

## A Detailed Investigation of Substituent Effects on N–H Bond Enthalpies in Aniline Derivatives and on the Stability of Corresponding N-Centered Radicals

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The N–H bond dissociation enthalpies (BDE's) of 40 anilines ( $p\text{GC}_6\text{H}_4\text{NH}_Y$ ) from series **1** to **4** with  $\alpha$ -Y and  $p$ -G substituents and the stability of related radicals ( $p\text{GC}_6\text{H}_4\text{N}\dot{\text{Y}}$ ) were studied using ab initio (MP2) and density functional methods (B3LYP) with large basis sets. The results show that both methods reproduce earlier experimental BDEs within 2–3 kcal/mol and satisfactorily predict the  $\alpha$  and remote substituent effects on BDEs ( $\Delta\text{BDEs}$ ), as they reproduced the experimental  $\Delta\text{BDEs}$  within less than 1 kcal/mol. Furthermore, the conventional radical stabilization enthalpy ( $\text{RSE} = -\Delta\text{BDE}$ ) was found to be invalid to represent the trend of the radical stabilization because the molecule effect (ME) can contribute more to RSE than the radical effect (RE) for certain series (**1** and **4**). These radicals are in fact *stabilized by electron-withdrawing groups (EWGs) but destabilized by electron-donating groups (EDGs)*, a phenomenon just opposite to the observed *O*-behavior of many other aromatic heteroatomic radicals studied so far. These radicals are thus assigned as a new radical class, Class counter-*O* (or  $\bar{O}$ ) according to Walter's terminology. Moreover, the excellent multi-parametric Hammett-type correlations indicated that the para substituent effects on BDEs originate mainly from polar effects, but those on radical stability originate from both spin delocalization and polar effects. The atomic charge and spin population variations at a radical center due to  $p$ -G substitution were also found to correlate satisfactorily with REs. These results show that the spin delocalization effect should be explicitly considered in accounting for both  $\Delta\text{BDEs}$  and radical stabilization effects. Finally, an overall substituent effect scale for radical stability has been proposed, and the overall substituent effect on the N-radicals was found to conform to the Captodative Principle.

### Introduction

Knowledge of the bond dissociation enthalpies (BDEs) has been accumulated substantially in the past decade owing to the recent development of both experimental<sup>1,2</sup> and quantum chemical<sup>3</sup> techniques. One of the most practical applications of the derived BDE data is to take the relative BDE values for the stabilization energies of free radicals (RSEs),<sup>2</sup> currently a highly focused area in both chemistry and biology.

In this regard, the electronic effects of para substituent G (abbreviated as  $p$ -G or  $p\text{G}$  below) on X–H bond

strengths of the molecules with the formula  $p\text{-GC}_6\text{H}_4\text{XH}_n$  have been widely investigated.<sup>1,4,5,11,12</sup> When X is C, it was generally found that the C–H bonds are weakened by all  $p$ -G substituents.<sup>6</sup> This coincidentally agrees with Walter's early prediction<sup>7</sup> that carbon radicals should belong to a so-called "Class *S*" category, where *S* denotes

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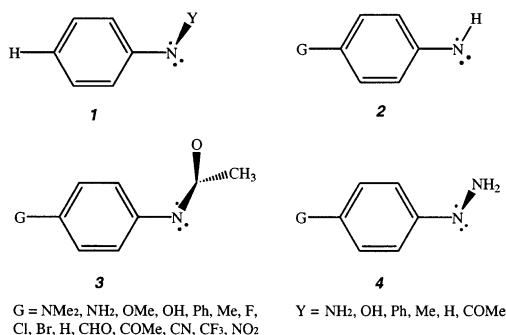
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radicals being stabilized by both electron-donating (EDG) and electron-withdrawing groups (EWG) in the *same* direction. Walter also predicted that the existence of an electron lone pair at the spin-centered atom such as O, N, or S should be the criterion for a radical to show an “*O*-type” (*O* for opposite) behavior, i.e., being stabilized by EDG but destabilized by EWG. This has generally been verified by the extensive X–H (X = O, N, S, etc.) BDE studies of this group and others.<sup>1,6,8</sup> Recently, in contrast to Walter’s predictions and previous observations in the literature, our experimental BDE studies have indicated that certain C-centered radicals (with no electron lone pair on the spin-centered atom) can be modified to demonstrate Class *O* behavior by structure perturbations at the benzylic  $\alpha$  position.<sup>9</sup> A uniform rationale for the conversion of a benzylic radical (Class *S*) to a Class *O* radical has been proposed.<sup>5</sup> Naturally, this rationale also points to the possibility for a novel radical class, Class counter-*O* ( $\bar{O}$ ), in which a radical is *stabilized by EWG but destabilized by EDG*. In fact, our study of N–H bonds in  $pGC_6H_4NHP^+Ph_3Br^-$  series<sup>9</sup> has already suggested the  $\bar{O}$  substituent effect on BDEs. Furthermore, the ESR data of  $pGC_6H_4C(Me)OMe$  radicals also support the possibility of this new radical class.<sup>10</sup>

The complexity of radical behavior points to a definite need for a more general understanding of the rules governing the patterns of the substituent effect for radicals with the general formula  $pGC_6H_4XH_nY$  (where *Y* denotes an  $\alpha$ -substituent). In this regard, theoretical calculation is frequently used to analyze this kind of sophisticated problems. However, until recently, the diversity of radical behavior has in fact largely been ignored,<sup>5,11,12</sup> so the problem relating to the direction and magnitude of the effect of substituents on the stability of these aromatic radicals still remains largely unsolved. Nonetheless, it should be noted that recently, using both theoretical calculations and the radical-equilibrium electron paramagnetic resonance (REqEPR) technique,<sup>13</sup> Pratt et al. examined the substituent effects on the N–X (X = H, Me, OH and F) BDEs in aromatic amines and on the stability of the related ArNH radicals<sup>11</sup> and found that the EDG and EWG have comparable weakening and strengthening effects on the N–H bond and that the effects on the radical and molecule stability are also comparable whereas in phenols the former seems to be much larger than the latter. Along a similar line but using better optimized geometries, Song et al.<sup>12</sup> also calculated the N–X (X = H, Me, F, Cl, Li) BDEs and found that the substituent effects on N–X are significantly affected by the X group. In these reports, the stress was mainly on the remote substituent effects on BDEs rather than on the radical stability. Furthermore, in their quantitative analysis of the radical stability, the effect

CHART 1. Four Series of N-Centered Radicals



of the spin delocalization was not discussed. Moreover, the  $\alpha$  substituent effects on the aromatic aminyl BDEs and on radical stability are not sufficiently dealt with.<sup>14</sup>

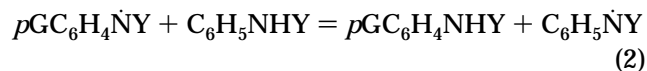
In the present work, we conducted a theoretical study of the nitrogen species,  $pGC_6H_4NY$  (Chart 1, Y = H, Ac, NH<sub>2</sub>, etc.) to exemplify the relative importance of resonance, induction, and spin delocalization effects of para and  $\alpha$  substituents on N-radical stability and on N–H BDEs,<sup>11,12</sup> using extended Hammett correlations. We demonstrate herein that the spin delocalization is important to the radical stability, and that the  $\alpha$ -Y effects substantially affect the *p*-G effects on both stability of the N-radicals and corresponding aniline derivatives, and they are substantially larger than the *p*-G effects. Other practical clues to understand and predict the directions of radical substituent effects are also disclosed.

