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Radical Nucleophilic Substitution of 2-(4-Halophenyl)-2-methyl-1-chloropropane with Enolate Ions of Ketones

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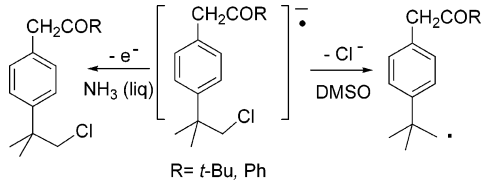


The photoinitiated reaction of 2-(4-halophenyl)-2-methyl-1-chloropropane **2a**,**b** (halogen = Br, I, respectively) with the anions of pinacolone (**3a**) and acetophenone (**3b**) either in DMSO or in liquid ammonia are reported. In DMSO, the main reaction is the $S_{RN}1$ nucleophilic substitution at the aromatic (C_{sp2}-halogen) center with substitution or reduction at the aliphatic (C_{sp3}-Cl) one. In liquid ammonia, the main reaction is substitution at the aromatic C-halogen site. This difference in product distribution is ascribed to modifications in the rate constant of C_{sp3}-Cl dissociation of the radical anions proposed as intermediates in going from DMSO (rt) to liquid NH_3 (−33 °C).

Electron transfer (ET) reactions are of relevance in organic chemistry and in organic synthesis. One example of the latter is the $S_{RN}1$ nucleophilic substitution of aromatic and aliphatic halides, which as a result of electronic, steric, or strain factors are poorly reactive through polar processes.[1] The initiation step of this mechanism involves an ET from an adequate electron source to the substrate. This reaction may follow a stepwise pathway with radical anions as intermediates. This is the case for aromatic halides[2] and for alkyl halides substituted by π acceptors.[3] The dissociation of these intermediates into radicals is ascribed to an intra-DET (intramolecular-dissociative ET) from the π system, in which the extra electron first locates, to the σ C-halogen bond that fragments.[2,3] The situation is presented in eq 1 for alkyl halides bearing a π acceptor. The possibility for this reaction to follow a concerted-dissociative ET pathway (inter-DET) is also shown.

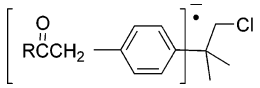
$$(Ac_\pi)\text{-}RX \xrightarrow{\text{inter-ET}} (Ac_\pi)^{\bullet}\text{-}RX \xrightarrow{\text{intra-DET}} Ac_\pi\text{-}R^{\bullet} + X^- \quad (1)$$

π RA

inter-DET

Within either the dissociative or the stepwise picture, the number of σ bonds between the π and σ acceptors, their relative orientation, spatial proximity, and their ionization potential−electron affinity relationship are important factors for the dissociation into radicals (eq 1).[4,5] Catalysis by substituents (facilitated inter-DET or inter-ET/intra-DET) has been observed in the $S_{RN}1$ reaction of different π substituted aliphatic systems[6] for which theoretical evidence of the importance of the distance and relative orientation of the acceptors has been presented.[7]

Focusing our interest on this type of ET reaction, we decided to study the feasibility of the C−Cl dissociation in radical anions of the following general type:[5]



1$^{\bullet-}$ **a** (R=*t*-Bu), **b** (R=Ph)

These radical anions could be generated in situ by reaction of 2-(4-bromophenyl) (**2a**) or 2-(4-iodophenyl)-2-methyl-1-chloropropane (**2b**) with the enolate ions $RCOCH_2^-$, **3a** (R = *t*-Bu) and **3b** (R = Ph). It is expected that the radical anions **2**$^{\bullet-}$, formed by photo ET from the enolate ions, will dissociate into radicals **4** (eq 2), which by coupling with the enolate anion will afford radical anion **1**$^{\bullet-}$ (eq 3). We propose to take the dissociation of **1**$^{\bullet-}$ into radicals **5** (eq 4) as a qualitative estimation of the efficiency of the *intra*-DET form the $RCOCH_2C_6H_4$- moiety to the C-Cl bond; the effect of RC(O) groups with different electron affinities (R = *t*-Bu, Ph) being inspected.

