34	−0.05	−0.009
i	*m*-CO_2Me	0.99	0.35	(−0.06)[b]	−0.014
j	H	0.65	0.0	0.0	0.0
k	*p*-NMe_2	0.54	−0.32	0.90	(0.104)[c]
l	*p*-F	0.45	0.00[g]	−0.08	−0.011
m	*p*-OMe	0.38	−0.28	0.24	0.018

[a] Measured by ESR in Me_2SO at 20 °C, initial concentration ca. 0.1 mM. [b] Calculated from Arnold's data based on the correlation between these scales (see text). [c] Calculated from Creary's data. The large stabilizing effect of *p*-NMe_2 on a radical center was also observed by Bordwell (ref 34). [d] Based on pK_a of *p*-cyano-phenol (13.2) in Me_2SO (ref 33). The pK_a values correlate very well with σ^- values (ref 31). The σ^- value calculated from this correlation is 0.91. The recommended values (ref 18) are 0.88–1.02. Since the solution-assisted resonance effects (refs 31 and 32) are larger for carbon acids than for oxygen acids, the 0.95 value seems appropriate. [e] The negative-charge stabilization by Me_3N^+ is diminished in Me_2SO, as indicated by pK_a = 14.7 of the corresponding phenol (ref 33). The literature (ref 18) values for this substituent are 0.66–0.96. [f] Assumed. Exclusion of this point does not significantly affect the double-parameter correlations. [g] Based on pK_a of *p*-fluorophenol (18.1) in Me_2SO (ref 33). [h] Reference 18. [i] Reference 17. [j] Reference 16.

served by UV/vis spectroscopy (Figure 1) or by NMR. The radicals were not detected by ESR or UV/vis.

Two examples of the quantitative conversion of radical anions into the anion (2^-) are shown in Figure 1. Both spectra were obtained by reducing the radical anion precursors (**1a** and **1j**) with the same amount of Li^+ TTNB$^{\bullet-}$ solution. In the case of **1j**, the first spectrum (obtained as rapidly as possible after mixing) is identical with one obtained by reduction of *p-tert*-butylnitrobenzene (i.e. **1a**–**m**$^{\bullet-}$ have λ_{max} = 333 and 462 nm). The last spectrum taken represents a point were changes in intensity of the two bands were no longer noticeable. This last spectrum is identical with one obtained by treatment of 3-(4′-nitrophenyl)pentane with an excess of dimsyl anion (i.e. 2^- has λ_{max} = 333 and 436 nm). The two arbitrarily selected intermediate scans illustrate clearly the isosbestic points for the process. The first spectrum obtained for the more rapidly decaying radical anion of **1a** (see below) already shows some reaction. The initial absorbance at 333 nm is lower than that observed for **1j**$^{\bullet-}$, and the presence of significant amount of 2^- is apparent. However, at the end of the reaction there is no significant difference between the amount of 2^- present in the two cases. Similar results were obtained for other radical anions under study. These observations clearly indicate that the measured rates correspond to the cleavage of the central C–C bond, and that, under the conditions of the kinetic measurements, the stoichiometry of the reduction is the same for all compounds. An estimate of extinction coefficients of $1^{\bullet-}$ and 2^- (see Experimental Section) indicated that one molecule of radical anion yields one molecule of 2^-. Thus, the radical fragments were not reduced by $1^{\bullet-}$ to the corresponding anions under these conditions.

In reactions carried out on a preparative scale, where the concentration of the radical anions was at least 10 times higher, the radicals yielded both coupling and reduction products.[25,26] The identity of the isolated products depended on the work-up procedure.[25] For example, 3-(4′-nitrophenyl)pentane was obtained quantitatively only upon quenching of the reaction mixtures with carefully deoxygenated water (or MeOH). Under typical conditions where the quenching agent was not deoxygenated, large quantities of 3-(4′-nitrophenyl)pentan-3-ol and other products of oxidation of 2^- were also produced. For instance,[25] after quenching with O_2 the products from the cleavage of **1a**$^{\bullet-}$ included 3-(4′-nitrophenyl)pentan-3-ol (95%) and 3-(4′-cyanophenyl)pentane (96%). After quenching with O_2/MeOH/H_2O, the radical anion of **1j** gave 3-(4′-nitrophenyl)pentane (51%), 3-(4′-nitrophenyl)pentan-3-ol (16%), 1-(4′-nitrophenyl)propanone (27%), 3-phenylpentane (3%), and a tetramer derived from the 3-phenyl-3-pentyl radical (80%). Similarly, after MeOH/H_2O quenching, **1k**$^{\bullet-}$ yielded 3-(4′-nitrophenyl)-pentane (25%), 3-(4′-nitrophenyl)-pentan-3-ol (60%), 2,4-diethyl-3,4-bis[4′-(dimethylamino)phenyl]hexane (30%), and 3-[4′-(*N*,*N*-dimethylamino)phenyl]pentan-3-ol (50%).

Activation parameters were estimated from rate constants measured at several temperatures (six or more) in the 15–45 °C range. At 20 °C, the free energies of activation for the most rapidly (**1a**$^{\bullet-}$) and most slowly (**1m**$^{\bullet-}$) decaying radical anions were 19.5 kcal/mol ($\Delta H^{\ddagger}$ = 17.1 ± 0.9 kcal/mol, $\Delta S^{\ddagger}$ = −8 ± 4 eu) and 21.5 kcal/mol ($\Delta H^{\ddagger}$ = 22.8 ± 0.8 kcal/mol, $\Delta S^{\ddagger}$ = 3 ± 2 eu), respectively. The observed activation parameters exclude an intramolecular electron jump to the other ring as a kinetically significant step. In the most favorable case (**1a**$^{\bullet-}$) such an electron jump would require $\Delta G^{\ddagger}$ = 27 kcal/mol, since the difference in the reduction potentials of *p*-nitrotoluene[27] and *p*-cyanotoluene[28] is almost 1.2 V.

A comparison of these activation energies with those observed for homolytic cleavage of the parent hydrocarbon[29] or one of its substituted derivatives, **1k**, allows us to approximately place the transition state for radical anion cleavage along the reaction coordinate. The free energy of activation for homolytic cleavage of 3,4-diethyl-3,4-diphenylhexane[29] calculated at 293 K is ca. 33 kcal/mol, and that for **1k** is 34 kcal/mol.[6] As expected, substitution on the phenyl ring has only a small effect on the activation energy for homolysis. The reverse reaction, radical coupling, is believed[29] to have a very small activation energy, due mostly to entropic factors. Under such conditions, the activation energy may serve as an approximation (upper limit) of the free energy of the homolytic process (ΔG(**1**)).

The free-energy change for the radical anion cleavage, $\Delta G(1^{\bullet-})$, can be estimated[6] from the free energy of homolysis, ΔG(**1**), and the difference (ΔE) between redox potentials of **1** and 2^-. This estimate is based on a simple thermodynamic cycle, wherein the aniomesolytic cleavage

(26) The observed or isolated products may not be assumed to be derived from the primary products. Primary products are defined as the fragments produced directly from the scission process. If, for some reason, the primary products did not represent the most stable electron apportionment, a rapid electron-transfer equilibration would be expected to follow.

(27) Maki, A. H.; Geske, D. H. *J. Am. Chem. Soc.* **1961**, *83*, 1852.

(28) Rieger, P. H.; Bernal, I.; Reinmuth, W. H.; Fraenkel, G. *J. Am. Chem. Soc.* **1963**, *85*, 683. The reduction potential of *p*-cyanotoluene in DMF is −2.75 V vs Ag electrode. The reduction potentials of 7,7,8,8-tetracyanoquinodimethane and 4-nitrobenzonitrile measured under identical conditions are −0.2 and −1.25 V. The redox potentials of these compounds measured in CH_3CN vs SCE gave 0.19 (Peover, M. E. *Trans. Faraday Soc.* **1962**, *58*, 2370) and −0.88 V (ref 27). These data imply a solvent and reference electrode correction of ca. 0.38 V, yielding a 2.38 V value for *p*-cyanotoluene in CH_3CN vs SCE.

(29) Krat, G.; Beckhaus, H.-D.; Rüchardt, C. *Chem. Ber.* **1984**, *117*, 1748.

is related to the homolytic process by one-electron reduction of 1 and one-electron oxidation of 2^-. The difference in these redox potentials (ΔE) is ca. 14 kcal/mol.[6] The driving force for the radical anion cleavage ($\Delta G(1^{\bullet-}) = \Delta G(1) - \Delta E$) is, therefore, ca. 19–21 kcal/mol. This value is very close to the measured activation energies for cleavage of **1a–m**$^{\bullet-}$, indicating that the transition state for fragmentation of $1^{\bullet-}$ must be late and resemble the products.

The ESR spectrum of ^{13}C2-labeled $\mathbf{1l}^{\bullet-}$ has confirmed that the scissile bond overlaps with the π-system. The coupling constant of that carbon was substantial (a_{C2} = 3.4 G), suggesting that the conformation of these radical anions is similar to that observed for the neutral molecules (NMR, molecular mechanics, X-ray).[19,20]

In summary, the irreversible C–C bond scission in $1^{\bullet-}$ provides an experimentally unambiguous system where the initial unpaired electron density is highly localized, and where the redistribution of the electron density is associated only with the breaking of the C–C bond. This process should be quite smooth since the scissile bond is able to overlap with the π-system. The predicted late transition state and thermodynamic considerations suggest that the relative rates of cleavage should reflect the radical-stabilizing effect of the X substituents.

Recently, two independent $\sigma^{\bullet}$ scales have been established for benzylic radicals. The Creary scale ($\sigma^{\bullet}_C$) is based on rearrangement of arylmethylenecyclopropanes.[17] The Arnold scale ($\sigma^{\bullet}_A$) is derived from ESR coupling constants of benzylic radicals.[16] Both scales are apparently free from polar effects and are linearly related ($\sigma^{\bullet}_C = 0.051 + 8.13\sigma^{\bullet}_A$, $r = 0.94$, $n = 16$). Arnold et al. have also shown[30] that cumyl radicals yield similar $\sigma^{\bullet}$ values with minor polar deviations for para substituents. When applied to our data, all these scales yield almost identical results, and for reasons of clarity we will limit our discussion to the more extensive $\sigma^{\bullet}_A$ parameters.