## Results

The theoretical and experimental N–H BDEs at 298.15 K for series **2**<sup>1,15–17</sup> are presented in Table 1, and corresponding  $\Delta$ BDEs are presented in Table 2. The *p*-G effect on radical stability as approximated by the conventional radical stabilization enthalpy (RSE  $\equiv -\Delta$ BDE(G)) is given in eq 1

$$RSE = BDE(H) - BDE(G) \quad (1)$$

which corresponds to the enthalpy change of the following isodesmic reaction (eq 2)<sup>18</sup>



This approximation assumes that the substituent effect on the stability of the undissociated molecule is trivial compared with that on the radical. This assumption has recently been found to be untrue by several studies<sup>5,11,19</sup> because those studies showed that the substituent effects on the stability of the undissociated molecules can be

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**TABLE 1. Theoretical and Experimental BDE's for Series 2<sup>a</sup>**

G/Y	EC <sup>b</sup>	PR <sup>c</sup>	PAC <sup>d</sup>	B3LYP	MP2	ΔBDE <sup>e</sup>	ΔBDE <sup>f</sup>
NMe <sub>2</sub>				83.7	87.8	-7.0	-6.1
NH <sub>2</sub>		86.0		84.5	88.6	-6.3	-5.6
OMe	90.4	87.2		86.6	90.1	-4.1	-4.1
OH				86.7	90.3	-4.0	-3.8
Me	92.0	88.7	87.5	89.2	92.1	-1.5	-1.9
Ph				89.4	92.4	-1.3	
F			88.8	89.5	92.4	-1.3	0.3
Cl	92.4			90.3	93.1	-0.4	0.1
Br	92.3			90.5	92.1	-0.2	0.5
H	92.3	89.1	89.7	90.7	93.3	0.0	0.0
Ac	94.2	90.6		92.6	94.8	1.9	2.7
CN	95.2	91.8		93.3	95.6	2.6	3.1
CF <sub>3</sub>	96.5	92.0		93.3	95.6	2.6	3.1
CHO				93.3	95.4	2.6	2.9
NO <sub>2</sub>	96.7			94.8	96.3	4.1	4.7
ρ <sup>+</sup>	3.9	3.0		4.3	3.4	4.6	4.3
R <sup>2</sup>	0.860	0.974		0.980	0.962	0.980	0.963

<sup>a</sup> Basis set was 6-311+G(2d,2p), and values are given in kcal/mol. <sup>b</sup> From ref 1d. <sup>c</sup> From ref 15a. <sup>d</sup> From ref 17. <sup>e</sup> From this work. <sup>f</sup> From ref 11.

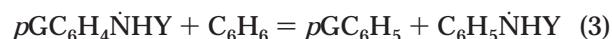
**TABLE 2. Substituent Effect on BDE<sup>a</sup>**

G,Y series	1	2	3	4
NMe <sub>2</sub>		-7.0	-7.9	-2.8
NH <sub>2</sub>	-16.7	-6.3		
OMe	-	-4.1	-4.3	-1.9
OH	-17.6	-4.0		
Ph	-7.2	-1.3		
Me	-3.0	-1.5	-1.5	-0.6
F		-1.3	-1.2	-0.1
Cl		-0.4	-0.6	-0.4
Br		-0.2	-0.4	-0.2
H	0.0	0.0	0.0	0.0
Ac	4.1	1.9	1.6	0.5
CN		2.6	1.9	0.7
CF <sub>3</sub>		2.6	2.2	0.8
CHO		2.6		
NO <sub>2</sub>		4.1	3.0	1.1
ρ <sup>+</sup>	-13.0	4.3	4.3	1.6
R <sup>2</sup>	0.900	0.980	0.986	0.963

<sup>a</sup> The data were calculated using B3LYP/6-311+G(2d,2p) and based on ΔBDE = BDE<sub>G,Y</sub> - BDE<sub>H</sub> (given in kcal/mol).

compared to those of corresponding radicals. Nevertheless, it is still hoped<sup>2</sup> that RSE gives the right direction of the radical stabilization.

The *p*-G effect on the undissociated molecule, the molecule stabilization effect (ME), was defined<sup>5c</sup> as the enthalpy change of the isodesmic reaction in eq 3.<sup>4,5,18,20-22</sup>



ME is expected to measure the interaction between the *p*-G and the α-substituted N-center (-NHY). Similarly, the *p*-G effect on the radical stabilization, the radical effect (RE),<sup>5</sup> was defined by the enthalpy change of another isodesmic reaction (eq 4):



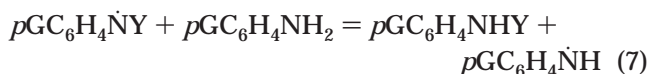
From eqs 2-4, it is clear that RSE = RE - ME. If ME is small, RSE approaches to RE, and so it can be used to

determine the direction of the radical stabilization. The calculated RSE, ME, and RE results using B3LYP/6-311+G(2d,2p) are compiled in Table 4 (for 2-4). Thus, defined ME and RE correspond to Pratt et al.'s<sup>11</sup> MSE and RSE, respectively, but in opposite signs (that is, ME = -MSE).

In this work, the α-Y effects on radical stability (RE<sub>α-Y</sub>(G), Y = Ac, NH<sub>2</sub>) and on molecule stability (ME<sub>α-Y</sub>(G)) were also defined as the enthalpy changes of reactions 5 and 6, respectively.



The related α-Y effect on N-H BDEs was similarly defined on the basis of reaction 7:



The calculated α-RE, α-ME, and α-RSE values of series 1 (G = H) are presented in Table 5.

To examine the relative stability of the *p*-Y radical *p*YC<sub>6</sub>H<sub>4</sub>NH to the α-Y radical C<sub>6</sub>H<sub>5</sub>NY, we calculated the radical isomerization enthalpy, ER<sub>α-Y-p-Y</sub>, of reaction C<sub>6</sub>H<sub>5</sub>NY → *p*YC<sub>6</sub>H<sub>4</sub>NH. From reactions 4 and 5, we can readily derive eq 8.

$$RE_{\alpha-Y} = RE_{p-Y} + ER_{\alpha-Y-p-Y} \quad (8)$$

Molecule isomerization enthalpy, EM<sub>α-Y-p-Y</sub>, of reaction C<sub>6</sub>H<sub>5</sub>NHY → *p*YC<sub>6</sub>H<sub>4</sub>NH<sub>2</sub> was also used in deriving the relationship between α- and *p*-Y effects on molecules (eq 9).

$$ME_{\alpha-Y} = ME_{p-Y} + EM_{\alpha-Y-p-Y} \quad (9)$$

These results are also presented in Table 5 for series 1.

Since the atomic charge and the spin density on a radical center also contains information about the substituent effect on the stability of the radical,<sup>5b</sup> they were also calculated using the natural bond orbital (NBO) scheme<sup>23</sup> from B3LYP/6-311+G(2d,2p) orbitals. The calculated relative charge (ΔC) and spin density (ΔS) as defined in eq 10 are listed in Table 5 (for 1) and the Supporting Information (for 2-4) and were correlated with the radical stability.

$$\Delta S = S(H) - S(G) \text{ and } \Delta C = C(H) - C(G) \quad (10)$$

## Discussion

**Agreement between Theoretical and Experimental N-H BDEs and ΔBDEs.** The calculated and experimental N-H BDEs for series 2 are compiled in Table 1. The experimental data were mainly derived from three methods, i.e., Bordwell and Cheng's<sup>1,16,24</sup> *p*K<sub>a</sub>-based EC

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**TABLE 3. Correlation of RE, RSE, and ME by Charton's Equation<sup>a</sup>**

series	L	D	R	h <sup>b</sup>	R <sup>2</sup>	sd <sup>c</sup>	y	L <sup>d</sup> (%)	D <sup>d</sup> (%)
RE									
1	-19.36	22.24	-99.84	-4.49	0.9984	0.77	0.088	17.8	53.5
2	-1.95	-2.98	-12.43	4.16	0.9837	0.24	0.152	16.5	46.2
3	-3.27	-5.39	-16.97	3.14	0.9956	0.22	0.086	17.9	47.9
4	1.20	1.91	-7.24	-3.80	0.9754	0.15	0.203	17.2	44.5
RSE = -ΔBDE									
1	-	-23.59	-	-	0.9493	2.40	0.291	-	100.0
2	-4.51	-8.33	-8.98	1.08	0.9942	0.30	0.090	19.7	66.4
3	-2.90	-8.07	-15.46	1.92	0.9940	0.32	0.100	13.4	60.4
4	-1.58	-2.77	-5.27	1.90	0.9765	0.23	0.198	19.7	56.1
ME									
1	-27.02	45.83	-94.48	-2.06	0.9866	4.24	0.258	15.3	68.0
2	2.63	5.34	-3.43	-0.64	0.9927	0.20	0.101	19.3	71.7
3	-0.39	2.69	-1.58	-0.59	0.9886	0.11	0.138	7.4	81.7
4	2.59	4.71	-1.94	-0.41	0.9874	0.24	0.145	23.7	69.8