The results obtained in the irradiated reactions of **2** with anions **3a**,**b** are presented in Table 1. In the DMSO irradiated reaction of **2a** with the enolate ion **3a** (≈1:10 substrate/nucleophile ratio) nucleophilic substitution is achieved and products **7a**−**10a** are formed, although in low overall yields (eq 5, Table 1, exp 1).[8] In this reaction, the same amount of bromide and chloride anions was released (∼40% each), their

(1) (a) Rossi, R. A.; Pierini, A. B.; Peñéñory, A. B. *Chem. Rev.* **2003**, *103*, 71. (b) Rossi, R. A.; Pierini, A. B.; Santiago, A. N. In *Organic Reactions*; Paquette, L. A., Bittman, R., Eds.; Wiley: New York, 1999; p 1.

(2) (a) Savéant, J.-M. *Advances in Physical Organic Chem*istry; Tidwell, T. T., Ed.; Academic Press: New York, 2000; p 35. (b) Costentin, C.; Robert, M.; Savéant, J.-M. *Chem. Phys.* **2006**, *324*, 40−56. (c) Savéant, J.-M. *Adv. Phys. Org. Chem.* **1990**, *26*, 1.

(3) In addition to ref 2, representative references on the subject are (a) Andrieux, C. P.; Robert, M.; Saeva, F. D.; Savéant, J.-M. *J. Am. Chem. Soc.* **1994**, *116*, 7864. (b) Antonello, S.; Maran, F. *J. Am. Chem. Soc.* **1997**, *119*, 12595. (c) Pause, L.; Robert, M.; Savéant, J.-M. *J. Am. Chem. Soc.* **2001**, *123*, 4886.

(4) Jones, G. A.; Paddon-Row, M. N.; Carpenter, B. K.; Piotrowiak, P. *J. Phys. Chem. A* **2002**, *106*, 5011−5021 and references therein.

(5) For kinetic data on intra-DET of phenyl-substituted 4-benzoyloxy-1-methylcyclohexyl bromides in DMF, see: Antonello, S.; Maran, F. *J. Am. Chem. Soc.* **1998**, *120*, 5713.

(6) (a) Lukach, A. E.; Morris, D. G.; Santiago, A. N.; Rossi, R. A. *J. Org. Chem.* **1995**, *60*, 1000. (b) Santiago, A. N.; Takeuchi, K.; Ohga, Y.; Nishida, M.; Rossi, R. A. *J. Org. Chem.* **1991**, *56*, 1581. (c) Duca, J. S.; Gallego, M. H.; Pierini, A. B.; Rossi, R. A. *J. Org. Chem.* **1999**, *64*, 2626.

(7) (a) Vera, D. M. A.; Pierini, A. B. *J. Phys. Org. Chem.* **2002**, *15*, 894. (b) Uranga, J. G.; Vera, D. M. A.; Santiago, A. N.; Pierini, A. B. *J. Org. Chem.* **2006**, *71*, 6596.

(8) The reactions in DMSO strongly depend on the susbtrate:nucleophile ratio used. With a 1(substrate):3(nucleophile) ratio, **6** is the main product formed at short irradiation times.

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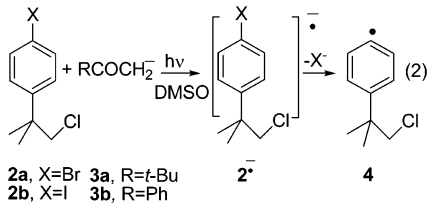
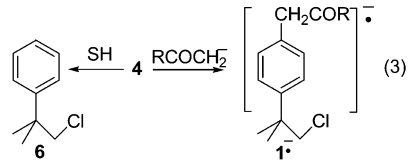
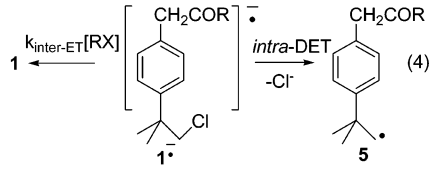
TABLE 1. Substitution Reactions of Compounds 2 with Enolate Ions of Ketones 3, in DMSO or Liquid Ammonia[a]