The most appropriate[18] substituent constants reflecting relative stabilization of a negative charge for our benzylic system are σ^- values which include the possibility of direct resonance. However, with the exception of strongly electron withdrawing substituents in the para position and *p*-F group, σ^-'s are identical[18] with σ's. A minor complication is caused by the fact that these parameters are somewhat solvent dependent,[31,32] especially for charged or strongly interacting substituents. The selection of appropriate σ^- values for our study was based on the extensive pK_a measurement[33] in Me_2SO for substituted phenols. In most cases these values agree well with those recommended by Exner.[18] It should be pointed out, nevertheless, that in analyses of substituent effects, the selection of the substituent constants (σ) is always to some degree arbitrary. Accordingly, our discussion is based mostly on the observed trends rather than on strict analysis of the regression coefficients. The substituent constants selected for analysis of our data are collected in Table I.

The relative rates of cleavage do not correlate at all with $\sigma^{\bullet}$ parameters. Lack of such correlation excludes formation of an unpolarized or weakly polarized radical center on carbon 2 in the transition state. An interesting trend appears, however, when the kinetic data are plotted against

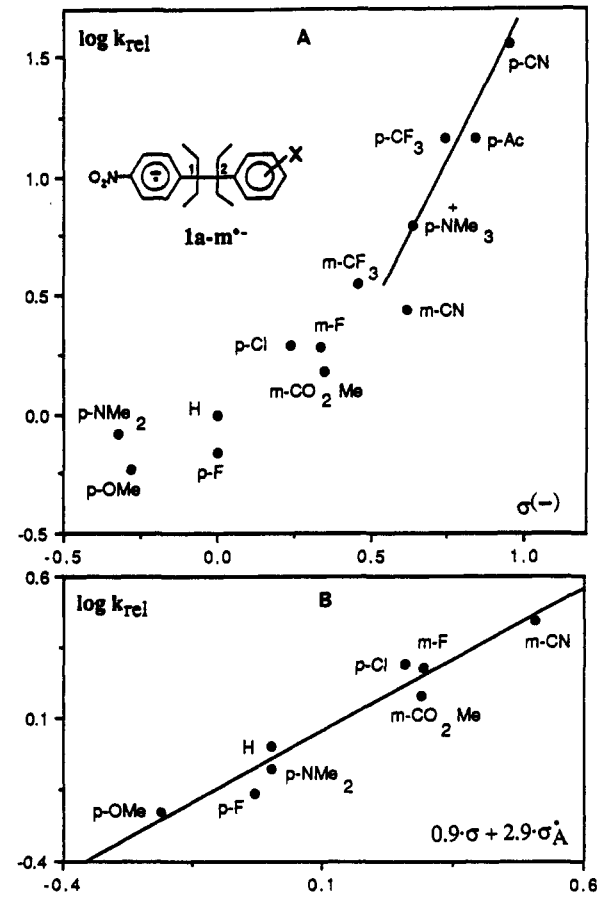


Figure 2. Hammett plot for relative rates of cleavage of Li^+ $1^{\bullet-}$ in Me_2SO at 20 °C. Part A includes all data points plotted vs σ^-. The line drawn corresponds to $\rho^- = 2.5$. Part B shows a double parameter correlation for compounds with slowest rates.

σ^- parameters (Figure 2A). A pronounced upward curvature of the plot is observed for electron-withdrawing substituents reaching a ρ^- value of ca. 2.5. This trend is consistent with the development of a significant negative charge on carbon 2, contrary to predictions based on thermodynamic considerations (see above).

A linear relation is obtained when a double parameter equation[16] is used which takes into account both radical and anion stabilization by the substituents ($\log k_{rel} = 1.4\ (\pm 0.1)\sigma^- + 4.4\ (\pm 1.2)\sigma^{\bullet}_A$; $r = 0.968$, where ρ^- and $\rho^{\bullet}$ are obtained from the fitting procedure). A closer analysis indicates, however, that the good correlation is due mostly to the eight compounds with slowest rates (**1f–m**$^{\bullet-}$). The other radical anions (**1a–e**$^{\bullet-}$) show large deviations from the best fit line. For example, $\mathbf{1f}^{\bullet-}$ (X = *m*-CN) falls below the line while radical anions bearing the *p*-CF_3 group or *p*-CN lie significantly above the correlation line. Taking into account that *m*-CN and *p*-CF_3 substituents are predicted to destabilize the radical center and that the *p*-CN group is expected to stabilize it, these trends indicate that radical stabilizing (destabilizing) abilities are not important for the most rapidly decaying radical anions. In fact, the double parameter equation obtained for **1f–m**$^{\bullet-}$ (Figure 2B) gives a slightly better fit ($\log k_{rel} = 0.9\ (\pm 0.1)\sigma^- + 2.9\ (\pm 0.9)\sigma^{\bullet}_A$; $r = 0.972$).

Accordingly, we propose that the observed nonlinearity of the Hammett plot is due to the interference of two distinctive modes of cleavage. The rates for the radical anions with strongly electron withdrawing substituents correlate with σ^- parameters alone. Particularly informative data points are provided by the radical anions with *p*-trimethylammonium and *p*-trifluoromethyl groups (**1b**$^{\bullet-}$

(30) Arnold, D. R.; Nicholas, A. M. de P.; Snow, M. S. *Can. J. Chem.* **1985**, *63*, 1150.
(31) Bordwell, F. G. *Acc. Chem. Res.* **1988**, *21*, 456.
(32) Taft, R. W.; Bordwell, F. G. *Acc. Chem. Res.* **1988**, *21*, 463.
(33) Bordwell, F. G.; McCallum, R. J.; Olmstead, W. N. *J. Org. Chem.* **1984**, *49*, 1424. We are thankful to Prof. Bordwell for providing additional pK_a data. A few pK_a data can also be found: Arnett, E. M.; Venkatasubramaniam, K. G. *J. Org. Chem.* **1983**, *48*, 1569.

and $\mathbf{1d}^{\bullet-}$). The former substituent is not expected to stabilize the radical center and the latter most probably destabilizes the radical ($\sigma^{\bullet}_{A} = -0.009$). The destabilizing effect of the p-CF_3 was also found by Bordwell.[34] The fit of these points into the correlation with other electron-withdrawing groups which are able to stabilize the radical center supports the mechanism based mainly on charge delocalization across the scissile bond. This mode of cleavage may, perhaps, be formally described as an elimination-like process.[8a,35]

The importance of the charge delocalization across the scissile bond in the transition state is also emphasized by the data obtained for the dinitro derivative **1n** (X = p-NO_2).[36] The radical anion of **1n** decays at least 10^3 times faster than $\mathbf{1a}^{\bullet-}$. The decay of $\mathbf{1n}^{\bullet-}$ is, however, *bimolecular*. It involves formation and rapid fragmentation of the dianion, wherein each of the two unpaired electrons is delocalized on one nitroaryl moiety.[36] The cleavage of this dianion can be compared with the radical anion fragmentation in the context of the driving force difference between these two processes.[36] As we have discussed above, $\Delta G(\mathbf{1}^{\bullet-}) = \Delta G(\mathbf{1}) - \Delta E$. By analogy, the driving force for the dianion cleavage $\Delta G(^{-\bullet}\mathbf{1}^{\bullet-}) = \Delta G(\mathbf{1}) - 2\Delta E$, i.e. it is more negative than that for radical anion process by ca. 14 kcal/mol. It is not surprising, therefore, that the dianion fragmentation is faster than the corresponding cleavage of the radical anion. Nevertheless, as already indicated, the radical anion cleavage exhibits only a small intrinsic barrier[6,36] (i.e. $\Delta G^{\ddagger}(\mathbf{1}^{\bullet-}) \approx \Delta G(\mathbf{1}^{\bullet-})$) while the dianion fragmentation has a large kinetic barrier ($\Delta G^{\ddagger}(^{-\bullet}\mathbf{1}^{\bullet-}) \gg \Delta G(^{-\bullet}\mathbf{1}^{\bullet-})$).[36] This disparity is not due to the difference in exergonicity of the two processes,[36] but could be accounted for by the inability of the dianion to delocalize the negative charge across the scissile bond due to charge repulsion.

A comparison of activation energies and free energies for mesolysis between $\mathbf{1m}^{\bullet-}$ and a hypothetical cleavage of $\mathbf{1n}^{\bullet-}$ also provides evidence for the kinetic importance of charge delocalization. For $\mathbf{1m}^{\bullet-}$ the intrinsic barrier ($\Delta G^{\ddagger}(\mathbf{1m}^{\bullet-}) - \Delta G(\mathbf{1m}^{\bullet-})$) is ca. 2.8 kcal/mol.[6] The upper limit for the activation energy for cleavage of $\mathbf{1n}^{\bullet-}$ can be estimated to be 18.5 kcal/mol (see Experimental Section), thus giving the intrinsic barrier of 1.5 kcal/mol or less for this process.[36] This difference illustrates the kinetic advantage of fragmentation with charge transfer (eq 1b). In a hypothetical cleavage of $\mathbf{1n}^{\bullet-}$ the charge can be symmetrically delocalized between the halves in the transition state, and fully transferred to the "departing" fragment.[12] Any benefit of such delocalization is diminished in $\mathbf{1m}^{\bullet-}$, and an alternative mode of scission becomes dominant in this case (see below).

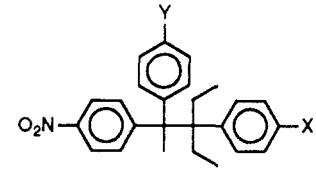
We suggest that the double-parameter correlation obtained for the slowest decaying radical anions ($\mathbf{1f}$–$\mathbf{m}^{\bullet-}$) corresponds to a transition state wherein the extra electron is shared by both benzylic carbons, and the substituent X interacts with both the charge and the spin. These interactions are diagnostically counter productive in some cases. For example, the dimethylamino group strongly stabilizes the radical center ($\sigma^{\bullet}_{A} = 0.104$) but destabilizes the negative charge ($\sigma = -0.32$). The methoxy group behaves similarly.