<sup>a</sup> Based on B3LYP/6-311+G(2d,2p) values and in Charton's triparametric (LDR) correlations.<sup>30</sup> <sup>b</sup> R/D. <sup>c</sup> Standard deviation. <sup>d</sup> Weighted percentage.<sup>45,46</sup>

**TABLE 4. Para-Substituent Effects on Molecular and Radical Stability<sup>a</sup>**

G series	RE			ME			RSE		
	2	3	4	2	3	4	2	3	4
NMe <sub>2</sub>	4.6	7.1	0.6	-2.5	-0.8	-2.2	7.0	7.9	2.8
NH <sub>2</sub>	3.6			-2.5			6.2		
OMe	2.0	3.3	-0.2	-2.1	-1.0	-2.0	4.1	4.3	1.9
OH	1.8			-2.1			4.0		
Me	0.9	1.3	0.0	-0.7	-0.2	-0.5	1.5	1.5	0.6
Ph	1.4			0.1			1.3		
F	0.0	0.3	-0.5	-1.3	-0.9	-0.7	1.3	1.2	0.1
Cl	0.1	0.2	0.0	-0.3	-0.4	-0.3	0.4	0.6	0.4
Br	0.1	0.2	0.1	-0.1	-0.3	-0.2	0.2	0.4	0.2
H	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ac	0.3	-0.4	1.6	2.2	1.2	2.1	-1.9	-1.6	-0.5
CN	-0.4	-1.2	1.3	2.2	0.7	2.0	-2.6	-1.9	-0.7
CF <sub>3</sub>	-1.1	-1.7	0.6	1.5	0.5	1.4	-2.6	-2.2	-0.8
CHO	0.1			2.8			-2.6		
NO <sub>2</sub>	-1.0	-2.0	1.8	3.1	1.0	2.9	-4.1	-3.0	-1.1
ρ <sup>+</sup>	-2.0	-3.5	0.5	2.4	0.8	2.1	-4.3	-4.3	-1.6
R <sup>2</sup>	0.900	0.970	0.222	0.856	0.597	0.810	0.980	0.986	0.963

<sup>a</sup> Calculated using B3LYP/6-311+G(2d,2p) (given in kcal/mol). RE and ME are radical and molecule stabilization enthalpies (see eqs 4 and 3), respectively. RSE is defined as -ΔBDE(G) (RE - ME, eq 1).

**TABLE 5. α Substituent Effects on Stability and Isomerization of Radicals and Anilines in Series 1<sup>a</sup>**

Y	RE <sub>α-Y</sub>	ER <sub>α-Y-p-Y</sub>	ME <sub>α-Y</sub>	EM <sub>α-Y-p-Y</sub>	RSE	ΔC <sup>b</sup>	ΔS
NH <sub>2</sub>	-11.2	-14.8	-27.9	-25.4	16.7	-0.3010	-0.0082
OH	-21.4	-23.2	-39.0	-36.8	17.6	-0.4471	-0.0507
Me	-5.9	-6.7	-8.9	-8.2	3.0	-0.1745	-0.0512
Ph	0.3	-1.2	-6.9	-7.0	7.2	-0.1532	0.0528
H	0.0	0.0	0.0	0.0	0.0	0.0000	0.0000
Ac	3.4	3.1	7.5	5.3	-4.1	-0.1024	0.0400

<sup>a</sup> RE<sub>α-Y</sub> and ME<sub>α-Y</sub> are radical and molecule stabilization enthalpies by α-Y (eqs 5 and 6 with G = H), respectively. ER<sub>α-Y-p-Y</sub> and EM<sub>α-Y-p-Y</sub> denote the isomerization enthalpies for radicals and anilines, respectively, calculated using B3LYP/6-311+G(2d,2p) (given in kcal/mol). <sup>b</sup> Calculated using ΔS(Y) = S(H) - S(Y) and ΔC(Y) = C(H) - C(Y), where C and S denote the NBO atomic charge and spin on the radical center, respectively (C(H) = -0.5470, S(H) = 0.4968).

(electrochemical) method, Jonsson's<sup>15a,c</sup> PR (pulse radiolysis) method, and Ingold's<sup>17</sup> PAC (photoacoustic calorimetry) method. The latter two methods gave similar but lower BDEs for a limited number of anilines (Table 1). The higher EC values were deemed to be a result of the neglect of the solvent and hydrogen bond effects in their derivation,<sup>1,17</sup> but certain evidence indicates otherwise.<sup>15</sup>

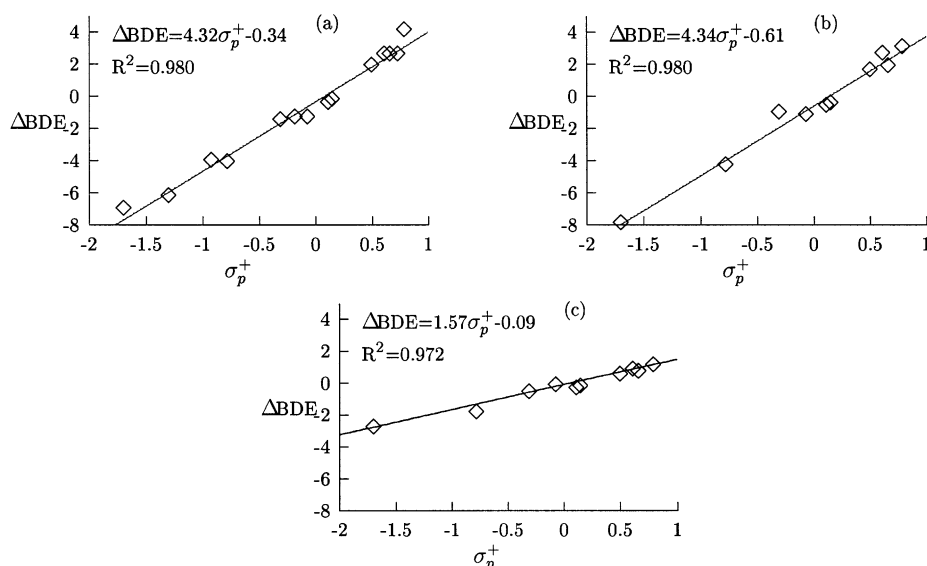
As shown in Table 1, B3LYP BDEs of **2** are generally lower than those from MP2 by about 2–4 kcal, and for EDGs the differences are larger. This is consistent with

the observation in the previous work.<sup>25,26</sup> The MP2 N–H BDEs agree better with the EC data<sup>1d</sup> as their average deviation was much smaller than that of the B3LYP BDEs (0.5 and 2.3 kcal, respectively, for series **2**), whereas the B3LYP data agree better with the PR and PAC data. These differences indicate that the true values may fall into somewhere between these two extreme

(25) Curtiss, L. A.; Raghavachari, K.; Redfern, P. C.; Pople, J. A. *J. Chem. Phys.* **1997**, *106*, 1063.

(26) (a) DiLabio, G. A.; Pratt, D. A.; LoFaro, A. D.; Wright, J. S. *J. Phys. Chem. A* **1999**, *103*, 1653. (b) Barckholtz, C.; Barckholtz, T. A.; Hadad, C. M. *J. Am. Chem. Soc.* **1999**, *121*, 491.





**FIGURE 1.** Correlation plots of  $\Delta\text{BDE}$ 's with  $\sigma_p^+$  for series (a) **2**, (b) **3**, and (c) **4**.

experimental data sets because it is known that B3LYP tends to underestimate the BDEs.<sup>5,11</sup>

The calculated  $\Delta\text{BDE}$ s of series **2** are in very good agreement with experiment as also shown in Table 1 (see also the Supporting Information). For example, the average deviations of MP2 and B3LYP for series **2** were only 0.9 and 0.7 kcal, respectively. The main difference between Pratt's  $\Delta\text{BDE}$ s<sup>11</sup> and our results lies in the description of the remote substituent effects of F, Cl, and Br. Agreeing with PAC experiment<sup>17</sup> and a recent calculation,<sup>12</sup> this work indicates a reasonable bond weakening of *p*-F (−1.2 kcal/mol) rather than a small bond strengthening (0.3 kcal/mol).<sup>11</sup> For series **3**, our B3LYP  $\Delta\text{BDE}$ s are in even better agreement with Cheng's EC experiment,<sup>1c</sup> as indicated by the average deviation of 0.5 kcal and the maximum deviation of 0.8 kcal. This indicates that the B3LYP  $\Delta\text{BDE}$ s presented here represent the true substituent effects on N–H bond strength for all the species considered in this work.<sup>27</sup>

**Substituent Effects on N–H Bond Strengths.** The most notable feature of the substituent effects on N–H BDEs shown in Table 2 is that for all the substituted series EDGs and the halogens weaken the N–H bond, whereas EWGs enhance the N–H bond. This confirms the previous experimental observation and theoretical work<sup>11,12</sup> that the N–H bond varies in an *O*-pattern upon remote substitution (*vide supra*).