						products % yields[c,d]	
expt	substrate (M)	Nu^- (M)	solvent	X^- [b] (%)	Cl^- (%)	monosubstitution-reduction	disubstitution
1	**2a** (0.038)[e]	**3a** (0.4)	DMSO	39	37	**7a** (9), **8a** (6),	**9a**−**10a** [f]
2	**2b** (0.040)[g]	**3a** (0.4)	DMSO	70	75	**7a** (15), **8a** (25)	**9a** (15), **10a** (15)
3	**2a**[h]	**3a**	DMSO	11	13		
4	**2b**[i]	**3a**	DMSO	13	13		
5	**2b** (0.040)	**3b** (0.24)	DMSO	70	65	**7b**,[j] **8b** (43)[k]	**9b** (26), **10b**[j]
6	**2b** (0.036) [l]	**3b** (0.24)	DMSO	<2	<2		
7	**2b** (0.035)[m]	**3b** (0.24)	DMSO	132		**8b** (20)[k]	**9b** (13.4), **10b**[j]
8	**2a** (0.010)	**3a** (0.03)	NH_3 (liquid)	83	35	**1a** (30)	**7a** (10), **11a** (18)
9	**2b** (0.004)[n]	**3b** (0.059)	NH_3 (liquid)	67		**1b** (52)	**7b** (−), **11b** (−)

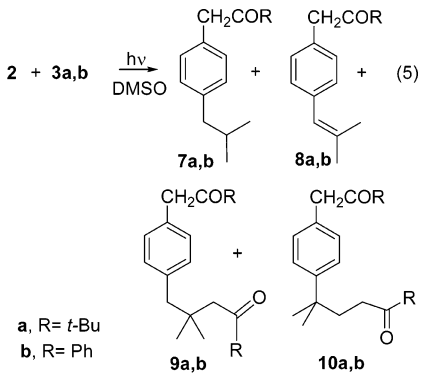
[a] Irradiated reactions (λ_{max} = 350 nm, time = 120 min) unless otherwise indicated. [b] Percentage of Br or I ions released from **2a** or **2b**, respectively. [c] Determined on the basis of **2a** or **2b** concentration. Quantified by GC using the internal standard method. [d] In most reactions (2-chloro-1,1-dimethylethyl)-benzene (**6**) is formed (3−5%). [e] **2a** recovered (63%). [f] Products not quantified. [g] **2b** recovered (19%). [h] Dark reaction. [i] Performed in the presence of *p*-DNB (22 mol % with respect to **2b**). [j] Traces of product detected. [k] Quantified together with **8b′** (isomer with the double bond at the terminal position ($PhCOCH_2-C_6H_4-CH_2C(Me)=CH_2$)). [l] In the presence of *p*-DNB (6.4 mol % with respect to **2b**). [m] Dark reaction in the presence of $FeBr_2$ (48.3 mol % with respect to **2b**). [n] Dark reaction in the presence of $FeSO_4$ (119 mol %).







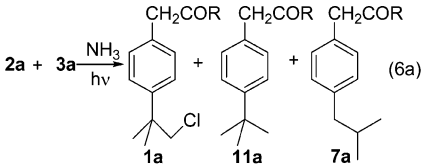
ratio being constant at all reaction times as determined from sampling experiments. Similar product distribution but higher overall yields of substitution were obtained when the 4-iodo derivative **2b** was used as substrate (Table 1, exp 2).



The anion of acetophenone **3b** does not react with **2a** either under our experimental conditions or even in the presence of acetone enolate anion when added as entrainment reagent.[9] However, it reacts with **2b**, releasing iodide and chloride anions in similar yields. In this reaction, **8b** and **9b** were the main products formed (eq 5, Table 1, exp 5).

The initiation with $FeBr_2$[10,1a] lowers the overall yield of substitution obtained when **2b** reacts with **3b** (Table 1, exp. 7). Despite this fact, the product distribution obtained is similar to the one formed under irradiation, a result being taken as evidence that the same mechanistic pathway under both type of initiations is favored.

A different product distribution was obtained when the reactions were performed in liquid ammonia. In this solvent, compound **2a** reacts with the enolate ion **3a** to afford the monosubstitution product with chloride retention **1a** as main product (∼30%) together with compounds **11a** and **7a** in lower yields (eq 6a, Table 1, exp 8).