The ratio $\rho^{\bullet}/\rho^{-} = 3.1$ obtained for $\mathbf{1f}$–$\mathbf{m}^{\bullet-}$ indicates similar importance of stabilization of charge and radical character in the transition state. Arnold et al.[37] have estimated that one σ_A unit corresponds to ca. 22 kcal/mol of radical stabilization energy. The energy equivalent of the σ scale could be estimated from the ρ^{-} value obtained from measurements of pK_a values of the corresponding α,α-dialkylbenzyl anions in Me_2SO. Unfortunately, such data are not available. However, as found[31] by Bordwell, the ρ values differ only slightly for various anions in this solvent. For example, phenols, phenylacetonitriles, and diphenylmethanes have Hammett-plot slopes equal to 5.3, 5.9, and 5.7, respectively. The alkyl groups are expected to increase the ρ value, perhaps to ca. 8–10, which corresponds to ca. 11–14 kcal/mol per σ unit. These estimates would scale the $\rho^{\bullet}/\rho^{-}$ ratio to ca. 1.5–1.9.

A similar response to radical and anion stabilization by the remote substituent has been observed in the electrochemical reduction of substituted benzyl halides.[38,39] The observed reduction potentials yielded an improved correlation[16] when the double parameter treatment was used, giving a $\rho^{\bullet}/\rho^{-}$ ratio equal to 6.7. These reactions are believed to involve dissociative electron transfer from the electrode to the organic acceptor with an apparent strong involvement of the carbon–halogen σ^* orbital.

All these observations point to involvement of a σ^* radical-anion configuration in the transition state for cleavage of $\mathbf{1f}$–$\mathbf{m}^{\bullet-}$. As indicated in the introduction, such a mode of cleavage is operational for radical anions where the scissile bond is orthogonal to the π-system, but is not expected for systems where the orbitals in question can overlap.[11] It is quite possible that the strained structure[40] of our radical anions contributes to the plausibility of this mechanism.

A further confirmation of the coexistence of two modes of cleavage was found in the decay kinetics of radical anions of **3a**–**d**, which are structurally and electronically related to $\mathbf{1b}^{\bullet-}$ and $\mathbf{1l}^{\bullet-}$.



3a: Y = F, X = CF_3
b: Y = F, X = F
c: Y = CF_3, X = CF_3
d: Y = CF_3, X = F

For radical anions with the p-CF_3 substituent on the "leaving" fragment[12] there was no measurable effect of the Y group on the rate of cleavage ($k_{3a}/k_{3c} = 1.0$). However, such an effect was easily observable for X = F ($k_{3d}/k_{3b} = 3.4$). This trend is consistent with a larger charge transfer across the scissile bond in $\mathbf{3a,c}^{\bullet-}$ (X = CF_3 compounds) than in $\mathbf{3b,d}^{\bullet-}$ (X = F series) in analogy to results obtained with $\mathbf{1}^{\bullet-}$.

Summary

The first extensive study of substituent effects on the cleavage of relatively nonpolar C–C bonds[41] in radical anions has provided insight into the mechanism of bond activation in such species. We conclude that the transition

(34) Bordwell, F. G.; Bausch, M. J. *J. Am. Chem. Soc.* **1986**, *108*, 1979.
(35) Kornblum, N. In *The Chemistry of Functional Groups*, Supplement F; Patai, S. Ed.; Wiley: New York, 1983; Chapter 10, p 361.
(36) Maslak, P.; Kula, J.; Narvaez, J. N. *J. Org. Chem.* **1990**, *55*, 2277.
(37) Nicholas, A. M. de P.; Arnold, D. R. *Can. J. Chem.* **1986**, *64*, 270.
(38) Tanner, D. D.; Plambeck, J. A.; Reed, D. W.; Mojelky, T. *J. Org. Chem.* **1980**, *45*, 5177.
(39) Streitwieser, A.; Perrin, C. *J. Am. Chem. Soc.* **1964**, *86*, 4938.
(40) The scissile-bond length in **1** (X = H) is 1.62 Å (X-ray, ref 20). This observation implies a low lying σ^* orbital in **1** and $\mathbf{1}^{\bullet-}$.
(41) Limited studies are described in ref 3. These studies also confirm a significant negative charge shift across the scissile bond.

state for these reactions is best described in terms of at least two electronic configurations. One of these configurations places significant negative charge on the departing fragment[12] (in the case of **1a–d**$^{\bullet-}$, 25% of the total charge assuming $\rho = 10$ for pK_as of the corresponding C–H acids, as discussed above), and perhaps resembles an elimination reaction. The second configuration may be represented as a σ^* radical anion. The fragmentation is kinetically controlled by the ability of the system to delocalize the charge across the scissile bond. For radical anions, where this tendency is reinforced by preexisting polarization of the scissile bond and by the thermodynamic stability of the intended products, the reaction is facile. However, if such a charge shift leads to extensive "counterthermodynamic" charge accumulation on the leaving fragment, an alternative mode of scission becomes dominant. This mode involves a large component of $\pi \rightarrow \sigma^*$ electron transfer followed by dissociation of the three-electron bond.[42]

The observed trends support the postulate[13] of kinetic control of the fragmentation reaction. It has to be noted, however, that the observed polarization of the transition state does not require that the primary products[26] reflect that polarization, as suggested by Walsh.[3] The charge transferred across the scissile bond on the way to the transition state might be transferred back after passage through the highest energy point. This charge redistribution might be accompanied by full solvation of the forming anion. However, the necessity for this redistribution indicates kinetic problems encountered in such systems where the transfer of the charge across the scissile bond is thermodynamically unfavorable. To minimize these problems a σ^* radical anion configuration becomes more dominant, even in systems where the direct overlap between π-SOMO and σ^* is possible. Generally, it is expected that this configuration will be of increased importance for reactions with late transition states where the charge transfer across the scissile bond leads to thermodynamically unfavorable products. The configuration with large charge transfer across the scissile bond will be dominant for early transition states.

Experimental Section

General. ^{1}H NMR spectra were taken on a Bruker WP-200 (200 MHz), Bruker AM-300 (300 MHz), and Bruker AM-360 (360 MHz) spectrometers. ^{13}C NMR spectra were recorded on the Bruker WP-200 (50.3 MHz), Bruker AM-300 (75.5 MHz), and Bruker AM-360 (90.6 MHz) instruments. Chemical shifts are reported in ppm referenced to Me_4Si. Infrared (IR) spectra were obtained by using a Perkin-Elmer Model 281 B infrared spectrophotometer. Absorption peaks are reported in cm^{-1}. All samples were thin film on NaCl plates. Mass spectra were taken on a Kratos MS 9/50 double focusing spectrometer in electron impact (EI) or chemical ionization (CI) mode. The most characteristic peaks in the mass spectra have been labeled, indicating the lost fragment or "half"-molecule fragment ($P^+/2N$ marks the nitro substituted half, $P^+/2X$ indicates the X-substituted half).

Preparative flash chromatography was performed with Machery Nagel silica gel 60, 230–400 mesh. Preparative HPLC was carried out on a Rainin Rabbit HP/HPX system equipped with Knauer variable-wavelength monitor, Shimadzu C-R3A Chromatopac integrator, Rheodyne 7125 sample injector, and 21.4-mm (i.d.) × 25-cm long, 8 μm silica column. For all runs, Aldrich or J. T. Baker HPLC solvents were used at a flow rate of 22 mL/min. Preparative thin-layer chromatography was performed on 1.0-mm Brinkmann precoated silica gel TLC plates with fluorescent indicator. Analytical thin-layer chromatography was carried out on EM precoated silica gel (0.25 mm) F_{254} plates. The proportion of solvents in mixtures used in chromatography techniques is reported as volume to volume ratios. All reagents, unless otherwise stated, were purchased from Aldrich. Anhydrous tetrahydrofuran and diethyl ether were distilled from potassium/sodium/benzophenone under argon.

Synthesis of Radical Anion Precursors. The nitro compounds were prepared by a modification of the procedure[19] developed by Rüchard et al. Most of the compounds were repeatedly recrystallized from EtOH before use. The details of structure of 1 are described elsewhere.[19,20]

3,4-Diethyl-3-(4′-nitrophenyl)-4-phenylhexane (1j). A solution of bromobenzene (20.0 g, 0.127 mol) in 100 mL of anhydrous THF was added dropwise to mechanically stirred magnesium turnings (3.1 g, 0.127 mol). When the reaction became vigorous an additional 100 mL of THF was poured in. The addition of bromobenzene was complete in 0.5 h, and the mixture was stirred for an additional 0.5 h. To the Grignard reagent a 1:1 THF solution of 3-pentanone (8.8 g, 0.102 mol) was added by drops over 1.0 h. The resulting thick white mixture was stirred for an additional 0.5 h and then treated with 200 mL of 20% NH_4Cl aqueous solution. The mixture was extracted twice with ether, and the combined organic fractions were dried over Na_2SO_4. The solvent was removed in vacuo and the desired 3-phenylpentan-3-ol purified by distillation under reduced pressure (bp 56 °C, 2 Torr, ca. 80% yield).

Mechanically stirred 3-phenylpentan-3-ol (10.33 g, 0.063 mol) was cooled to between 5 and 10 °C in an ice–salt bath and then treated with 42 mL of 40% hydrobromic acid in acetic acid, added through a dropping funnel at a slow enough rate to maintain the reaction temperature below 0 °C. The addition lasted ca. 1 h, after which the orange-pink slush was allowed to stir for an additional 0.5 h at 0 °C. Zinc dust (12.5 g, 0.19 mol) was then added in small portions so as to maintain the temperature below 5 °C. After all the zinc was added, the gray mixture was allowed to come to room temperature and then poured into water and extracted twice with hexane. The combined organic layers were washed with saturated aqueous sodium bicarbonate solution and water and dried over Na_2SO_4, and the solvent was removed in vacuo. The remaining light yellow oil was purified by flash column chromatography with hexane as an eluant (ca. 50% yield; 3-[4′-(3″-pentyl)phenyl]-3-phenylpentane was collected as a major impurity). A small sample of the column-purified 3,4-diethyl-3,4-diphenylhexane was purified further by preparative HPLC (99% hexane–1% CH_2Cl_2) and crystallized from ethanol, mp 40–42 °C (lit.[19] mp 46–47 °C). ^{1}H NMR (200 MHz, $CDCl_3$): 7.10–7.14 (m, 6 H), 6.92–7.00 (m, 4 H), 1.99 (q, J = 8 Hz, 8 H), 0.64 (t, J = 8.0 Hz, 12 H). IR: 3080, 3050, 2970, 2930, 2870, 1955, 1805, 1595, 1575, 1490, 1455, 1435, 1365, 1305, 1180, 1140, 1115, 1095, 1055, 1015, 895, 875, 840, 815, 805, 765, 730, 680. MS (EI, m/e, relative intensity): 294 (P^+, 3), 265 (P^+ – Et, 57), 236 (P^+ – 2Et, 2), 221 (2), 195 (2), 147 ($P^+/2$, 68), 117 (17), 115 (7), 105 (84), 91 (100).

