

Contrastive Photoreduction Pathways of Benzophenones Governed by Regiospecific Deprotonation of Imidazoline Radical Cations and Additive Effects

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In the photoreaction of benzophenones with 1,3-dimethyl-2-phenylbenzimidazoline (DMPBI), benzhydrols were major products. Addition of H₂O accelerated the reaction with no change in the product distribution, while AcOH, PhOH, and metal salts such as LiClO₄ and Mg(ClO₄)₂ were effective additives to produce benzpinacols. In contrast, benzpinacols were exclusively formed regardless of the solvent and the additive in the reactions with 2-(o-hydroxyphenyl)-1,3dimethylbenzimidazoline (o-HPDMBI). These observations are consistent with the hypothesis that DMPBI^{•+} donates a proton at the C₂ position to the benzophenone ketyl radicals while o-HPDMBI^{•+} donates a phenol proton.

Photoinduced electron-transfer (PET) processes provide useful methods to generate organic radical ions in solution, and the reaction pathways of radical ions are principally governed by not only their inherent property but also the surrounding medium including solvents and additives.¹ Because pairs of radical ions are uniquely generated with the PET methods in contrast to other nonphotochemical methods, specific interactions between the radical ion pairs are essentially important in the PET reaction systems.¹ Among the compounds that have been frequently subjected to PET reactions are amines² and ketones.³ Previously, we reported^{4,5} that 1,3-dimethyl-2phenylbenzimidazoline (DMPBI)⁶ and 2-hydroxyphenylCHART 1



1,3-dimethylbenzimidazolines (HPDMBI), shown in Chart 1, act as effective reagents to promote the photoinduced reduction of ketones. The synthetic utilities of these benzimidazolines are thus far recognized; however, their reaction behaviors in PET systems has been less explored. Therefore, we investigated photoreactions of benzophenone (**1a**), a simple but useful mechanistic probe substrate in various PET reactions,⁷ and *m*-methylbenzophenone (**1b**) with DMPBI and 2-(*o*-hydroxyphenyl)-1,3-dimethylbenzimidazoline (*o*-HPDMBI). Here, we report contrastive photoreduction pathways of **1** governed by regiospecific deprotonation of the radical cations of DMPBI and *o*-HPDMBI and by properties of the proton donors and metal salts.

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TABLE 1. Photoreaction of 1b with DMPBI

	solvent	additive (equiv vs 1b)	$\begin{array}{c} \operatorname{conv} \operatorname{of} \mathbf{1b}^c \\ (\%) \end{array}$	yields ^{c,d} (%)	
entry				2b	3b
1^a	MeCN	-	37	88	0
2^a	MeCN	$H_2O(13.9)$	88	88	0
3^a	MeCN	PhOH (6.0)	100	8	92
4^a	MeCN	AcOH (2.4)	100	0	100
5^a	MeCN	$LiClO_4(1.2)$	100	8	86
6^a	MeCN	$Mg(ClO_4)_2(1.2)$	89	7	91
7^b	DMF	_	4	0	0
8^b	DMF	$H_2O(13.9)$	14	100	0
9^b	DMF	AcOH (6.6)	56	6	86

^{*a*} **1b** (0.20 mmol), MeCN (4 mL), $\lambda > 280$ nm for 2 h for entries 1–6. ^{*b*} **1b** (0.20 mmol), BDMAP (0.010 mmol), DMF (2 mL), $\lambda > 360$ nm for 4 h for entries 7–9. ^{*c*} Determined with ¹H NMR. ^{*d*} Based on the conversion of **1b**.