When performing the reaction of **2b** with **3b** under $FeSO_4$ initiation, the monosubstituted compound with chloride retention **1b** was the only product formed (eq 6b, Table 1, exp 9). Photoinitiation cannot be used with **3b**, which under this condition does not initiate the substitution reaction of PhI in liquid ammonia[1] and also fails to react with **2a** or **2b** in this solvent.

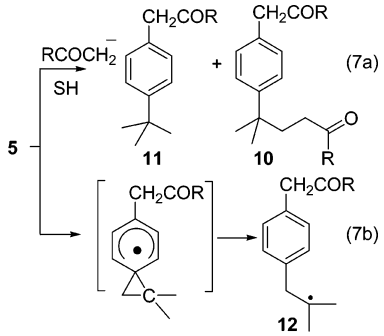
The different behavior shown by **3b**, which fails to photosubstitute **2a**,**b** in $NH_{3(liq)}$ but succeeds with **2b** in DMSO; the feasibility of anion **3a** to photosubstitute **2a,b** in DMSO and **2a** in $NH_{3(liq)}$; the similar product distribution obtained either under irradiation or Fe^{2+} initiation; the lack of substitution in the absence of light (Table 1, exp 3); and the inhibition of the irradiated reaction of **2b** with anions **3a,b** by *p*-dinitrobenzene (*p*-DNB), a well-known radical anion scavenger (Table 1, exps 4 and 6) are evidences that favor an $S_{RN}1$-type mechanism for the system.

(9) Under *entrainment* conditions the addition of a tiny amount of a Nu^- more reactive at initiation allows the less reactive Nu^- to start its own propagation.

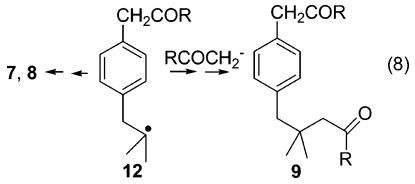
(10) Van Leeuwen, M.; McKillop, A. *J. Chem. Soc., Perkin Trans. 1*, **1993**, 2433.

Based on this mechanistic proposal and as indicated in eq 2, once the radical anion of the substrate is formed, it dissociates into radicals **4**. The main reactions followed by this radical are coupling with the nucleophile to give $\mathbf{1}^{-\bullet}$ (eq 3) or hydrogen abstraction from the solvent to give neophyl chloride **6** (eq 3). The latter reaction is favored in DMSO, under diluted conditions and with a 1:3 substrate/anion ratio.[8,11]

Under conditions that favor the formation of $\mathbf{1}^{-\bullet}$ this intermediate may transfer its extra electron to the substrate to afford the substitution product with chlorine retention (**1**) or may dissociate into radicals **5,** reaction that prevails in DMSO (eq 4).[12] Radicals **5** can be reduced by the solvent to give **11** or can react with the nucleophile to give the unrearranged disubstitution compound **10** (eq 7a).



Radicals **5** can also rearrange to the tertiary radicals **12**[13] (eq 7b) that are responsible for the ultimate formation of **7**[14] and **8** and, by coupling with the ketone enolate, for the formation of the rearranged disubstitution compounds **9** (eq 8).[15]



Whereas in DMSO the main products formed with enolate ions **3a** and **3b** originate from radicals **5** and **12**, respectively, in liquid ammonia, monosubstitution with chlorine retention is the main product with **3a** and the only product formed with **3b** (eq 6).

The fact that **1** is the main product in $NH_{3(liq)}$ is evidence that $\mathbf{1}^{-\bullet}$ is indeed an intermediate in this solvent. This type of radical anion is known to have considerable negative charge localization in the carbonyl moiety[7b] and so can be further stabilized toward dissociation by a polar protic solvent.[16] It is then expected that, stabilized by $NH_{3(liq)}$ as well as by the low reaction temperature, $\mathbf{1}^{-\bullet}$ will survive long enough to transfer its odd electron to the substrate (eq 4). On the other hand, the stability of these radical anions has been shown to decrease in polar aprotic solvents.[16] We do not know if $\mathbf{1}^{-\bullet}$ is formed in DMSO or if as the radical-nucleophile coupling of eq 3 takes place, the C−Cl bond dissociates to give **5** (eqs 3 and 4 simultaneously).