To a stirred solution of 3,4-diethyl-3,4-diphenylhexane (5.0 g, 0.017 mol) in 100 mL of acetic anhydride 3 mol equiv of concentrated nitric acid (3.5 mL, 0.050 mol) were added. The nitric acid was added slowly so as to maintain the temperature of the solution near room temperature. After about 2 h, TLC analysis with 50% hexane–50% CH_2Cl_2 eluant showed three major spots corresponding to starting material (R_f 0.90), mononitrated product (R_f 0.65), and dinitrated product (R_f 0.40). The reaction mixture was poured into a large volume of ice–water (500 mL) and stirred until the acetic anhydride was completely hydrolyzed. The organic residue was extracted into hexane (2 × 200 mL) and washed twice with saturated aqueous $NaHCO_3$ and once with water. The hexane layer was dried over anhydrous Na_2SO_4 and the solvent was removed in vacuo. Separation by flash column chromatography (hexane–CH_2Cl_2 gradient) and crystallization from absolute ethanol afforded the desired **1j** in ca. 20% yield (1.1 g, 0.003 mol), mp 81–83 °C. The structure of **1j** was confirmed by single-crystal X-ray analysis.[20] ^{1}H NMR (360 MHz, $CDCl_3$): 7.97 (d, J = 9.0 Hz, 2 H), 7.12 (m, 3 H), 7.02 (d, J = 9.0 Hz, 2 H), 6.87 (m, 2 H), 2.11 (m, 2 H), 2.00 (m, 6 H), 0.73 (t, J = 8.0 Hz, 6 H), 0.71 (t, J = 8.0 Hz, 6 H). ^{13}C NMR (125.8 MHz, $CDCl_3$): 153.1, 145.3, 143.3, 130.7, 129.7, 126.5, 125.5, 121.2, 52.6, 51.9, 25.3, 25.1, 10.4, 10.3. IR: 3080, 3050, 2970, 2940, 2880, 1600, 1590, 1510, 1455, 1370,

(42) Similar conclusions for cleavage of C–O bonds have been obtained by an elegant method developed by R. D. Guthrie (Guthrie, R. D.; Shi, B. *J. Am. Chem. Soc.* **1990**, *112*, 3136).

1335, 1175, 1120, 1090, 1065, 1035, 1020, 995, 835, 810, 735, 705, 685. MS (EI, *m/e*, relative intensity): 310 (P^+ – Et, 1), 240 (2), 193 ($P^+/2N$ + 1, 36), 147 ($P^+/2X$, 48), 117 (11), 115 (8), 105 (76), 91 (100), 77 (4).

From the same reaction mixture the more polar **3,4-diethyl-3,4-bis(4′-nitrophenyl)hexane (1n)** was isolated in 30% yield, mp 105–106 °C. The structure of this compound was confirmed by X-ray analysis.[20] ^1H NMR (360 MHz, $CDCl_3$): 8.02 (d, J = 9.0 Hz, 4 H), 7.05 (d, J = 9.0 Hz, 4 H), 1.94–2.15 (m, 8 H), 0.75 (t, J = 7.28 Hz, 12 H). ^{13}C NMR (90.6 MHz, $CDCl_3$): 152.0, 145.7, 130.6, 121.5, 52.7, 25.5, 10.2. MS (EI, *m/e*, relative intensity): 355 (P^+ – Et, 2), 337 (P^+ – NO_2 + 1, 2), 326 (P^+ – 2Et, 13), 308 (11), 296 (8), 193 ($P^+/2N$ + 1, 100), 176 (5), 164 (15), 161 (6), 150 (91), 146 (18), 136 (33), 131 (19), 120 (11), 116 (23), 106 (12), 104 (17), 91 (15), 78 (12).

3,4-Diethyl-3-(4′-nitrophenyl)-4-[4″-(*N*,*N*-dimethylamino)phenyl]hexane (1k). 3,4-Diethyl-3,4-bis(4′-nitrophenyl)hexane (**1n**, 240 mg, 0.625 mmol) was dissolved in 100 mL of ethanol and then treated with approximately 250 mg of 10% Pd/C catalyst and 3 equiv of hydrazine monohydrate (91 μL, 1.88 mmol). The mixture was refluxed for 20 min and filtered to remove the catalyst, and the solvent was evaporated in vacuo. The residue was dissolved in dichloromethane, washed with water, and dried over sodium sulfate, and the solvent was removed once again. Flash column chromatography using a hexane–ethyl acetate gradient gave starting material, mono-amino, and bis-amino products in ca. 25%, 50%, and 25% yield, respectively. The monoamino compound, 3,4-diethyl-3-(4′-nitrophenyl)-4-(4″-aminophenyl)hexane (77.8 mg, 0.22 mmol), was dissolved in 7 mL of acetonitrile and treated with 37% formaldehyde–water (187 μL, Fisher), sodium cyanoborohydrate (41 mg), and glacial acetic acid (23 μL). After 3.5 h, a second portion of acetic acid (23 μL) was added and stirring continued for 0.5 h. The reaction mixture was then diluted with 30 mL of ether and washed twice with 1 M KOH solution and once with brine. The organic layer was dried over anhydrous Na_2SO_4, and the solvent was evaporated in vacuo. The residue was purified by column chromatography using petroleum ether–ethyl acetate eluant (9:1, R_f 0.7). Crystallization from ethanol gave orange crystals of **1k** in 60% yield, mp 105–106 °C. The structure of this compound was confirmed by X-ray.[20] ^1H NMR (360 MHz, $CDCl_3$): 7.97 (d, J = 9.0 Hz, 2 H), 7.04 (d, J = 9.0 Hz, 2 H), 6.71 (d, J = 8.5 Hz, 2 H), 6.52 (d, J = 8.5 Hz, 2 H), 2.92 (s, 6 H), 2.10 (m, 2 H), 1.96 (m, 6 H), 0.73 (t, J = 8.2 Hz, 1 H). ^{13}C NMR (125.8 MHz, $CDCl_3$): 153.6, 148.2, 145.2, 131.0, 130.6, 130.4, 121.1, 110.6, 52.9, 51.2, 40.4, 25.5, 25.4, 10.5, 10.4. MS (EI, *m/e*, relative intensity): 353 (P^+ – Et, 0.5), 335 (P^+ – NO_2 – 1, 2), 324 (P^+ – 2Et, 2), 306 (14), 190 ($P^+/2X$, 100), 175 (6), 162 (17), 160 (41), 148 (8), 145 (13), 144 (11), 136 (10), 134 (13), 130 (10), 116 (16), 91 (9), 77 (6). MS (CI – CH_4, *m/e*, relative intensity): 228 (3), 218 (2), 190 (100), 174 (4), 162 (20).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(4″-methoxyphenyl)hexane (1m). 3,4-Diethyl-3-(4-nitrophenyl)-4-(4-aminophenyl)hexane (330 mg, 0.9 mmol) in 5 mL of dry ether was added to 3 equiv of boron trifluoride etherate (330 μL) at −15 °C. To this rapidly stirring mixture was added 1.2 equiv of *tert*-butyl nitrite (130 μL) in 2 mL of dry ether by drops over 10 min. The temperature was maintained at −15 °C for 10 more min and then allowed to rise to 0 °C, and the mixture was stirred for 20 min. During this time the cloudy yellow mixture turned dark green and a tarry precipitate formed on the flask and stirring bar. The supernatant was decanted and the brown residue rinsed with a fresh portion of dry ether. The crude diazonium tetrafluoroborate was dissolved in 100 mL of methanol and refluxed for 1.5 h. The methanol was removed in vacuo and the crude product separated by column chromatography (hexane–CH_2Cl_2 gradient) followed by preparative TLC with use of petroleum ether–ethyl acetate (9:1). A colorless oil, pure by NMR, was collected in 3% yield (11.1 mg, 0.03 mmol). ^1H NMR (300 MHz, $CDCl_3$): 7.97 (d, J = 9.0 Hz, 2 H), 7.02 (d, J = 9.0 Hz, 2 H), 6.76 (d, J = 9.0 Hz, 2 H), 6.68 (d, J = 9.0 Hz, 2 H), 3.79 (s, 3 H), 1.84–2.18 (m, 8 H), 0.71–0.78 (m, 12 H). MS (EI, *m/e*, relative intensity): 340 (P^+ – Et, 0.5), 323 (P^+ – NO_2, 1), 311 (P^+ – 2Et), 293 (6), 193 ($P^+/2N$ + 1, 4), 177 ($P^+/2X$, 100), 163 (5), 149 (11), 147 (14), 135 (44), 121 (83), 117 (5), 115 (9), 105 (6), 103 (6), 91 (12), 77 (6), 69 (7).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(4″-fluorophenyl)hexane (1l) was prepared by the Grignard reaction of (4-fluorophenyl)magnesium bromide and 3-pentanone followed by coupling of the resulting 3-(4′-fluorophenyl)pentan-3-ol with 3-phenylpentan-3-ol, by using the procedure described for **1j**. The resulting mixture of dimers was nitrated in acetic anhydride as described for **1j** and separated by flash column chromatography (hexane–CH_2Cl_2 gradient). The desired product was further purified by HPLC (hexane–CH_2Cl_2, 9:1), giving **1l** in 10% overall yield. **1l** was also prepared in 5% yield by the thermal decomposition in vacuo of the diazonium tetrafluoroborate salt described above. ^1H NMR (300 MHz, $CDCl_3$): 7.99 (d, J = 9.0 Hz, 2 H), 7.02 (d, J = 9.0 Hz, 2 H), 6.80–6.84 (m, 4 H), 1.86–2.15 (m, 8 H), 0.71–0.77 (m, 12 H). MS (EI, *m/e*, relative intensity): 355 (P^+ – 2, 1), 338 (P^+ – F, 2), 326 (P^+ – 2 – Et, 13), 296 (19), 193 ($P^+/2N$ + 1, 12), 165 ($P^+/2X$, 36), 150 (28), 135 (33), 123 (52), 115 (26), 109 (100), 103 (11), 91 (17), 83 (6), 78 (9).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(3″-fluorophenyl)hexane (1h) was prepared by the Grignard reaction of (3-fluorophenyl)magnesium bromide and 3-pentanone followed by coupling of the resulting 3-(3′-fluorophenyl)pentan-3-ol with 3-phenylpentan-3-ol, by using the procedure described for **1j**. The crude product was nitrated in acetic anhydride as described above, then purified by column chromatography (hexane–CH_2Cl_2 gradient) and crystallized from absolute ethanol giving **1h** in 10% overall yield, mp 65.5–66.5 °C. ^1H NMR (200 MHz, $CDCl_3$): 8.00 (d, J = 9.0 Hz, 2 H), 7.07 (d, J = 9.0 Hz, 2 H), 7.00–7.16 (m, br, 1 H), 6.80–6.93 (m, br, 1 H), 6.63 (d, J = 8.5 Hz, 2 H), 1.82–2.21 (m, 8 H), 0.75 (t, J = 7.5 Hz, 12 H). MS (EI, *m/e*, relative intensity): 328 (P^+ – Et, 2), 258 (3), 193 ($P^+/2N$ + 1, 54), 165 ($P^+/2X$, 28), 150 (12), 147 (10), 137 (13), 135 (11), 123 (100), 115 (11), 109 (77), 105 (16), 91 (24), 78 (7), 69 (8).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(4″-chlorophenyl)hexane (1g) was prepared by the Grignard reaction of (4-chlorophenyl)magnesium bromide and 3-pentanone followed by coupling of the resulting 3-(4-chlorophenyl)pentan-3-ol with 3-phenylpentan-3-ol, by using the procedure described for **1j**. Nitration in acetic anhydride, column chromatography (hexane–CH_2Cl_2 gradient), and crystallization from ethanol afforded the final product in 10% overall yield as colorless crystals, mp 84–85 °C. ^1H NMR (300 MHz, $CDCl_3$): 7.99 (d, J = 9.0 Hz, 2 H), 7.12 (d, J = 8.8 Hz, 2 H), 7.03 (d, J = 9.0 Hz, 2 H), 6.78 (d, J = 8.8 Hz, 2 H), 1.84–2.16 (m, 8 H), 0.74 (t, J = 8.75 Hz, 6 H), 0.73 (t, J = 8.75 Hz, 6 H). MS (EI, *m/e*, relative intensity): 194 ($P^+/2N$ + 2, 45), 183 ($P^+/2X$, 17.5), 181 ($P^+/2X$, 55), 151 (8), 141 (20), 139 (62), 137 (8), 127 (34), 125 (100), 115 (16), 103 (12), 91 (10), 78 (7).