We first conducted a preparative photoreaction (λ > 280 nm) of 1a and DMPBI (1.2 equiv versus 1a) in THF and found low conversion of 1a (21%) and predominant formation of benzhydrol (2a) (78% yield).^{8,9} Although addition of H_2O (13.9 equiv versus 1a) increased the conversion of 1a to 48%, 2a was still the sole product (85%). When H₂O was replaced with AcOH (6.6 equiv versus 1a), however, a significant amount of benzpinacol (3a, 47%) was obtained along with 2a (53%) at 65%conversion of 1a. To investigate in detail the photoreaction of benzophenone-DMPBI systems, we then conducted photoreactions of 1b and DMPBI under various conditions, as shown in Table 1, in which the quantities of 1b, 2b, and 3b in the reaction mixtures were easily determined with ¹H NMR based on the signals of the methyl protons of 1b, 2b, and 3b. In the reactions with the proton donors, the conversion of 1b was significantly increased in the presence or absence of 1,6-bis(N,N'dimethylamino)pyrene (BDMAP)^{4b-e,5,10} as a sensitizer (entries 2-4 or 8 and 9).¹¹ Addition of the proton donors also changed the yields of 2b and 3b in varying extent, apparently depending on the acidity of proton donors (pK_a¹² in water: H₂O 15.75; PhOH 10.0; AcOH 4.75) (entries 2-4 and 8 and 9). Note that addition of metal salts such as $LiClO_4$ and $Mg(ClO_4)_2$ markedly changed the product distribution (entries 5 and 6).¹³ Interestingly, photoreactions of 1b with triethylamine, N,N-diethylaniline, N,N-dimethylaniline, or tribenzylamine in aqueous MeCN predominantly produced 3b (59-95%) along with a small amount of 2b (2–11%).

A plausible reaction mechanism for the reaction of **1** with DMPBI is proposed in Scheme **1**. Light-induced single electron transfer (SET) produces a radical ion pair





 $[DMPBI^{\bullet+}\ 1^{\bullet-}].^{14}$ Subsequent proton transfer (PT) produces a radical pair [5 and 4] that successively undergoes SET to give a DMPBI-derived cation (5^+) and a carbanion (4^{-}) .¹⁵ Protonation to 4^{-} gives 2 in the presence of H₂O. Feasibility of the SET process between 5[•] and 4[•] could be consistent with the fact that the formation of 2 was predominant in the case of DMPBI and not in the cases of simple tertiary amines.¹⁶ In the presence of AcOH and PhOH, these proton donors intercept 1^{•-} with protonation to give 4[•].¹⁸ Because the potential reducing agent 5[•] is not generated in this case, 4[•] survives to undergo dimerization with another 4[•] to 3. Ion pair exchange⁷ⁱ between [DMPBI⁺⁺ 1⁻⁻] and the metal salt, represented by LiClO₄ in Scheme 1, also prevents PT from DMPBI⁺⁺ to 1⁻⁻ to give the metal-coordinated ketyl radical (Li⁺1^{•-}) that dimerizes to **6**, which finally converts to 3.

(14) Feasibility of electron transfers between 1 and amines was confirmed by discussion using their redox potential data. For details, see the Supporting Information.

⁽⁸⁾ A preliminary observation that the irradiation of **1a** with DMPBI predominantly produced **2a** in aqueous MeCN was reported.^{4c}

⁽⁹⁾ Yields of the products reported in this Note represent those based on the conversion of the corresponding starting materials unless otherwise stated.

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⁽¹¹⁾ Similar marked change of the product distribution depending on the proton donors was also observed in the BDMAP-sensitized photoreaction of cyclohexylphenyl ketone with DMPBI in DMF (alcohol/pinacol = 100:0 for H_2O and 10:90 for AcOH).

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⁽¹³⁾ Although the influence of alkali metal salts on the PET processes of **1a** and amines has been thoroughly investigated,⁷ⁱ surprisingly, the influence of the salts on the product formation has not been explored well.

⁽¹⁵⁾ One reviewer suggested another possible pathway in which the ion radical pair [DMPBI⁺⁺ 1^{•-}] is converted to an ion pair [5⁺ PhArCH-O⁻] by a hydrogen atom transfer. This pathway must be a minor one, even if it exists, because a hydrogen atom transfer from DMPBI⁺⁺ to the sterically more crowded ketyl carbon of 1^{•-} should be less likely than a proton transfer to the oxy anion part of 1^{•-}.