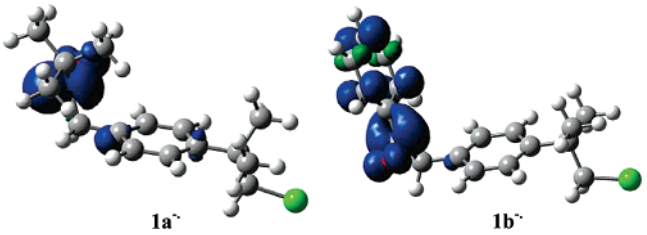


FIGURE 1. B3LYP/6-31+G* unpaired spin density of $\mathbf{1a}^{-\bullet}$ and $\mathbf{1b}^{-\bullet}$ in methanol.

The unpaired spin distribution of $\mathbf{1a}^{-\bullet}$ and $\mathbf{1b}^{-\bullet}$ evaluated at the B3LYP level in methanol, to model a polar protic solvent, within a continuum solvent model (see Supporting Information) is presented in Figure 1. As it can be seen in the figure, the unpaired electron localizes almost completely on the PhCO moiety in intermediate $\mathbf{1b}^{-\bullet}$, whereas it slightly spreads on the aromatic moiety of the -CH_2-C_6H_4-$C(Me)_2$- bridge in $\mathbf{1a}^{-\bullet}$. This spin distribution is as expected from the electron acceptor ability of the *t*-BuCO and PhCO moieties of both intermediates and indicates a more favored intra-DET to the C−Cl bond in $\mathbf{1a}^{-\bullet}$ than in $\mathbf{1b}^{-\bullet}$. In agreement with this finding, a low percentage of products from dissociation of the C−Cl bond is formed in $NH_{3(liq)}$ only by reaction with carbanion **3a**.

The results here presented are another example of facilitated intra-DET in DMSO (rt) with respect to liquid ammonia (−33 °C) and of the effect exerted by the increase in electron affinity of the transferring moiety.

On the other hand, the percentage of products formed in DMSO from the rearranged radical **12**, higher with enolate **3b** than with **3a**, could be indicating that the *para*-substituted radical **5** rearranges faster than its unsubstituted analog.[13,17] Another possibility is for the intra-DET of $\mathbf{1}^{-\bullet}$ to be concerted with the radical rearrangement.

Experimental Section

Materials. Potassium *tert*-butoxide, pinacolone, acetophenone, and 1-chloro-2-methyl-2-phenylpropane were commercially available. DMSO was distilled under vacuum and stored under molecular sieves (4 Å). Similarly, acetone and acetophenone were distilled and stored on molecular sieves (4 Å). 2-(4-Bromophenyl)-1-chloro-2-methylpropane (**2a**) was prepared from 1-chloro-2-methyl-2-phenylpropane following a brominating technique for toluene

(11) The rate of hydrogen abstraction of phenyl radicals in DMSO has been determined to be 2.8×10^6 M^{-1} s^{-1}, and that for the the coupling of a phenyl-type radical (4-*tert*-butylphenyl) with $Me_3COCH_2^-$ is 3.3×10^9 M^{-1} s^{-1} (see: Branchi, B.; Galli, C.; Gentili, P. *Eur. J. Org. Chem.* **2002**, 2844).

(12) By sampling experiments it was demonstrated that **1** is not formed in the reaction media. If formed, it would be in its anionic form as a result of the basic conditions and thus poorly reactive for substitution by ET. On these bases, its intermediacy in forming disubstitution can be excluded.

(13) The rate constant for rearrangement of the unsubstituted analog of **5**, is 403 s^{-1} at 298 K (see: Weber, M.; Fischer, H. *J. Am. Chem. Soc.* **1999**, *121*, 7381).

(14) The rate constant of hydrogen abstraction from THF by an aliphatic radical is $\approx 10^3-10^4$ M^{-1} s^{-1} (pseudo first order). See: (a) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151. (b) Newcomb, M.; Park, S. U. *J. Am. Chem. Soc.* **1986**, *108*, 4132.

(15) $PhCOCH_2^-$ ions couple with neophyl ($C_6H_5C(CH_3)_2CH_2^{\bullet}$) radicals with a rate constant of 2.5×10^5 M^{-1} s^{-1} (see: Argüello, J. E.; Peñéñory, A. B.; Rossi, R. A. *J. Org. Chem.* **2000**, *65*, 7175). A lower rate constant is estimated for the coupling of neophyl radicals with *t*-$BuCOCH_2^-$ anion.