3,4-Diethyl-3-phenyl-4-(3′-formylphenyl)hexane. 3,4-Diethyl-3-phenyl-4-(3′-methylphenyl)hexane was prepared by coupling of 3-phenylpentan-3-ol with the alcohol derived from the Grignard addition of (3-methylphenyl)magnesium bromide to 3-pentanone, by using the procedure described for **1j**. After low molecular weight materials were removed (2 h at 0.2 Torr, and 70 °C), the coupling mixture (7.10 g, ca. 23 mmol) was dissolved in 100 mL of carbon tetrachloride and treated with *N*-bromosuccinimide (6.14 g, 34.5 mmol) and benzoyl peroxide (100 mg, 0.4 mmol). The mixture was stirred and brought to reflux. A second equal portion of benzoyl peroxide was added 1 h later, and reflux continued for 1.5 h. After the solution was allowed to stand overnight, the floating precipitate was filtered off and the solvent removed in vacuo. The crude product, containing 3,4-diethyl-3-phenyl-4-[3′-(bromomethyl)phenyl]hexane (total mass 10.6 g), was dissolved in a minimum amount of DMSO (25 mL) and added to a suspension of sodium bicarbonate (11 g) in 50 mL of DMSO at 100 °C with argon bubbling through it. After 10 min the darkened solution was cooled in an ice bath, then poured into water and extracted with hexane–dichloromethane (9:1). The organic layer was washed twice with water and dried over sodium sulfate, and the solvent was removed in vacuo. The desired aldehyde (ca. 10% over yield) was separated by column chromatography (hexane–CH_2Cl_2, 1:1). ^1H NMR (360 MHz, $CDCl_3$): 9.82 (s, 1 H), 7.62 (d, J = 7.5 Hz, 1 H), 7.30 (s, 1 H), 7.27 (t, J = 7.5 Hz, 1 H), 7.13 (d, J = 7.5 Hz, 1 H), 7.0–7.2 (m, br, 3 H), 6.83 (m, br, 2 H), 1.95–2.20 (m, 8 H), 0.65–0.80 (m, 12 H).

3,4-Diethyl-3-phenyl-4-(4′-formylphenyl)hexane. This intermediate was prepared in similar manner to the meta derivative described above in ca. 10% yield. ^1H NMR (360 MHz, $CDCl_3$): 9.97 (s, 1 H), 7.65 (d, J = 8.5 Hz, 2 H), 7.08 (d, J = 8.5 Hz, 2 H),

7.05–7.18 (m, 3 H), 6.87–6.98 (m, 2 H), 1.90–2.17 (m, 8 H), 0.63–0.74 (m, 12 H).

3,4-Diethyl-3-(4′-nitrophenyl)-4-[3″-(methoxycarbonyl)-phenyl]hexane (1i). To 3,4-diethyl-3-phenyl-4-(3′-formylphenyl)hexane (1.51 g) in 45 mL of dichloromethane was added ca. 100 mg of triethylbenzylammonium chloride, and a solution of 1.5 g of $KMnO_4$ in 30 mL of water. The two-phase mixture was stirred at room temperature for 18 h. The dark brown mixture was treated with $NaHSO_3$ and brought to pH 2 with 12 M HCl, and the organic layer was separated and evaporated in vacuo. The crude carboxylic acid was dissolved in 100 mL of methanol with 1 mL of concentrated sulfuric acid and stirred for 36 h. The methanol was removed in vacuo, and the residue was dissolved in ether and washed twice with water. The ether layer was separated, dried over sodium sulfate, evaporated, and submitted to column chromatography using hexane–dichloromethane (3:1) to give 27% yield of the ester. This ester was nitrated as described for **1j**. The crude product was purified by chromatography (ether–hexane) yielding **1i** in ca. 15% overall yield. Part of that material was further purified by HPLC (hexane–CH_2Cl_2 9:1) to give a light yellow oil which failed to crystallize. ^1H NMR (300 MHz, $CDCl_3$): 7.97 (d, J = 9.0 Hz, 2 H), 7.82 (d, J = 8.0 Hz, 1 H), 7.53 (s, 1 H), 7.21 (t, J = 8.0 Hz, 1 H), 6.95–7.07 (m, br, 3 H), 3.89 (s, 3 H), 1.90–2.19 (m, 8 H), 0.75 (t, J = 7.5 Hz, 12 H). MS (EI, m/e, relative intensity): 351 ($P^+ - NO_2$, 5), 339 (14), 326 (5), 321 ($P^+ - Et - NO_2 - 1$, 27), 307 (29), 205 ($P^+/2X$, 44), 193 ($P^+/2N + 1$, 23), 191 (13), 177 (18), 173 (11), 163 (78), 149 (93), 145 (36), 135 (12), 131 (49), 129 (36), 119 (25), 115 (100), 105 (39), 91 (73), 77 (39).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(3″-cyanophenyl)hexane (1f). 3,4-Diethyl-3-phenyl-4-(3′-formylphenyl)hexane (1.5 g, 4.6 mmol) was combined with 50 mL of acetonitrile–water (1:1), stirred rapidly, and treated with excess hydroxylamine-*O*-sulfonic acid (1.57 g, 13.9 mmol). After 30 min the aldehyde went completely into solution. The reaction mixture was heated in a water bath to 65 °C and stirred for 30 min. The cooled solution was poured into 50% aqueous NaOH and extracted with ether–hexane (1:4). The organic layer was washed twice with brine and dried over sodium sulfate, and the solvent was removed. The nitrile (540 mg, 37% yield) was isolated by column chromatography (hexane–CH_2Cl_2 gradient) and subsequently nitrated in acetic anhydride as described for **1j**. Column chromatography (hexane–CH_2Cl_2, 1:1) was used to isolate the desired **1f** as a colorless oil in 30% overall yield. The sample used for kinetic studies was further purified by HPLC (hexane–CH_2Cl_2, 7:3) and crystallized from ethanol, mp 82–84 °C. ^1H NMR (360 MHz, $CDCl_3$): 8.01 (d, J = 9.0 Hz, 2 H), 7.46 (d, J = 8.0 Hz, 1 H), 7.27 (s, 1 H), 7.22 (t, J = 8.0 Hz, 1 H), 6.88–7.07 (m, br, 3 H), 1.82–2.17 (m, 8 H), 0.75 (t, J = 7.5 Hz, 12 H). MS (EI, m/e, relative intensity): 306 ($P^+ - 2Et$, 3), 288 (3), 276 (4), 207 (3), 193 (47), 176 (5), 172 ($P^+/2X$, 18), 164 (8), 150 (32), 146 (7), 142 (20), 137 (19), 136 (12), 130 (100), 116 (67), 104 (18), 90 (14), 78 (12).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(4″-cyanophenyl)hexane (1a) was prepared in analogous fashion to **1f**. Treatment of the corresponding aldehyde (see above) with hydroxylamine-*O*-sulfonic acid gave the nitrile, 3,4-diethyl-3-phenyl-4-(4′-cyanophenyl)-hexane, which was nitrated with nitric acid in acetic anhydride. After isolation by column chromatography (hexane–CH_2Cl_2 gradient), the colorless oil was crystallized from ethanol, giving **1a** in 40% overall yield, mp 126–126.5 °C. ^1H NMR (360 MHz, $CDCl_3$): 8.00 (d, J = 9.0 Hz, 2 H), 7.46 (d, J = 8.5 Hz, 2 H), 7.03 (d, J = 9.0 Hz, 2 H), 6.98 (d, J = 8.5 Hz, 2 H), 1.90–2.15 (m, 8 H), 0.74 (t, J = 7.5 Hz, 12 H). MS (EI, m/e, relative intensity): 326 (3), 318 ($P^+ - NO_2$, 1), 306 ($P^+ - 2Et$, 12), 288 (9), 276 (4), 193 ($P^+/2N + 1$, 27), 173 ($P^+/2X + 1$, 41), 164 (12), 157 (24), 150 (34), 142 (47), 136 (22), 130 (86), 116 (100), 104 (19), 91 (15).