The effect of  $\alpha$ -Y on BDEs in series **1** is substantially larger than that in the para series. This should be primarily due to the shorter distance between  $\alpha$ -Y and the N-center that enhances the electronic interaction.<sup>8</sup> An ED  $\alpha$ -Y in the –NH<sub>2</sub> or –N<sub>2</sub> group can strongly interact with the neighboring electron lone pair of the N atom, and the interaction in the latter should be smaller

because the electron density at the –N<sub>2</sub> radical center is smaller than that at the –NH<sub>2</sub> molecule center. Consequently, the stability difference ( $\Delta\text{BDE} = \text{ME} - \text{RE}$ ) between molecule and radical would be negative (see Table 2) as the molecule would be more severely destabilized by an ED  $\alpha$ -Y. On the other hand, an EW  $\alpha$ -Y can delocalize the lone pair electrons of the nitrogen atom in NH<sub>2</sub> and thus stabilize molecules. This then explains the strengthening effect of EWGs on the N–H bond. This electron repulsion and depletion argument is consistent with the results from our Charton correlation analyses<sup>28</sup> (negative  $\eta$  indicating electron-rich NH<sub>2</sub> and N<sub>2</sub>, see Table 3 for series **1**).

Polar interaction has been found to dominate the overall remote substituent effect for series **2**. A plot of 14 B3LYP  $\Delta\text{BDE}$ s *vs.* experimental  $\sigma_p^+$ s<sup>29</sup> shows a good line (Figure 1a,  $R^2 = 0.980$ , Exner's  $\psi = 0.150$ <sup>30</sup>). This correlation is similar to that found in the PR experimental study<sup>15a</sup> with 9  $\Delta\text{BDE}$ s and in a recent DFT B3LYP study<sup>11</sup> with 14  $\Delta\text{BDE}$ s. Our slightly smaller slope (4.3 versus 4.6) compared with Pratt's mainly arises from the use of two different  $\sigma_p^+$  values, −0.92 and 0.73<sup>29</sup> for OH and CHO in this work, respectively, rather than −0.78 and 0.47 by Pratt.<sup>11</sup> If the latter values are used, the slope would be 4.5, but the correlation would be slightly worse ( $R^2 = 0.976$ ). In addition, the use of B3LYP-optimized geometries<sup>11</sup> instead of Pratt's AM1 geometries<sup>11</sup> also contributes to the difference because for halogens, the latter<sup>11</sup> led to N–H bond strengthening whereas both the former and Song's B3LYP/6-31+G\* geometries<sup>12</sup> predicted similar bond weakening. Figure 1a also indicates that larger deviations occur at the EWGs end of the line, implying that the simple correlation is not sufficient to account for the  $\Delta\text{BDE}$ s. The dual parametric LD equa-

(27) The deviations of series **1** and **4** from experiment were considerably larger. For series **1**, this may stem partly from the shifts of the radical and molecule centers, and partly from the possible larger uncertainties of the experimental data collected from different sources (see the Supporting Information). Nevertheless, the percentage deviations are quite comparable to those for *p*- $\Delta\text{BDE}$ s because the  $\alpha$ -Y effect is much greater than its *p*-G counterpart. For series **4**, main deviation arises from the two *p*-EWGs (−4.5 kcal/mol), CN, and CF<sub>3</sub>.

(28) Charton, M. *Prog. Phys. Org. Chem.* **1987**, *16*, 287. In the Charton equation,  $\Delta\text{BDE} = L\sigma_l + D\sigma_d + R\sigma_r + h$ , *L*, *D*, and *R* denote the contribution from local effect ( $\sigma_l$ ), the intrinsic resonance effect ( $\sigma_d$ ), and the sensitivity ( $\sigma_r$ ) of the substituent to the electron demand of the active center, respectively.

(29) Hansch, C.; Taft, A. L.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165 and references therein.

(30) Exner. *Collect. Czech. Chem. Commun.* **1966**, *31*, 3222.

tion<sup>31</sup> did not result in a better correlation but revealed that the resonance contribution ( $R^+$  weighted 77.7%) dominates the  $\Delta$ BDEs as expected.

Better correlation was indeed obtained when the spin delocalization was included in the dual-parameter Hammett analysis using  $\sigma_p^{+29}$  and Creary's spin parameter  $\sigma_c^{31}$  ( $R^2 = 0.988$ ,  $\psi = 0.132$ ). Even better correlation was obtained using Charton's LDR equation<sup>28</sup> (see Table 3), which may stem mainly from its indirect inclusion of the spin contributions in the  $\sigma_e$  term. In summary, the contribution from spin delocalization plays a definite role in N–H  $\Delta$ BDEs of series **2**.

As shown in Table 2, the  $p$ -G effect on BDEs in series **3** follows the trend in series **2** (Figure 1b). As expected, due to the EW  $\alpha$ -Ac, the electronic demand of the donor N atoms in series **3** is greater than that in series **2** ( $\eta$ , 1.92 viz. 1.08, Table 3), which explains the slightly larger EDG effects and smaller EWG effects than those in series **2**. However, the LD correlation ( $R^2 = 0.990$ ,  $\psi = 0.119$ ) was significantly improved compared with that in series **2** and indicated larger resonance contribution in this series (weighted 88.3 vs 77.7%). In addition, the LDR correlation was only slightly improved.

Although the direction of the substituent effect on BDEs for series **4** is the same as that in the other two para series (Table 2), the magnitude of the effect is much smaller. This is also shown by the smallest slope (1.57) of the correlation of B3LYP  $\Delta$ BDEs with  $\sigma_p^+$  (Figure 1c) among the three para series. Moreover, no improvement was found by using the LD equation or LDR equation (Table 3) with polar parameters. Interestingly, inclusion of spin delocalization in these correlations gave very good results, indicating its significance to  $\Delta$ BDEs in this series.

It is worth noting that, as indicated in Table 3, for para series the induction of  $p$ -G ( $L\sigma_i$ ) strengthens the N–H bond, and the response to the electron demand ( $R\sigma_e$ ) weakens the bond (except for F), whereas the intrinsic resonance ( $D\sigma_d$ ) either enhances (for EWGs) or weakens (for EDGs) the bond. Since the induction contribution is usually larger than that of the response, the  $p$ -EWGs strengthen the N–H bonds.

#### Para Substituent Effect on N-Radical Stability.

The RE, ME, and RSE data for series **2–4** are presented in Table 4. The net (REs) and conventional radical stabilization enthalpies (RSEs) of series **2** in this Table 4 (columns 3 and 9) are very similar to Pratt's results<sup>11</sup> and indicate that these two scales for the radical stability are in general pointing to the same direction, i.e.,  $p$ -EDGs and  $p$ -EWGs stabilize and destabilize the N-radical, respectively. Since the signs of the ME values are in general opposite to those of the REs and RSEs (Table 4), the RE scale appears to be weaker than the RSE scale, i.e.,  $|\text{RE}| \leq |\text{RSE}|$ , a phenomenon just opposite to that found in the  $\alpha$ -EWG ( $-\text{CN}$ )-substituted benzylic radicals studied previously where RE was larger than RSE (i.e.,  $|\text{RE}| \geq |\text{RSE}|$ ).<sup>5</sup> This is because the electrostatic interaction of  $p$ -Gs with electron-rich  $-\text{NH}_2$  ( $\sigma_p^- = -0.15$ ) in anilines is in the direction opposite to that with electron-deficient  $-\text{CH}_2\text{CN}$  ( $\sigma_p^- = +0.11$ ) in the  $\alpha$ -CN-substituted toluenes. This indicates that RSE can only be viewed as

an approximation rather than a generally suitable index for radical stability as previously believed.