(16) Andrieux, C. P.; Robert, M.; Savéant, J.-M. *J. Am. Chem. Soc.* **1995**, *117*, 9340. Costentin, C.; Robert, M.; Savéant, J.-M. *J. Am. Chem. Soc.* **2004**, *126*, 16834.

(17) In the reaction of $C_6H_5C(CH_3)_2CH_2I$ with **3b** in DMSO, monosubstitution at the primary radical and at the rearranged radical occurs in 55% and 16% yields, respectively (see ref 15).

derivatives described in the literature.[18] 1-Chloro-2-(4-iodophenyl)-2-methylpropane (**2b**) was prepared by iodination of 1-chloro-2-methyl-2-phenylpropane following the procedure by Barluenga and col,[19] using IPy_2BF_4 as iodinating agent.

The procedure followed in the reactions of compounds **2** with the anions **3a**,**b** is presented in Supporting Information and is as previously described.[1b]

2-(4-Bromophenyl)-1-chloro-2-methylpropane (2a). Isolated as colorless oil after distillation at reduced pressure. ^{1}H NMR (acetone-d_6) δ 1.41 (s, 6H), 3.54 (s, 2H), 7.41 (d, 2H, J = 8.9 Hz), 7.51 (d, 2H, J = 8.9 Hz). ^{13}C NMR ($CDCl_3$) δ 26.3, 39.5, 55.7, 120.3, 127.7, 131.2, 144.8. *m*/*z* 248 (13.1), 246 (11.4), 199 (100.0), 197 (98.5), 171 (23.9), 169 (30.8), 118 (37.1), 117 (24.5), 116 (23.2), 115 (27.2), 91 (7.5), 77 (5.8), 51 (6.5). HRMS calcd for $C_{10}H_{12}BrCl$ 245.98109, 247.97814 (247.97904), 249.97609; found 245.98156, 247.979598, 249.97693.

1-Chloro-2-(4-iodophenyl)-2-methylpropane (2b). Isolated as pale yellow oil after distillation at reduced pressure. ^{1}H NMR (CCl_4) δ 1.4 (s, 6H), 3.6 (s, 2H), 7.17 (d, 2H, J = 9.6 Hz), 7.71 (d, 2H, J = 9.6 Hz). ^{13}C NMR ($CDCl_3$) δ 26.3, 39.6, 55.7, 91.9, 128.0, 137.2, 145.5. *m*/*z* 296 (5.7), 294 (18.2), 246 (9.8), 245 (100.0), 217 (20.5), 127 (4.8), 118 (38.9), 117 (27.7), 116 (11.2), 115 (19.7), 91 (7.6), 77 (5.8), 51 (7.3). HRMS calcd for $C_{10}H_{12}ClI$ 293.96723 (295.96428); found 293.96803 (295.96492).

1-[4-(2-Chloro-1,1-dimethyl-ethyl)-phenyl]-3,3-dimethyl-2-butanone (1a). Isolated by column chromatography as colorless oil. ^{1}H NMR (acetone-d_6) δ 1.19 (s, 9H), 1.40 (s, 6H), 3.76 (s, 2H), 3.87 (s, 2H), 7.16 (d, 2H, J = 8.3 Hz), 7.36 (d, 2H, J = 8.3 Hz). ^{13}C NMR ($CDCl_3$) δ 26.5, 39.7, 42.8, 44.8, 56.5, 126.1, 129.7, 133.3, 144.5, 213.1. *m*/*z* 266 (1.5), 230 (5.4), 181 (3.0), 145 (10.6), 133 (7.5), 117 (5.4), 105 (2.5), 85 (20.0), 57 (100.0). HRMS calcd for $C_{16}H_{23}ClO$ [M + 1] 267.15157, 269.14862; found 267.15096, 269.14988.