3,4-Diethyl-3-(4′-nitrophenyl)-4-[3″-(trifluoromethyl)-phenyl]hexane (1e). The Grignard reaction of [3-(trifluoromethyl)phenyl]magnesium bromide and 3-pentanone followed by coupling of the resulting 3-[3′-(trifluoromethyl)phenyl]pentan-3-ol with 3-phenylpentan-3-ol, by using the procedure described for **1j** yielded a mixture of dimers. After volatile compounds were removed under 0.2 Torr and 70 °C, the crude mixture of dimers was nitrated in acetic anhydride as described for **1j**. Column chromatography (hexane–CH_2Cl_2 gradient) gave a light yellow oil (which failed to crystallize) in ca. 15% overall yield. The sample used for kinetic studies was further purified by HPLC (hexane–CH_2Cl_2, 9:1). ^1H NMR (300 MHz, $CDCl_3$): 7.98 (d, J = 9.0 Hz, 2 H), 7.41 (d, J = 7.5 Hz, 1 H), 7.29 (t, J = 7.5 Hz, 1 H), 7.13 (d, J = 9.0 Hz, 1 H), 6.85–7.07 (m, br, 3 H), 1.88–2.20 (m, 8 H), 0.76 (t, J = 7.5 Hz, 6 H), 0.75 (t, J = 7.5 Hz, 6 H). MS (EI, m/e, relative intensity): 349 ($P^+ - 2Et$, 7), 331 (5), 215 ($P^+/2X$, 14), 193 ($P^+/2N$, 43), 185 (12), 173 (100), 165 (11), 159 (78), 150 (18), 137 (16), 133 (12), 131 (14), 115 (30), 104 (15), 91 (19), 78 (17).

3,4-Diethyl-3-(4′-nitrophenyl)-4-[4″-(trifluoromethyl)-phenyl]hexane (1b) was prepared as described above for the meta isomer. 3,4-Diethyl-3,4-bis[4′-(trifluoromethyl)phenyl]-hexane crystallized out of the mixture of dimers. The rest was nitrated in acetic anhydride as described for **1j**. The nitrated material was purified by column chromatography (hexane-CH_2Cl_2 gradient) and was crystallized from ethanol, giving **1b** in ca. 15% overall yield, mp 75–77 °C. ^1H NMR (300 MHz, $CDCl_3$): 7.99 (d, J = 9.0 Hz, 2 H), 7.41 (d, J = 8.5 Hz, 2 H), 7.04 (d, J = 9.0 Hz, 2 H), 6.99 (d, J = 8.5 Hz, 2 H), 1.90–2.15 (m, 8 H), 0.74 (t, J = 7.5 Hz, 12 H). MS (EI, m/e, relative intensity): 215 ($P^+/2X$, 14), 193 ($P^+/2N$, 100), 173 (98), 159 (57), 150 (17), 137 (20), 131 (8), 115 (12), 104 (9), 91 (10), 78 (9).

3,4-Diethyl-3-(4′-nitrophenyl)-4-[4″-(trimethylammonio)-phenyl]hexane Iodide (1d). The dimethylamino compound **1k** (200 mg) was dissolved in 20 mL of anhydrous ether, treated with excess methyl iodide (ca. 200 mg), and stirred at room temperature for 2 h. The precipitated ammonium salt was collected and recrystallized three times from ethanol to give 90% yield of shiny off-white crystals, mp 158–159 °C. ^1H NMR (360 MHz, $CDCl_3$): 8.02 (d, J = 9.0 Hz, 2 H), 7.73 (d, J = 9.0 Hz, 2 H), 7.13 (d, J = 9.0 Hz, 2 H), 7.07 (d, J = 9.0 Hz, 2 H), 4.01 (s, 9 H), 1.88–2.13 (m, 8 H), 0.66–0.77 (m, 12 H). MS (EI, m/e, relative intensity): 353 ($P^+ - Et$, 3), 335 ($P^+ - NO_2 - 1$, 2), 324 (P^+, 2 Et, 23), 306 ($P^+ - NO_2 - Et$, 16), 294 (5), 280 (2), 190 ($P^+/2X$, 100), 160 (44), 148 (13), 146 (10), 145 (15), 144 (14), 142 (27), 134 (18), 130 (11), 127 (11), 115 (20), 91 (11).

3,4-Diethyl-3-(4′-nitrophenyl)-4-(4″-acetylphenyl)hexane (1c) was produced by Friedel–Crafts acylation of 3,4-diethyl-3,4-diphenylhexane followed by nitration in acetic anhydride. A solution of 3,4-diethyl-3,4-diphenylhexane (1.2 g, 4.1 mmol) in 50 mL of dichloromethane at 0 °C was treated with a mixture of 517 mg of $AlCl_3$, 290 μL of acetyl chloride, and 20 mL of dichloromethane added by drops over 45 min. The dark orange-red solution was brought to room temperature and stirred for an additional 30 min, then washed twice with water, and dried over sodium sulfate, and the solvent was removed in vacuo. Column chromatography with hexane–dichloromethane (1:1) gave 630 mg (46% yield) of an almost colorless oil. This methyl ketone was treated with nitric acid in acetic anhydride solution as described for **1j** and the product was purified by column chromatography (hexane–CH_2Cl_2 gradient) to afford 400 mg (25% overall yield) of **1c** as a light yellow oil. A small sample was further purified by HPLC (hexane–dichloromethane, 6:4) before submitting it for kinetic studies. ^1H NMR (300 MHz, $CDCl_3$): 7.99 (d, J = 9.0 Hz, 2 H), 7.76 (d, J = 8.5 Hz, 2 H), 7.05 (d, J = 9.0 Hz, 2 H), 6.99 (d, J = 8.5 Hz, 2 H), 2.59 (s, 3 H), 1.91–2.18 (m, 8 H), 0.76 (t, J = 7.5 Hz, 6 H), 0.75 (t, J = 7.5 Hz, 6 H). IR: 3065, 2955, 2920, 1730, 1680, 1600, 1505, 1445, 1390, 1330, 1255, 1180, 1090, 995, 935, 835, 795, 730, 685. MS (EI, m/e, relative intensity): 335 ($P^+ - NO_2$, 1), 323 ($P^+ - 2Et$, 2), 305 (2), 293 (3), 193 (4), 189 ($P^+/2X$, 8), 178 (5), 174 (11), 159 (15), 150 (14), 147 (25), 145 (14), 133 (23), 131 (15), 129 (125), 115 (58), 105 (36), 91 (41), 90 (25), 77 (21), 57 (23), 43 (100).

3,4-Diethyl-3-(4-nitrophenyl)-4-(4-fluorophenyl)hexane-4′-^{13}C. To a cooled, septum-capped flask containing carbon-^{13}C dioxide (99 atom % ^{13}C, 250 mL, 0.011 mol, Aldrich) was added slowly 1 M (4-fluorophenyl)magnesium bromide in THF (18 mL, 0.018 mole, Aldrich). During the procedure argon was allowed to displace the consumed $^{13}CO_2$. The flask was allowed to warm to room temperature, shaken well, and allowed to sit for 10 min. The ice bath was replaced and 50 mL of 20% aqueous NH_4Cl was added slowly. The reaction mixture was then poured into ether and washed twice with water and twice with saturated aqueous sodium bicarbonate. The aqueous layers were made acidic with HCl and back-extracted with methylene chloride. All organic fractions were combined, dried over sodium sulfate, and evaporated to a white solid, mp 170–179 °C. The crude 4-fluorobenzoic

acid was dissolved in 150 mL of dry methanol, treated with 1 g of $SOCl_2$, and refluxed for 1 h. The methanol was removed in vacuo and the residue dissolved in ether and washed twice with water and twice with aqueous sodium bicarbonate solution. After the solvent was removed, the fragrant oil (methyl 4-fluorobenzoate) was treated with excess ethylmagnesium bromide in THF (16 mL, 2 M, Aldrich) followed by 50 mL of 20% aqueous NH_4Cl. The mixture was allowed to cool, extracted with ether, and washed with aqueous $NaHCO_3$. The crude product was purified by column chromatography (hexane–CH_2Cl_2 gradient), giving 1.22 g (61% yield based on $^{13}CO_2$) of 3-(4-fluorophenyl)pentan-3-ol-3-^{13}C as a clear liquid (MS: 183 (P^+, 2), 165 (2), 154 (100), 136 (7), 124 (9), 116 (2), 109 (5), 96 (4), 91 (3)). This tertiary alcohol (398 mg, 2.17 mmol) was coupled with 1.20 g 3-phenylpentan-3-ol (7.27 mol) by using the HBr–AcOH, Zn procedure described for **1j**. After the solvent was extracted, washed, dried, and evaporated in the same manner as **1j**, the crude coupling product was nitrated as described for **1j**. Isolation by flash column chromatography (hexane–CH_2Cl_2 gradient) and HPLC (hexane–CH_2Cl_2, 9:1) afforded 75 mg of the desired 3,4-diethyl-3-(4-nitrophenyl)-4-(4-fluorophenyl)hexane-4-^{13}C (6% yield from $^{13}CO_2$). The oil crystallized upon standing to colorless crystals, mp 89–90 °C. ^1H NMR (360 MHz, $CDCl_3$): 7.98 (d, J = 9.0 Hz, 2 H), 7.01 (d, J = 9.0 Hz, 2 H), 6.80 (m, 4 H), 1.84–2.17 (m, 8 H), 0.72 (m, 12 H). IR: 2960, 2920, 2870, 1600, 1505, 1335, 1215, 1150, 995, 830, 800, 730, 715, 680. MS (EI, m/e, relative intensity): 282 (1), 193 ($P^+/2N$ + 1, 15), 166 ($P^+/2X$, 6), 135 (16), 123 (57), 116 (8), 109 (100), 103 (7), 91 (6), 86 (6), 84 (9).