The best single-parameter correlation of REs in series **2** with  $\sigma_p^+$  was poor as shown by an  $R^2$  of 0.900<sup>11</sup> ( $\psi = 0.34$ ), which is similar to Song's result,<sup>12</sup> but worse than Pratt's ( $R^2 = 0.952$ ),<sup>11</sup> probably due to their lack of the halogen substituents and use of different  $\sigma_p^+$  values mentioned above. In fact, the correlation using Pratt's  $\sigma_p^+$ s and non-halogen REs did give a better result ( $R^2 = 0.939$ ). The di-parametric LD correlation showed only marginal improvement ( $R^2 = 0.910$ ,  $\psi = 0.34$ ). These results indicate that polar effect alone cannot satisfactorily account for the stability of the N-radicals in this series.

Inclusion of spin delocalization improves the correlation of radical stabilization effect in this series substantially. For example, any di-parametric correlation using  $\sigma_p^+$  and a spin delocalization parameter ( $\sigma_{jj}^*$ ,<sup>32</sup> or  $\sigma_c^{31}$ ,<sup>31</sup> or  $\sigma_\alpha^{33}$ ) led to an excellent improvement ( $R^2 \geq 0.992$  and  $\psi \leq 0.13$ ), and the best was  $\text{RE} = (18.48 \pm 1.49)\sigma_c - (1.89 \pm 0.07)\sigma_p + 0.12 \pm 0.04$  ( $\psi = 0.097$ ). These results (see also Figure 2) indicate that inclusion of spin delocalization<sup>34</sup> is crucial to sufficient accounting for the N-radical stabilization (positive  $\rho$ ).

Admittedly, the REs LDR correlation also showed a good line (Table 3), but this again implies that this model indirectly incorporates certain spin delocalization effect. In addition, the positive  $\eta$  for REs (4.16, Table 3) indicates that the radical  $-\text{NH}$  center is electron deficient, and the negative  $\eta$  ( $-0.64$ ) for ME indicates the electron-rich molecular  $\text{NH}_2$  center as suggested by Pratt.<sup>11</sup> However, the ratio of  $|\Sigma|\text{RE}|/|\Sigma|\text{ME}|$  (0.74 for series **2**) cannot be used as the measure for magnitude of EW power of the two centers<sup>11</sup> because the spin delocalization contributes to RE but not to ME.

Compared with series **2**, the much better correlation of REs for series **3** with polar parameter  $\sigma_p^+$  indicates an enhanced significance of polar effect on radical stability due to an increase of electronic demand at the N-radical center by  $\alpha$ -Ac substitution. Spin delocalization in the series **3** radicals is also important to their stability, as indicated by the improvement of the RE correlation when this effect was included. The best correlations were obtained using  $\sigma_p^+$  with  $\sigma_c$  ( $R^2 = 0.996$ ,  $\psi = 0.078$ , Figure 2) or  $\sigma_{jj}^*$  ( $R^2 = 0.996$ ,  $\psi = 0.065$ ).

The LDR correlation of REs was also improved ( $\psi = 0.086$ , Table 3). The greater absolute  $R$  value ( $-16.97$ , item 4 in Table 3) compared with that of series **2** ( $-12.43$ , item 3) indicates stronger substituent response of the  $N$ -acetyl radical stability to the electron demand of the radical center due to an increase of the electron deficiency at the radical center by the  $\alpha$ -Ac group ( $\eta = 3.14$ , Table 3).

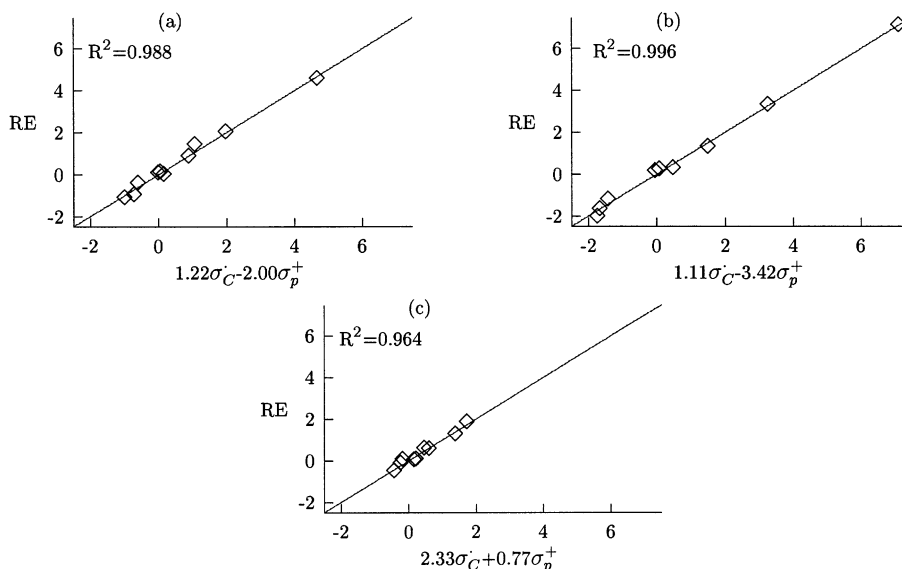
In contrast to series **2** and **3**, the  $p$ -G substituent effect on phenylhydrazino radicals in series **4** showed quite different behavior. First, the direction of the substituent effect on RE is opposite to that of series **2** and **3**; i.e., EDGs (except for  $\text{NMe}_2$ ) and EWGs tend to **destabilize**

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(33) Dust, J. M.; Arnold, D. R. *J. Am. Chem. Soc.* **1983**, *105*, 1221. Dust, J. M.; Arnold, D. R. *J. Am. Chem. Soc.* **1983**, *105*, 6531.

(34) Viehe, H. G.; Janousek, Z.; Merényi, R.; Stella, L. *Acc. Chem. Res.* **1985**, *18*, 148.

(31) Creary, X.; Mehrsheikh-Mohammadi, M. E.; McDonald, S. *J. Org. Chem.* **1987**, *52*, 3254.



**FIGURE 2.** Correlation plots of N-radical stability with  $\sigma_p^+$  and  $\sigma_C^-$  for series (a) **2**, (b) **3**, and (c) **4**.

and **stabilize** the ArNNH<sub>2</sub> radical, respectively. This is perhaps the first theoretically known aromatic N-radical that belongs to the Class Counter- $\bar{O}^{\bar{p}}$  (i.e., Class  $\bar{O}$ ). Up to now, this type of radical substituent effect has been overlooked as it has only been observed in very limited cases experimentally, as mentioned above.<sup>10,24,34</sup> Second, the direction of RSE variations differs from that of RE, indicating that the RSEs should not be taken as a direct measure of radical stabilization for radicals in this series either.

To examine the Class  $\bar{O}$  behavior further, various linear correlations were performed for REs in series **4**. First, no acceptable correlation was found using  $\sigma_p^+$  alone ( $R^2 = 0.23$ ,  $\psi = 0.98$ ). Though not satisfactory, the  $\sigma_p^-$  correlation of REs was nevertheless considerably improved ( $R^2 = 0.77$ ,  $\psi = 0.53$ ), indicating that the radical center ( $-\text{NNH}_2$ ) is not as electron deficient as those in series **2** and **3**. Next, the di-parametric correlation using both polar ( $\sigma_p^-$ ) and spin parameters,  $\sigma_C^-$ ,  $\sigma_{\alpha^*}$ , or  $\sigma_{\text{H}}$ ,<sup>32</sup> gave significantly better results (same  $R^2 = 0.956$ ,  $\psi = 0.254$  for  $\sigma_C^-$ ). As shown in Figure 2c, the spin delocalization effect on RE in this series is the largest among the three para series (weighted 54.3 vs 19.0 for **2** and 11.2% for **3**). Moreover, the coefficients of the polar effect (+0.77 for  $\sigma_p^+$  or +1.01 for  $\sigma_p^-$ ) were positive, and the  $\eta$  from the LDR correlation is negative ( $-3.8$ , Table 3), indicating that the  $-\text{NNH}_2$  radical center is electron-rich in nature. In conclusion, the Class  $\bar{O}$  behavior can be viewed as a result of two related factors—the polar effect on the phenylhydrazino radicals that reverses the direction of Class  $\bar{O}$  radical stabilization<sup>5</sup> due to its electron-rich nature at the N-radical center and the spin delocalization that plays a relatively larger role than that it does in Class  $\bar{O}$  radicals.