1-(4-Isobutyl-phenyl)-3,3-dimethyl-butan-2-one (7a). Isolated by column chromatography as colorless oil. ^{1}H NMR (acetone-d_6) δ 0.89 (d, 6H, J = 6.6 Hz), 1.18 (s, 9H), 1.78−1.91 (m, 1H), 2.45 (d, 2H, J = 7.3 Hz), 3.84 (s, 2H), 7.08 (s, 4H). ^{13}C NMR ($CDCl_3$) δ 22.4, 26.4, 30.1, 42.9, 44.6, 45.0, 129.1, 129.2, 132.1, 140.0, 213.1. *m*/*z* 232 (3.0), 147 (6.2), 131 (1.6), 115 (2.1), 105 (11.4), 104 (5.2), 85 (12.1), 77 (3.7), 57 (100.0). HRMS calcd for $C_{16}H_{24}O$ 232.18272; found 232.18283.

3,3-Dimethyl-1-[4-(2-methyl-prop-1-enyl)-phenyl]-butan-2-one (8a). Isolated by column chromatography as colorless oil. ^{1}H NMR (acetone-d_6) δ 1.15 (s, 9H), 1.84 (d, 3H, J = 1.2 Hz), 1.87 (d, 3H, J = 1.4 Hz), 3.85 (s, 2H), 6.25 (m, 1H), 7.1 (m, 4H). *m*/*z* 231 (8.8), 230 (37.4), 146 (16.8), 145 (100.0), 129 (16.5), 128 (16.0), 115 (13.8), 105 (11.7), 85 (13.3), 77 (13.1), 57 (94.1), 41 (36.1). HRMS calcd for $C_{16}H_{22}O$ 230.167066; found 230.167508.

6-[4-(3,3-Dimethyl-2-oxo-butyl)-phenyl]-2,2,5,5-tetramethyl-hexan-3-one (9a). Isolated by column chromatography as a pale yellow solid. ^{1}H NMR ($CDCl_3$) δ 0.99 (s, 6H), 1.09 (s, 9H), 1.19 (s, 9H), 2.31 (s, 2H), 2.73 (s, 2H), 3.76 (s, 2H), 7.05 (s, 4H). ^{13}C NMR ($CDCl_3$) δ 26.4, 26.5, 27.5, 34.0, 42.9, 44.6, 44.7 45.4, 46.8, 128.9, 130.6, 132.5, 137.5, 231.1. *m*/*z* 330 (3.4), 273 (34.9), 245 (8.6), 217 (36.6), 203 (10.6), 187 (20.6), 155 (10.2), 132 (6.7), 117 (12.9), 105 (4.2), 104 (3.1), 85 (11.3), 57 (100). HRMS calcd for $C_{22}H_{34}O_2$ [M + 1] 331.25588; found 330.2637.

6-[4-(3,3-Dimethyl-2-oxo-butyl)-phenyl]-2,2,6-trimethyl-heptan-3-one (10a). Isolated by column chromatography as a pale yellow solid. ^{1}H NMR ($CDCl_3$) δ 1.02 (s, 9H), 1.20 (s, 9H), 1.29 (s, 6H), 1.87 (t, 2H, J = 7.8 Hz), 2.21 (t, 2H, J = 7.8 Hz), 3.77 (s, 2H), 7.11 (d, 2H, J = 8.4 Hz), 7.25 (d, 2H, J = 8.0 Hz). ^{13}C NMR ($CDCl_3$) δ 26.3, 26.4, 27.6, 29.0, 32.2, 37.1, 38.0, 42.8, 44.6, 125.8, 129.3, 130.9, 132.2, 146.8, 213.0. *m*/*z* 273 (20.6), 231 (10.6), 230 (60.8), 217 (4.4), 215 (7.5), 187 (37.3), 146 (9.1), 145 (11.5), 131 (9.0), 105 (8.8), 104 (15.4), 103 (4.1), 85 (16.8), 57 (100). HRMS calcd for $C_{22}H_{34}O_2$ [M +1] 331.25588; found 330.2642.