2-(4′-Fluorophenyl)-2-(4″-nitrophenyl)-3-ethyl-3-[4‴-(trifluoromethyl)phenyl]pentane (3a) was prepared by the general procedure described for **1j**. The Grignard reaction of (4-fluorophenyl)magnesium bromide with acetophenone gave the desired 1-phenyl-1-(4′-fluorophenyl)ethanol. This tertiary alcohol was coupled with 3-[4′-(trifluoromethyl)phenyl]pentan-3-ol. The crude yellow oil (an attempt to remove half-molecule side products by reduced pressure distillation resulted in considerable decomposition loss of the triphenyl product) was nitrated in acetic anhydride by using the procedure described for **1j**. Separation by column chromatography (hexane–CH_2Cl_2 gradient) and HPLC (hexane–ethyl acetate 97:3) and crystallization from ethanol afforded **3a** in ca. 5% overall yield, mp 115–116 °C. ^1H NMR (300 MHz, $CDCl_3$): 8.02 (d, J = 9.3 Hz, 2 H), 7.41 (d, J = 9.3 Hz, 2 H), 7.38 (d, J = 8.3 Hz, 2 H), 7.06–7.13 (m, 2 H), 6.93 (d, J = 9.0 Hz, 2 H), 6.88 (d, J = 8.3 Hz, 2 H), 2.17–2.47 (m, 4 H), 1.85 (s, 3 H), 0.78 (m, 6 H). MS (EI, m/e, relative intensity): 430 (P^+ – Et, 2), 412 (P^+ – NO_2, – 1, 3), 401 (P^+ – 2Et, 10), 383 (P^+ – NO_2 – Et – 1, 16), 245 ($P^+/2N$, 46), 243 (60), 230 (38), 228 (5), 215 ($P^+/2X$, 26), 200 (16), 196 (53), 187 (25), 185 (30), 183 (35), 177 (7), 173 (65), 165 (19), 159 (100), 151 (11), 145 (14), 133 (14), 131 (11), 123 (12), 121 (17), 117 (14), 115 (16), 109 (10), 101 (10), 91 (13).

2-(4′-Nitrophenyl)-3-ethyl-2,3-bis(4″-fluorophenyl)pentane (3b) was prepared by coupling of 3-(4′-fluorophenyl)pentan-3-ol with 1-phenyl-1-(4′-fluorophenyl)ethanol by using the procedure described for **1j**. The mixture was nitrated, and the product was purified thoroughly by column chromatography (hexane–CH_2Cl_2 gradient) and HPLC (hexane–ethyl acetate 97:3), but refused to crystallized from ethanol. After several months the neat oil (ca. 5% overall yield) solidified on standing, mp 85–95 °C. ^1H NMR (300 MHz, $CDCl_3$): 8.00 (d, J = 9.0 Hz, 2 H), 7.48 (d, J = 9.0 Hz, 2 H), 7.11 (m, 2 H), 6.70–6.93 (m, 6 H), 2.33 (m, 2 H), 2.20 (m, 2 H), 1.84 (s, 3 H), 0.78 (t, J = 7.5 Hz, 6 H). IR: 3070, 3040, 2970, 2930, 2870, 1600, 1505, 1390, 1365, 1335, 1220, 1150, 1095, 1050, 1035, 995, 835, 815, 775, 755, 715, 675. MS (EI, m/e, relative intensity): 394 (P^+ – Me, 1), 380 (P^+ – Et, 6), 363 (P^+ – NO_2, 2,), 351 (17), 333 (14), 243 ($P^+/2N$ – 1, 23), 230 (17), 212 (8), 196 (36), 183 (23), 177 (5), 165 ($P^+/2X$, 31), 137 (13), 135 (22), 133 (13), 123 (72), 12 (25), 115 (10), 109 (100), 103 (9), 101 (13), 95 (16), 77 (7), 75 (11).

2-(4′-Nitrophenyl)-3-ethyl-2,3-bis-[4″-(trifluoromethyl)-phenyl]pentane (3c) was prepared by coupling of 1-phenyl-1-[4′-(trifluoromethyl)phenyl]ethanol (obtained in the Grignard reaction of [4-(trifluoromethyl)phenyl]magnesium bromide with acetophenone) and 3-(4′-trifluorophenyl)pentan-3-ol by using the procedure described above. The crude mixture was nitrated in acetic anhydride as for **1j**. Isolation by column chromatography (hexane–CH_2Cl_2 gradient) and HPLC (hexane–ethyl acetate 97:3) gave the desired **3c** as a colorless oil which failed to crystallize (ca. 5% overall yield). ^1H NMR (360 MHz, $CDCl_3$): 8.03 (d, J = 9.0 Hz, 2 H), 7.46 (d, J = 8.5 Hz, 2 H), 7.38 (d, J = 9.0 Hz, 2 H), 7.35 (d, J = 9.0 Hz, 2 H), 7.27 (d, J = 8.5 Hz, 2 H), 6.94 (d, J = 9.0 Hz, 2 H), 2.39 (m, 2 H), 2.30 (m, 2 H), 1.88 (s, 3 H), 0.80 (t, J = 7.5 Hz, 6 H). IR: 3090, 3030, 2970, 2930, 2870, 1615, 1600, 1590, 1510, 1395, 1335, 1315, 1150, 1105, 1055, 995, 840, 770, 700. MS (EI, m/e, relative intensity): 462 (P^+ – NO_2 – 1, 4), 451 (P^+ – 2Et, 4), 433 (3), 293 ($P^+/2N$ – 1, 19), 280 (16), 246 (12), 233 (24), 227 (20), 215 ($P^+/2X$, 20), 207 (13), 200 (16), 196 (13), 185 (24), 178 (94), 173 (73), 165 (87), 159 (100), 151 (60), 145 (37), 133 (42), 131 (30), 127 (27), 115 (57), 109 (24), 102 (23), 91 (20), 77 (30).

2-[4′-(Trifluoromethyl)phenyl]-2-(4″-nitrophenyl)-3-ethyl-3-(4‴-fluorophenyl)pentane (3d) was prepared by using the procedure described above from 1-phenyl-1-[4′-(trifluoromethyl)phenyl]ethanol and 3-(4′-fluorophenyl)pentan-3-ol, followed by nitration of the crude mixture of dimers. Separation by column chromatography (hexane–CH_2Cl_2 gradient) and HPLC (hexane–ethyl acetate 97:3) followed by crystallization from ethanol gave **3a** as a white powder, mp 118–119 °C in ca. 7% overall yield. ^1H NMR (360 MHz, $CDCl_3$): 8.03 (d, J = 9.0 Hz, 2 H), 7.46 (d, J = 8.5 Hz, 2 H), 7.35 (d, J = 9.0 Hz, 2 H), 7.29 (d, J = 8.5 Hz, 2 H), 6.71–6.87 (m, 4 H), 2.36 (m, 2 H), 2.24 (m, 2 H), 1.87 (s, 3 H), 0.80 (t, J = 7.5 Hz, 6 H). MS (EI, m/e, relative intensity): 430 (P^+ – Et, 3), 424 (4), 413 (P^+ – NO_2, 12), 401 (P – 2Et, 76), 383 (55), 293 ($P^+/2N$ – 1, 54), 280 (35), 263 (20), 246 (14), 189 (19), 178 (31), 173 (30), 171 (16), 165 (40), 151 (11), 137 (16), 135 (61), 133 (17), 123 (34), 109 (100), 86 (21), 84 (33).

Kinetic Studies. In kinetic and UV/visible experiments as well as in product studies, all operations were performed under an argon atmosphere. Argon was purified by passing it over an oxygen-removal catalyst (BASF) and a drying agent ($CaSO_4$). Anhydrous solvents from Aldrich (Me_2SO) were deoxygenated by freeze–pump technique and stored over molecular sieves. The solvents were transferred with use of gas-tight syringes.

Radical anions were generated by mixing the nitro compounds with titrated solutions of lithium 2,4,6-tri-*tert*-butylnitrobenzenide[13,22] (Li^+, $TTNB^{\bullet-}$) and sodium or potassium 1-(*N*,*N*-dimethylamino)naphthalenide[23] (Na^+ or K^+ $DMAN^{\bullet-}$). In deoxygenated pentane, TTNB (Aldrich) was treated with 1 equiv of methyllithium. The precipitated yellow salt was washed with pentane and dissolved in Me_2SO yielding a violet-pink solution. The solubility of TTNB in Me_2SO is negligible. The concentration of the reducing agent was, therefore, determined by injecting an aliquot of $TTNB^{\bullet-}$ into oxygen-saturated hexane containing a GC standard ($C_{16}H_{34}$). The liberated TTNB was quantified by GC analysis. Naphthalenide salt solutions were prepared by reduction of DMAN with Na or K in THF, and were titrated against a dilute solution of I_2 in THF.

ESR spectra were recorded on a Varian E-Line spectrometer with a variable temperature accessory in 3 mm o.d. Pyrex tubes equipped with an internal copper–constantan (T) thermocouple. The sample temperature varied no more than 0.3 °C during the longest runs. In Me_2SO, radical anions derived from all tetraethyl derivatives exhibited identical ESR spectra: a_N = 10.15 ± 0.05 G, a_{Ho} = 3.30 ± 0.05 G, a_{Hm} = 1.10 ± 0.05 G. The spectrum of the *p*-*tert*-butylnitrobenzene radical anion recorded under identical conditions had a_N = 10.2 G, a_{Ho} = 3.3 G, a_{Hm} = 1.1 G. The decay of the ESR signal was fitted into zero-, first-, and second-order kinetics. In all cases very good fits were obtained to the first-order expression (r > 0.997) for up to 4 half-lives. The estimated errors of the reported rate constants are ca. 15%.