⁽¹⁶⁾ Electron-donating ability of **5** is considered to be greater than those of α -amino radicals derived from simple tertiary amines on the basis of the oxidation potentials of the benzthiazolyl radical that possesses a structure similar to that of **5** (-1.3 V versus SCE)^{17a} and those of simple α -amino radicals (ca. -1.0 V versus SCE).^{17b}

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⁽¹⁸⁾ Because the pK_a value of the protonated ketyl radical of **1a** in water has been reported to be 9.3, ¹⁹ the protonation to **1**⁻⁻ by AcOH or PhOH must be a reasonably efficient process.

TABLE 2. Photoreaction of 1b with o-HPDMBI

	solvent	additive (equiv vs 1b)	$\begin{array}{c} \operatorname{conv} \operatorname{of} \mathbf{1b}^c \\ (\%) \end{array}$	yields ^{c,d} (%)	
entry				2b	3b
1^a	MeCN	-	52	0	100
2^a	MeCN	$H_2O(13.9)$	47	0	100
3^a	MeCN	AcOH (6.6)	100	0	100
4^a	MeCN	$LiClO_4(1.2)$	100	0	100
5^a	MeCN	$Mg(ClO_4)_2(1.2)$	100	0	100
6^a	THF	_	86	0	100
7^a	THF	AcOH (6.6)	85	0	96
8^a	\mathbf{DMF}	-	54	8	91
9^b	\mathbf{DMF}	-	34	0	100
10^b	DMF	AcOH (6.6)	79	0	93

^{*a*} **1b** (0.20 mmol), solvent (4 mL), $\lambda \geq 280$ nm for 2 h for entries 1–8. ^{*b*} **1b** (0.20 mmol), BDMAP (0.010 mmol), DMF (2 mL), $\lambda \geq 360$ nm for 4 h for entries 9 and 10. ^{*c*} Determined with ¹H NMR. ^{*d*} Based on the conversion of **1b**.

We next conducted photoreactions of 1b with o-HPD-MBI and found a marked change in product distributions from those with DMPBI. As shown in Table 2, 3b was exclusively produced in high yield regardless of the reaction conditions. Particularly, the exclusive formation of 3b was contrastive to the predominant formation of 2b with DMPBI in the presence of H_2O . Significant conversion of 1b, even in the absence of proton donors, was also notable (entries 1, 6, and 8). Interestingly, addition of AcOH significantly increased the conversion of 1b in MeCN and DMF (compare entries 1 and 9 with 3 and 10, respectively); however, the conversion of 1b did not change very much with or without AcOH in THF (entries 6 and 7). Again, both $LiClO_4$ and $Mg(ClO_4)_2$ increased the conversion of 1b and led to the exclusive formation of 3b.

To gain further insight into the effects of the hydroxy substituent on the phenyl group at the C₂ position of DMPBI, we conducted photoreactions of **1b** with *p*-HPDMBI or 2-(*p*-methoxyphenyl)-1,3-dimethylbenzimid-azoline (ADMBI) in MeCN. The reaction with *p*-HPDMBI produced **3b** (94%) at 52% conversion of **1b**, whereas the reaction with ADMBI in the presence of H₂O (13.9 equiv versus **1b**) produced **2b** (98%) at 100% conversion of **1b**. The fact that *p*-HPDMBI behaves similarly to *o*-HPDMBI rather than ADMBI suggests that electron-donating properties of the hydroxy substituents of *o*- and *p*-HPDMBIs are not crucial factors, but their proton-donating abilities are responsible for the exclusive formation of **3b**.

On the basis of these observations, we propose a plausible mechanism for the reaction of *o*-HPDMBI and 1, as shown in Scheme 2. The initially generated *o*-HPDMBI⁺⁺ releases either a phenol proton (H_a) or a proton at the C₂ position (H_b) . If H_b^+ is transferred to 1⁻⁻, the resulting radical 7[•] would reduce 4[•] to 4⁻, which finally becomes 2 similarly to the reaction with DMPBI (see Scheme 1). However, this was not witnessed. Instead, *o*-HPDMBI⁺⁺ donates H_a^+ to 1⁻⁻, and the phenoxide part²⁰ of the resulting zwitter ion radical 8⁺⁺⁻ does not reduce 4[•] to 4⁻ so that 4[•] has an opportunity to undergo dimerization to 3. When a proper proton donor is added to the reaction system, protonations to 1⁻⁻ from the