**Correlation of RE with  $\Delta C$  and  $\Delta S$ .** Though correlations of radical stability with experimentally derived polar and spin parameters are often used to look into the nature of substituent effects, the lack of the important spin parameters for certain substituents such as NMe<sub>2</sub> and CHO limits their application. Here, we examined an alternative model, using the conceptually simple and readily available theoretical atomic charge ( $\Delta C$ ) and spin

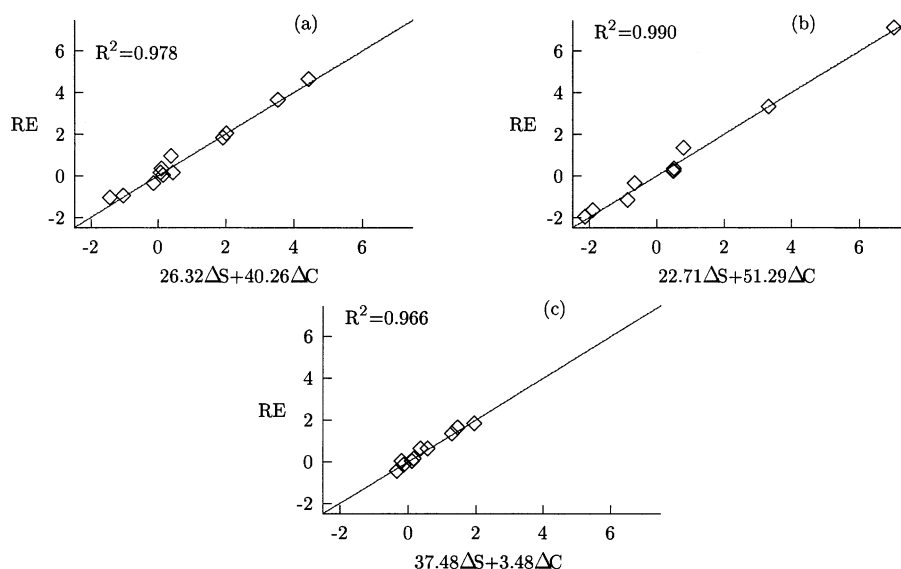
variations ( $\Delta S$ ) at the radical center as substituent constants for polar effect and spin delocalization. A previous study on phenoxy radicals found that such correlation of O-radical stability is reasonable.<sup>5b</sup> As shown in Figure 3, the correlations of REs for all three para series are almost equally good as those using experimental parameters (Figure 2). This shows that this model also works for the aromatic N-radicals.

As expected, the correlation for series **2** (Figure 3a) indicates the dominance of  $\Delta C$  (67.6%) over REs. In analogy, REs of the N-radicals in series **3** also correlated well ( $\psi = 0.124$ ) with  $\Delta C$  and  $\Delta S$  (Figure 3b) with similar weight of  $\Delta C$  (64.9%). On the contrary, the correlation for series **4** shows that the spin contribution dominates (95.4%) REs. This suggests that the polar contribution of  $p$ -G to the radical stabilization of this Class  $\bar{O}$  radical series may be less important than that of the Class  $\bar{O}$  radicals.

**Interplay between Para- and  $\alpha$ -Substituent Effects.** Because the isomerization process involves two isomers with the same number of nuclei, electrons, and spins, the isomerization enthalpy ( $\text{ER}_{\alpha\text{-Y}\rightarrow\text{p-Y}}$  or  $\text{EM}_{\alpha\text{-Y}\rightarrow\text{p-Y}}$ ) can thus stand for the difference of absolute thermodynamic stability<sup>35</sup> between the two isomers. On this basis, an absolute stability scale was established for the  $\alpha$  and para isomeric N-radicals, and the results for series **1** are presented in Table 5. Inspection of the data in Table 5 indicates that the  $p$ -EDG-substituted anilino radicals (and molecules) are always much more stable than corresponding  $\alpha$ -EDG substituted isomers, whereas the  $p$ -EWG radicals (and molecules) are less stable than their  $\alpha$ -EWG counterparts.

Table 5 also shows the interesting feature of the  $p$ -series **4** that the directions of RE variations in this  $\alpha$ -series (**1**) are opposite to those of their N–H bond strength variations ( $-\Delta\text{BDEs}$ , see eq 1). This is because the molecule effect dominates ( $|\text{ME}| > |\text{RE}|$ ) the RSEs, and the NNH<sub>2</sub> center becomes electron-rich ( $\eta = -4.49$ , Table 3). The latter may be the main reason  $\alpha$ -EDGs

(35) (a) Leroy, G. *Int. J. Quantum Chem.* **1983**, *23*, 271. (b) Pasto, D. J.; Krasnansky, R.; Zercher, C. *J. Org. Chem.* **1987**, *52*, 3062.



**FIGURE 3.** Correlation plots of N-radical stability with relative atomic charge ( $\Delta C$ ) and spin ( $\Delta S$ ) at radical centers for series (a) **2**, (b) **3**, and (c) **4**.

**TABLE 6.**  $\alpha$  Substituent Effects on Radical Stability for Series **3** and **4**<sup>a</sup>

G	RE $_{\alpha-Y}(G)$		GE $_{\alpha-Y}(G)$	
	$\alpha-Y = \text{Ac}$	$\alpha-Y = \text{NH}_2$	$\alpha-Y = \text{Ac}$	$\alpha-Y = \text{NH}_2$
NMe <sub>2</sub>	6.0	-15.2	9.2	-27.7
OMe	4.7	-13.4	8.6	-27.8
Me	3.9	-12.0	8.0	-27.8
F	3.7	-11.7	7.9	-27.9
Cl	3.6	-11.3	7.5	-27.9
Br	3.5	-11.2	7.4	-28.0
H	3.4	-11.2	7.5	-27.9
Ac	2.7	-9.9	6.5	-28.0
CN	2.7	-9.5	6.0	-28.1
CF <sub>3</sub>	2.9	-9.5	6.5	-28.0
NO <sub>2</sub>	2.4	-8.4	5.4	-28.1
$\rho^+$	-1.4	-2.6	-1.5	-0.2
R <sup>2</sup>	0.984	0.968	0.873	0.872

<sup>a</sup> RE $_{\alpha-Y}(G)$  and GE $_{\alpha-Y}(G)$  are defined in eqs 5 and 6, respectively, calculated using B3LYP/6-311+G(2d,2p) (given in kcal/mol).

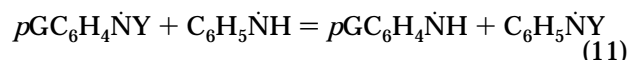
destabilize ( $RE < 0$ ), whereas the  $\alpha$ -EWGs stabilize ( $RE > 0$ ) the N-radical center. This is similar to REs in series **4** and can also be assigned to Class  $\bar{O}$ . Here again,  $\alpha$  RSE cannot serve as a guide for radical stability.

The Class  $\bar{O}$   $\alpha$  substituent effect observed here can also be understood by analyzing the charge and spin densities around the N-radical center. The calculated  $\Delta C$  and  $\Delta S$  on the N radical center are also presented in Table 5. The negative  $\Delta C$  and  $\Delta S$  values of strong EDGs indicate a depletion of electron density and an increase of spin density on the N radical center, respectively. Both factors result in radical destabilization. On the other hand, the positive  $\Delta S$  value of the strong EW  $\alpha$ -Ac substituted radical showed certain stabilization. These results clearly support the electron repulsion and depletion argument on N–H bond strength stated above.

The results for the  $\alpha$ -Y effect on radicals (RE $_{\alpha-Y}(G)$ ) for series **3** and **4** are given in Table 6. As shown in this table, the  $\alpha$  substituent effect on radical stability is similar to the case without a  $p$ -G (Table 5); that is, an  $\alpha$  EDG ( $-\text{NH}_2$ ) makes the radical less stable (RE $_{\alpha-Y} < 0$ ) for every  $p$ -G, whereas an  $\alpha$  EWG ( $-\text{Ac}$ ) does just the

opposite. This, again, is Class  $\bar{O}$  behavior. The larger  $\alpha$ -EDG effect as compared to the  $\alpha$ -EWG effect can also be attributed to the stronger electrostatic repulsion between the EDGs and the radical center. Similarly, inspection of the  $\alpha$  ME $_{\alpha-Y}(G)$  shows that it also belongs to Class  $\bar{O}$ . The molecule effect is even larger than that of the corresponding radicals. This implies that most previous conclusions on radical stability derived from BDE experiment may need to be reexamined as they have been based mainly on RSE without explicitly considering the ME $_{\alpha-Y}$ .