The initial concentration of the radical anions was ca. 0.1–1.0 mM. Within this range, the observed decays were independent of the concentration of $\mathbf{1}^{\bullet-}$ and 1/[reducing agent] ratios. In all cases the ESR signal decayed to noise level. No other ESR active species were detected during the kinetic runs.

Activation parameters were obtained by the measurement of decay rates in the 15–45 °C temperature range (at least six measurements per compound). The free energies of activation reported throughout the paper are calculated at 300 K. The activation parameters ($\Delta G^{\ddagger}$, in kcal/mol at 300 K; $\Delta H^{\ddagger}$, in kcal/mol; $\Delta S^{\ddagger}$ in cal/mol K) were as follows: $\mathbf{1b}^{\bullet-}$ 19.8, 21.9, 6.8; $\mathbf{1c}^{\bullet-}$ 19.8, 20.8, 3.0; $\mathbf{1d}^{\bullet-}$ 20.5, 18.6, –8.3. A linear extrapolation of these $\Delta G^{\ddagger}$ values (including $\mathbf{1a}^{\bullet-}$) vs σ^- values yields $\Delta G^{\ddagger}(\mathbf{1n}^{\bullet-})$

= 18.5 for a hypothetical unimolecular cleavage of $\mathbf{1n}^{\bullet-}$. This value is an upper limit since the curvature of the Hammett plot has not been taken into consideration.

UV/visible measurements were carried out at ambient temperature by using an HP-8452A spectrophotometer. Radical anion concentrations were in the 0.15 mM range. The radical anions were generated by mixing 1 or 4-*tert*-butylnitrobenzene with 1 equiv of Li^+ $TTNB^{\bullet-}$. The experiments with slowly decaying $\mathbf{1}^{\bullet-}$ and with the radical anion of 4-*tert*-butylnitrobenzene were used to estimate the extinction coefficients of the radical anions ($\epsilon_{333} \approx 8600\ M^{-1}\ cm^{-1}$, $\epsilon_{462} \approx 1000\ M^{-1}\ cm^{-1}$). The spectrum of $\mathbf{2}^-$ was generated in Me_2SO by treating 3-(4′-nitrophenyl)pentane with excess of potassium dimsyl ($\epsilon_{333} \approx 2400\ M^{-1}\ cm^{-1}$, $\epsilon_{436} \approx 6500\ M^{-1}\ cm^{-1}$ K).

Product Isolation.[25] In a typical procedure, 25–100 mg of the compound was dissolved in Me_2SO under anhydrous/anaerobic conditions to give ca. 10 mM solution. Reducing agent (Li^+ $TTNB^{\bullet-}$) (1 molar equiv) was added, and the mixture was stirred for approximately 4 half-lives. The reactions were quenched by addition of methanol–water or by passing a stream of O_2. Yield information was gathered by integration of NMR spectra (360 MHz) of the crude mixture. The products were isolated by flash column chromatography or HPLC and identified by comparison with independently prepared samples or by spectral analysis.

Cleavage of $\mathbf{1j}^{\bullet-}$ followed by $MeOH–H_2O$ quenching gave **3-(4′-nitrophenyl)pentane** (51%). ^1H NMR (360 MHz, $CDCl_3$): 8.16 (d, J = 9.0 Hz, 2 H), 7.30 (d, J = 9.0 Hz, 2 H), 2.47 (m, 1 H), 1.76 (m, 2 H), 1.57 (m, 2 H), 0.77 (t, J = 7.5 Hz, 6 H): MS (EI, m/e relative): 193 (P^+, 34), 164 (100), 147 (6), 136 (90), 117 (19), 115 (19), 106 (23), 91 (22), 78 (20). This material was independently prepared in quantitative yield by nitration of 3-phenylpentane (Wiley Organics) by using procedure described for **1j**. **3-(4′-nitrophenyl)pentan-3-ol** (16%). ^1H NMR (360 MHz, $CDCl_3$): 8.20 (d, J = 9.0 Hz, 2 H), 7.56 (d, J = 9.0 Hz, 2 H), 1.87 (m, 4 H), 1.70 (s, 1 H), 0.76 (t, J = 7.5 Hz, 6 H). MS (EI, m/e, relative intensity): 210 (P^+ + 1, 1), 180 (100), 150 (5), 134 (14), 115 (10), 105 (19), 91 (19), 77 (36), 65 (15). An authentic sample of the alcohol was prepared by treatment of $\mathbf{2}^-$ with O_2 in Me_2SO. **3-(4′-nitrophenyl)-1-propanone** (27%). ^1H NMR (360 MHz, $CDCl_3$): 8.33 (d, J = 9.0 Hz, 2 H), 8.13 (d, J = 9.0 Hz, 2 H), 3.07 (q, J = 7.5 Hz, 4 H), 1.27 (t, J = 7.5 Hz, 6 H). MS (EI, m/e, relative intensity): 179 (P^+, 10), 150 (100), 120 (8), 104 (22), 92 (8), 86 (12), 84 (18), 76 (11), 57 (6). **Tetramer of 3-phenyl-3-pentyl radical** (structure undetermined, 80%). ^1H NMR (360 MHz, $CDCl_3$): 7.52 (m, br, 2 H), 7.26 (m, br, 2 H), 7.11–7.23 (m, 10 H), 6.93 (m, br, 2 H), 6.50 (m, br, 2 H), 6.34 (m, br, 2 H), 2.04–2.25 (m, 3 H), 1.80–2.00 (m, 12 H), 1.42 (m, br, 2 H), 0.90 (m, br, 3 H), 0.68–0.80 (m, 6 H), 0.55–0.68 (m, 15 H). ^1H NMR (360 MHz, toluene-d_8, 100 °C): 7.48 (d, J = 7.5 Hz, 2 H), 7.25 (d, J = 7.5 Hz, 2 H), 6.99–7.18 (m, 8 H), 6.88 (d, J = 7.5 Hz, 2 H), 6.49 (s, 4 H), 2.03 (q, J = 7.2 Hz, 4 H), 1.88 (q, J = 7.2 Hz, 4 H), 1.83 (q, J = 7.2 Hz, 4 H), 1.83 (m, br, 4 H), 0.82 (m, br, 6 H), 0.74 (t, J = 7.2 Hz, 6 H), 0.68 (t, J = 7.2 Hz, 6 H), 0.63 (t, J = 7.2 Hz, 6 H). ^{13}C NMR (90.6 MHz, $CDCl_3$): 148.0, 144.9, 141.9, 141.4, 140.3, 130.1, 128.7, 128.5, 128.4, 128.1, 127.1, 126.7, 126.6, 126.2, 125.0, 86.0, 69.9, 51.5, 51.0, 27.6, 26.9, 25.9, 25.7, 25.3, 24.6, 10.5, 10.3, 9.1, 8.9, 8.7, 8.3. Molecular weight determination (Galbraith Laboratories, Inc.): 589. MS (EI, m/e, relative intensity): 324 (2), 307 (4), 292 (1), 278 (13), 177 (21), 161 (11), 147 (36), 132 (17), 121 (16), 117 (49), 115 (18), 105 (74), 91 (100), 71 (12). MS (CI, m/e, relative intensity): 391 (10), 324 (5), 307 (7), 279 (10), 177 (14), 161 (10), 147 (100), 135 (35), 117 (19), 105 (55), 91 (52), 71 (18). **3-phenylpentane** (3%). ^1H (200 MHz, $CDCl_3$): 7.10–7.30 (m, 5 H), 2.30 (m, 1 H), 1.45–1.78 (m, 4 H), 0.78 (t, J = 7.5 Hz, 6 H).

Cleavage of $\mathbf{1a}^{\bullet-}$ (quenching with O_2) gave 3-(4′-nitrophenyl)pentan-3-ol (95%) and **3-(4′-cyanophenyl)pentane** (94%). ^1H NMR (360 MHz, $CDCl_3$): 7.58 (d, J = 8.5 Hz, 2 H), 7.23 (d, J = 8.5 Hz, 2 H), 2.39 (m, 1 H), 1.72 (m, 2 H), 1.55 (m, 2 H), 0.75 (t, J = 7.5 Hz, 6 H). MS (EI, m/e, relative intensity): 173 (P^+, 18), 167 (47), 155 (22), 149 (100), 144 (43), 129 (7), 119 (13), 166 (84), 113 (15), 104 (12), 91 (40), 83 (10), 77 (10).

Cleavage of $\mathbf{1k}^{\bullet-}$ (quenching with $MeOH/H_2O$) gave 3-(4′-nitrophenyl)pentan-3-ol (60%), 3-(4′-nitrophenyl)pentane (25%), **3-[4′-(*N*,*N*-dimethylamino)phenyl]pentan-3-ol** (50%) (^1H NMR (360 MHz, $CDCl_3$): 7.24 (d, J = 9.0 Hz, 2 H), 6.72 (d, J = 9.0 Hz, 2 H), 2.93 (s, 6 H), 1.70 (m, 4 H), 0.76 (t, J = 7.5 Hz, 6 H); independent sample of this material was prepared by reduction of the corresponding nitro alcohol, followed by reductive methylation as described above), and **3,4-diethyl-3,4-bis-[4′-(*N*,*N*-dimethylamino)phenyl]hexane** (30%) (^1H NMR (360 MHz, benzene-d_6): 7.03 (d, J = 9 Hz, 4 H), 6.60 (d, J = 9 Hz, 4 H), 2.58 (s, 12 H), 2.06 (m, 8 H), 0.79 (t, J = 8.0 Hz, 12 H). MS (EI, m/e, relative intensity): 190 ($P^+/2$, 100), 160 (13), 148 (8), 134 (12); the authentic sample of this material was prepared by reduction of the corresponding dinitro compound followed by reductive methylation (see above)).

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