2-[4-(2-Chloro-1,1-dimethyl-ethyl)-phenyl]-1-phenyl-ethanone (1b). Isolated by column chromatography as a pale yellow oil.^{1}H NMR (acetone-d_6) δ 1.39 (s, 6H), 3.75 (s, 2H), 4.35 (s, 2H), 7.2−8.2 (m, 9H). ^{13}C NMR ($CDCl_3$) δ 26.4, 26.5, 39.6, 44.9, 55.6, 56.3, 126.2, 126.3, 128.5, 128.6, 129.5, 130.2, 130.3, 132.6, 133.2, 133.7, 136.7, 144.6, 197.6. *m*/*z* 289 (2.1), 288 (1.3), 287 (6.6), 238 (4.0), 237 (3.3), 195 (4.0), 182 (3.1), 147 (1.7), 133 (7.4), 132 (10.8), 117 (12.5), 107 (12.1), 106 (100), 105 (100.0), 104 (40.4), 91 (6.0), 78 (9.7), 77 (46.1). HRMS calcd for $C_{18}H_{19}ClO$ [M +1] 287.12027, 289.11732; found 287.12054, 289.11840.

2-[4-(2-Methyl-propenyl)-phenyl]-1-phenyl-ethanone (8b). Isolated by column chromatography together with **8b′** (**8b** in higher proportion according to GC relative peak areas). ^{1}H NMR (acetone-d_6) δ 1.85 (m, 6H), 4.34 (s, 2H), 6.25 (s, 1H), 7.1−7.7 (m, 7H), 8.05 (d, 2H, J = 10 Hz). *m*/*z* 251 (1.0), 250 (8.7), 145 (3.2), 129 (3.7), 128 (3.4), 115 (4.7), 106 (7.9), 105 (100.0), 77 (41.2). HRMS calcd for $C_{18}H_{18}O$ 250.13576; found 250.13548.

2-[4-(2-Methyl-allyl)-phenyl]-1-phenyl-ethanone (8b′). Isolated by column chromatography together with **8b** (**8b** in higher proportion according to GC relative peak areas). ^{1}H NMR (acetone-d_6) δ 1.64 (s, 3H), 3.30 (s, 2H), 4.3 (s, 2H), 4.75 (m, 2H), 7.1−7.7 (m, 7H), 8.05 (d, 2H, J = 10 Hz). *m*/*z* 251 (4.5), 250 (25.3), 146 (3.8), 145 (31.9), 130 (4.7), 129 (10.3), 128 (11.2), 115 (11.1), 106 (7.5), 105 (100.0), 77 (40.1). HRMS calcd for $C_{18}H_{18}O$ 250.13576; found 250.13548.

3,3-Dimethyl-4-[4-(2-oxo-2-phenyl-ethyl)-phenyl]-1-phenyl-1-butanone (9b). Isolated by column chromatography as yellow oil. ^{1}H NMR (acetone-d_6) δ 1.05 (s, 6H); 2.8 (s, 2H), 2.9 (s, 2H), 4.3 (s, 2H), 7.15 (d, 2H, J = 8.0 Hz), 7.23 (d, 2H, J = 8.0 Hz), 7.4−7.6 (m, 6H), 7.95 (d, 2H, J = 6.9 Hz), 8.09 (d, 2H, J = 6.9 Hz). ^{13}C NMR (acetone-d_6) δ 27.4, 35.0, 45.0, 47.5, 47.6, 128.4, 128.9, 129.0, 129.1, 129.6, 131.1, 133.1, 133.4, 137.4, 137.7, 197.6, 200.1. *m*/*z* 250 (33.0), 145 (8.3), 105 (100.0), 77 (44.6). HRMS calcd for $C_{26}H_{26}O_2$ [M + 1] 371.20111; found 371.20218.

1-(4-*tert*-Butyl-phenyl)-3,3-dimethyl-butan-2-one (11a).[20] Isolated by column chromatography as a colorless oil. ^{1}H NMR (acetone-d_6) δ 1.17 (s, 18H), 3.80 (s, 2H), 7.1 (m, 4H). *m*/*z* 233 (1.1), 232 (5.2), 147 (10.7), 133 (8.4), 85 (17.8), 57 (100.0). **11a** was compared with an authentic sample synthesized by reaction of 4-bromo-*tert*-butylbenzene with **3a** in DMSO, following the general procedure described in Supporting Information.

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Supporting Information Available: General methods; ^{1}H NMR and ^{13}C NMR spectra of compounds **1**, **2**, and **7**−**10**; computational procedure and summary of B3LYP calculations for the radical anions discussed. This material is available free of charge via the Internet at http://pubs.acs.org.

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