SCHEME 2



proton donor and from o-HPDMBI++ are competitive. This situation should be more plausible in polar solvents than in nonpolar solvents because a dissociation of [o-HPD-MBI⁺⁺ 1⁻⁻] is most likely to occur in the former solvents. Note that the addition of AcOH significantly increased the conversion of 1b in both MeCN and DMF, but not in THF (compare entries 1, 9, and 6 to 3, 10, and 7, respectively, in Table 2). The above hypothesis of the deprotonation regioselectivity of o-HPDMBI⁺⁺ is particularly noteworthy because the proton at the C_2 position of *o*-HPDMBI^{•+} (H_b) is considered to be more acidic than the phenol proton (H_a) judging from their expected acidities.²² Therefore, it must be assumed that the order of their kinetic acidities²⁵ is reverse to that of the corresponding thermodynamic acidities in these reaction systems.

In conclusion, we have found that the photoproduct distributions from 1 markedly changed depending on DMPBI or *o*-HPDMBI and also were influenced by the property of the additives. The contrastive observations between DMPBI and *o*-HPDMBI are consistent with the hypothesis that DMPBI⁺⁺ donates a proton at the C_2

(20) Reducing abilities of the phenoxide ions should be much lower than those of α -amino radicals, 16 judging form their oxidation potentials. The oxidation potential of the phenoxide ion was reported to be ca. 0 V versus SCE. 21

(22) Acidities of some amine radical cations were reported.²³ For example, the pK_a of the radical cation of N,N-dimethylaniline was estimated to be 9 in MeCN.^{23a} The pK_a value of phenol in MeCN was estimated to be 27.^{12,24}

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⁽²⁵⁾ The concept of kinetic acidity has been often applied to rationalize the reaction of radical ion pairs generated by PET processes.²⁶ Then it was suggested that the kinetic acidity of a certain radical cation is influenced by the nature of a radical anion generated simultaneously.

position to $1^{\bullet-}$, whereas *o*-HPDMBI⁺⁺ donates a phenol proton to $1^{\bullet-}$ rather than a proton at the C₂ position. Investigation of the factors to control the regioselectivity of deprotonation of *o*-HPDMBI⁺⁺ is the next subject to be undertaken.

Experimental Section

General Procedure for Photoreaction of 1b with Amines. A solution of 1b (0.20 mmol) and amine (0.24 mmol) with or without BDMAP (0.010 mmol) in a solvent (MeCN, THF, and DMF 4 mL; DMF 2 mL for the BDMAP sensitized reactions) in the presence or absence of H₂O, PhOH, AcOH, LiClO₄, or Mg-(ClO₄) ₂ was purged with N₂ for 5 min prior to irradiation. The irradiation and workup procedures were essentially the same as those of the reactions of 1a described in the Supporting Information. The photolyzates containing PhOH, LiClO₄, and Mg(ClO₄)₂ were worked up in the same manner to that containing AcOH. Each photoproduct mixture was analyzed with ¹H NMR (200 MHz) using triphenylmethane as an internal standard. Benzhydrol 2b²⁷ and benzpinacol 3b²⁸ were identified by comparison of their spectral data with those of the products obtained by the NaBH₄ and SmI₂ reductions of 1b, respectively. Quantities of 1b, 2b, and 3b were determined on the basis of integrations of the methyl peaks of these compounds (2.42 ppm for 1b, 2.34 ppm for 2b, 2.19 and 2.20 ppm for the two diastereomers of 3b) and the methine peak of triphenylmethane (5.56 ppm).

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Supporting Information Available: General experimental procedures, preparations of *o*-HPDMBI, *p*-HPDMBI, and ADMBI, their IR and NMR spectra and cyclic voltammogram, photoreaction procedure for **1a**, and additional discussion. This material is available free of charge via the Internet at http://pubs.acs.org.

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