Subtracting the  $\alpha$  effect of  $p$ -H from that of any other  $p$ -G,  $\Delta\text{RE}_{\alpha-Y}(G) = \text{RE}_{\alpha-Y}(G) - \text{RE}_{\alpha-Y}(\text{H})$ , we obtain the influence of the  $p$ -G on  $\alpha$  radical effect, that is, the interaction between  $\alpha$ -Y and  $p$ -G effects on the N-radical stabilization. The corresponding isodesmic reaction is shown in eq 11.

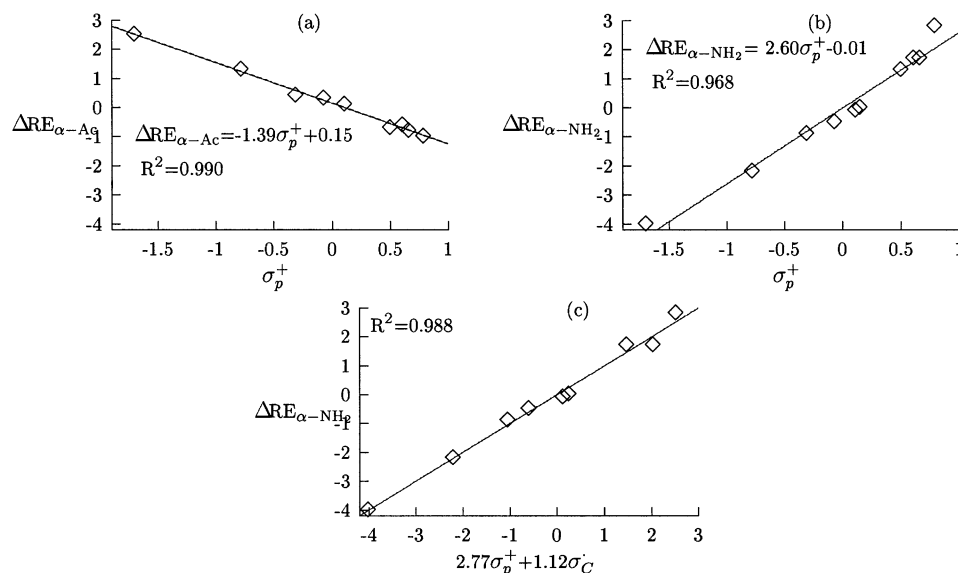


Since no undissociated molecules are involved in this reaction (eq 11), the influence can be unambiguously determined. As shown in Table 6, the radical-stabilizing effect of  $\alpha$  EWGs (acetyl, column 2) is reinforced by  $p$ -EDGs but depressed by  $p$ -EWGs. This trend is similar to that of the  $p$ -G effect in series **2**, so the overall radical effect of remote substitution in series **3** is larger than that in series **2**. Also worthy of mentioning is that the correlation of  $\Delta\text{RE}_{\alpha-\text{Ac}}(G)$  with  $\sigma_p^+$  was excellent (Figure 4,  $\psi = 0.119$ ), indicating that the polar effect of  $\alpha$ -Ac dominates the influence of the  $p$ -G group.

The influence of  $p$ -Gs on the  $\alpha$ -NH<sub>2</sub> effect on radical stability is opposite to the situation for  $\alpha$ -Ac effect (Table 6 and Figure 4). It shows the Class  $\bar{O}$  behavior for series **4**. In addition, the correlation of  $\Delta\text{RE}_{\alpha-\text{NH}_2}(G)$ 's with  $\sigma_p^+$  and  $\sigma_C$  is excellent (Figure 4c,  $\psi = 0.129$ ), indicating the importance of spin contribution to  $\Delta\text{RE}_{\alpha-\text{NH}_2}(G)$  than to  $\Delta\text{RE}_{\alpha-\text{Ac}}(G)$ , which is not so obvious in series **3**.

The substituent effects on radical stability may also be understood qualitatively on the basis of the Capto-

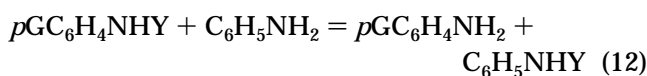




**FIGURE 4.** Correlation plot of para influence of  $\alpha$  effect on stability for (a) *N*-acetyl radicals, (b) *N*-amino radicals with  $\sigma_p^+$ , and (c) *N*-amino radicals with  $\sigma_p^+$  and  $\sigma_c$ .

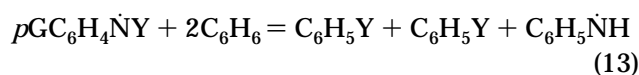
dative Principle.<sup>34</sup> For the *N*-radicals in series **3**, the principle predicts that with an  $\alpha$ -Ac electron captor, *p*EDGs as electron donors should stabilize, whereas *p*EWGs as electron captors destabilize the *N*-radical center, as the results in Tables 4–6 show. Similarly, for the series **4** *N*-radicals, this principle predicts that with an  $\alpha$ -NH<sub>2</sub> electron donor, *p*EWGs and *p*EDGs will stabilize and destabilize the *N*-radical center, respectively. As shown in these tables, this is the Class  $\bar{O}$  behavior. Therefore, this principle can also be used to account for the stability of nitrogen-centered radicals as it does for carbon radicals reported in the literature,<sup>34</sup> and it may also be used to predict the directions of substituent effect on the stability of other heteroatom-centered radicals.

Similar to eq 11, the  $\alpha$ -Y effect on the stability of anilines bearing a *p*-G can be defined by eq 12. The reaction enthalpies,  $\Delta ME_{\alpha-Y}(G) = ME_{\alpha-Y}(G) - ME_{\alpha-H}(G)$ , for  $\alpha$ -Ac and -NH<sub>2</sub>, are also presented in Table 6.



As shown in Table 6, though the  $\Delta ME_{\alpha-NH_2}(G)$  values are small, the  $\alpha$ -acetyl has, nevertheless, a greater effect on molecule stability than has the  $\alpha$ -NH<sub>2</sub>, and this effect is also in accordance with the Capto-dative Principle.

**Overall Substituent Effects on *N*-Radical Stability.** Combining  $\alpha$  and para substituent effects, we can define the overall substituent effects of  $pGC_6H_4\dot{N}Y$ ,  $RE_{Y,G}$ , referred to the reference  $C_6H_5\dot{N}H$  radical, using reaction eq 13.



$RE_{Y,G}$  can then be calculated as in eq 14

$$RE_{Y,G} \equiv RE_{\alpha,Y} + RE_{para,GY} \quad (14)$$

where  $RE_{\alpha,Y}$  and  $RE_{para,GY}$  denote the  $\alpha$ -Y effect of

**TABLE 7.** Overall Substituent Effects on Radical ( $RE_{Y,G}$ ) and Molecular ( $ME_{Y,G}$ ) Stability<sup>a</sup>

G	$RE_{Y,G}^b$			$ME_{Y,G}^b$		
	<b>3</b> Y = Ac	<b>2</b> Y = H	<b>4</b> Y = NH <sub>2</sub>	<b>3</b> Y = Ac	<b>2</b> Y = H	<b>4</b> Y = NH <sub>2</sub>
NMe <sub>2</sub>	10.5	4.6	-10.6	6.7	-2.5	-30.1
OMe	6.7	2.0	-11.4	6.5	-2.1	-29.9
Me	4.7	0.9	-11.2	7.8	-0.7	-28.4
F	3.7	0.0	-11.7	6.6	-1.3	-28.6
Cl	3.6	0.1	-11.2	7.1	-0.3	-28.2
Br	3.6	0.1	-11.1	7.2	-0.1	-28.1
H	3.4	0.0	-11.2	7.5	0.0	-27.9
Ac	3.0	0.3	-9.6	8.2	2.2	-25.8
CN	2.2	-0.4	-9.9	8.2	2.2	-25.9
CF <sub>3</sub>	1.7	-1.1	-10.6	8.5	1.5	-26.5
NO <sub>2</sub>	1.4	-1.0	-9.4	8.5	3.1	-25.0

<sup>a</sup> The data were calculated using B3LYP/6-311+G(2d,2p) (given in kcal). <sup>b</sup>  $RE_{Y,G}$  and  $ME_{Y,G}$  were defined as the enthalpies of reactions,  $pGC_6H_4\dot{N}Y + 2C_6H_6 = GC_6H_5 + C_6H_5Y + C_6H_5\dot{N}H$  and  $pGC_6H_4NHY + 2C_6H_6 = C_6H_5G + C_6H_5Y + C_6H_5NH_2$ , respectively.

$C_6H_5\dot{N}Y$  and the *p*-G effect of  $pGC_6H_4\dot{N}Y$ , respectively.  $RE_{Y,G}$  can also be obtained by  $RE_{Y,G} \equiv RE_{\alpha,YG} + RE_{para,G}$ , where  $RE_{\alpha,YG}$  and  $RE_{para,G}$  denote the  $\alpha$ -Y effect of  $pGC_6H_4\dot{N}Y$  and the *p*-G effect of  $pGC_6H_4\dot{N}H$ , respectively. From the above two relationships, we obtained eq 15 to calculate  $RE_{Y,G}$

$$RE_{Y,G} = RE_{\alpha,Y} + RE_{para,G} + \Delta RE_{para-G}(Y) \quad (15)$$

where  $\Delta RE_{para-G}(Y) = RE_{para,GY} - RE_{para,G} = RE_{\alpha,GY} - RE_{\alpha,G}$  is defined by eq 11 and shown in Figure 4.

The results for the overall substituent effects on radical stability are present in Table 7. Inspection of the data in this table indicates that the anilino radical (PhNH) can be most effectively stabilized by a strong EW  $\alpha$ -Y and a strong ED *p*-G such as in *p*NMe<sub>2</sub>C<sub>6</sub>H<sub>4</sub>NCOME.

Similarly, the overall substituent effects on molecular stability can be defined (eq 16)

$$ME_{Y,G} \equiv ME_{\alpha,Y} + ME_{para,GY} \quad (16)$$

where  $ME_{\alpha,Y}$  and  $ME_{para,GY}$  denote the  $\alpha$ -Y effect of  $C_6H_5-NHY$  and the  $p$ -G effect of  $pGC_6H_4NHY$ , respectively. The results are also given in Table 7 and can be rationalized on the Capto-dative Principle shown above.

## Conclusion

The stability of four series (1–4) of anilino radicals ( $pGC_6H_4NY$ ) and the related N–H BDEs have been studied using both ab initio MP2<sup>36</sup> and density functional B3LYP methods. The following conclusions have been obtained.

1. The experimental N–H BDEs can be reproduced within the experimental uncertainties by both methods with large basis set 6-311+G(2d,2p), but the substituent effects on the bond strength,  $\Delta$ BDEs, and on radical stability RE can be reproduced and predicted much more satisfactorily by both methods.

2. The effects of  $\alpha$  substituents were demonstrated to be significantly larger than those of para substituents.

3. Unlike the findings in the simple C–H BDE studies, electron-withdrawing and electron-donating substituents were confirmed to influence the N–H bond strength in opposite directions (strengthening and weakening the bond, respectively).

4. The corresponding N-radicals in para series 2 and 3 were also shown to be stabilized by EDGs and destabilized by EWGs (i.e., Class O).

5. Radicals in series 1 and 4 were found to belong to a new radical class, Class  $\bar{O}$ , as characterized by radical stabilization of EWGs and radical destabilization of EDGs, respectively.

6. In series 1 and 4, the conventional radical stabilization index (RSE =  $-\Delta$ BDEs) was found to be unsuitable for describing the true substituent effect on radical stabilization.

7. The atomic spin ( $\Delta$ Ss) and charge density changes ( $\Delta$ Cs) at the N-atom spin center due to  $p$ -Gs were found to correlate excellently with  $p$ -G's effect on the radical stability.

8. The N-radical stability can sufficiently be accounted for only by dual parametric Hammett-type correlations using both polar and spin delocalization parameters, rather than by simple Hammett correlations. This means that spin delocalization has to be quantitatively included in the study of the radical stabilization.

9. Overall substituent effects on N-radical stability can be qualitatively accounted for using the Capto-dative Principle.

## Theoretical Methods

Previous studies showed that the restricted open-shell (RO) Møller–Plesset perturbation (MP2) and B3LYP methods give quite realistic radical stabilization and bond dissociation

enthalpies (BDEs).<sup>22,26,37</sup> In this work, these methods (abbreviated as MP2 and B3LYP, respectively<sup>38,39</sup>) along with 6-311+G(2d,2p)<sup>18</sup> were thus used in the computation of the single-point total energies based on optimized geometries. For species in series 1 and 2, both methods were used, whereas for those in other series, only ROB3LYP was used. The fully optimized geometries of molecules and radicals involved were determined using restricted and unrestricted B3LYP/6-31G(d), respectively. The vibrational analyses were performed on the optimized geometries to verify the nature of their energy minima and to provide zero-point vibrational energies (ZPVEs) and thermal corrections. No imaginary vibrational frequencies were found in these analyses, indicating that the related molecules and radicals correspond to their lowest potential energy minima. The calculated BDEs were corrected with the scaled ZPVEs (by 0.9806<sup>40</sup>),  $PV$  term ( $RT$ ), and the thermal effect including the transitional ( $3RT/2$ ), rotational ( $3RT/2$ ), and vibrational motion. All these calculations in this paper were done using Gaussian package.<sup>41</sup>

The calculated substituent effects on N–H BDEs and on radical stability were further examined using Hammett-type analysis<sup>4,29,32</sup> including Charton's tri-parametric equation.<sup>28</sup> The fitting coefficients, their standard deviations, and other statistical quantities were calculated by the locally written programs which were based on standard statistical analysis.<sup>42</sup> The advantage of using the diparametric or LDR equation over the generally used simple Hammett equation is that the former enables us to understand much clearer the electronic nature of the concerned bonds and the radical centers. The relative importance of the contributing factors to the total effects of a substituent was examined by both stepwise regression and weighting scheme advocated by Shorter.<sup>43,44</sup> The quality of a correlation was assessed using not only correlation coefficient ( $r$ ) and standard deviations,<sup>43</sup> but also Exner's  $\psi$ <sup>30,43</sup> that enables the qualities of correlations with different degrees of freedom to be compared.

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**Supporting Information Available:** Theoretical and experimental bond dissociation enthalpies for anilines in series

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(44) The weight for  $L$  in the Charton's LDR equation, for example, can be evaluated using<sup>45</sup>  $w_L = [\sum(\sigma_i - \bar{\sigma})^2/(n - 1)]^{1/2}$ , where  $\bar{\sigma}$  is the arithmetic average of the  $n$  data points. The weighted contribution of the local effect is then given by  $L(\%) = 100Lw_L/(Lw_L + Dw_D + Rw_R)$ . The weights for other terms are defined in the same fashion. This scheme can estimate the factors that control the substituent effects more accurately than the commonly one because it puts all the substituent parameters derived from different experimental approaches on the same numerical scale.

(36) Fu, Y.; Liu, L.; Lin, B.-L.; Mou, Y.; Cheng, Y.-H.; Quo, Q.-X. *J. Org. Chem.* **2003**, 68, 4657. The N–H  $\Delta$ BDE results of this recent paper obtained using RMP2 are similar to our B3LYP results for the six common anilines 4-GPhNH-H, where G = Me, NH<sub>2</sub>, OH, F, CN, and NO<sub>2</sub>, but there are certain differences, in particular, for strong EDGs (NH<sub>2</sub>, OH) and EWGs (NO<sub>2</sub>), perhaps due to RMP2's insufficient accounting for the electron correlation. In addition, the  $\rho^+$  values of the Hammett regression between N–H  $\Delta$ BDEs for anilines 4-GPhNH-H and 4-GPhNNH<sub>2</sub>-H from this reference are smaller than those of the present paper perhaps due to the lack of strong ED and EW substituents such as NMe<sub>2</sub>, OMe, Ac, and CF<sub>3</sub> in the former data sets as well as the correlation correction.

**1–4**, para substituent effect on spin and charge populations at the N-radical centers for series **2–4**, a brief discussion on the geometries of anilines and related radicals, and optimized Cartesian coordinates and total energies for all related mol-

ecules and radicals. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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