

ARTICLE

Substituent Effects on Reduction Potentials of Meta-substituted and Para-substituted Benzylideneanilines

Lin-yan Wang^{a,b,c}, Chao-tun Cao^{b,c}, Chen-zhong Cao^{*a,b,c}

a. School of Chemistry and Chemical Engineering, Central South University, Changsha 410083, China

b. School of Chemistry and Chemical Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

c. Key Laboratory of Theoretical Organic Chemistry and Function Molecule, Ministry of Education, Hunan Provincial University Key Laboratory of QSAR/QSPR, Hunan University of Science and Technology, Xiangtan 411201, China

(Dated: Received August 13, 2015; Accepted on October 30, 2015)

Effects of meta-substituent of 3,4'/4,3'/3,3'-substituted benzylideneanilines (XBAYs) on the electrochemical reduction potentials ($E_{(\text{Red})}$) were investigated, in which 49 samples of target compounds were synthesized, and their reduction potentials were measured by cyclic voltammetry. The substituent effects on the $E_{(\text{Red})}$ of target compounds were analyzed and an optimality equation with four parameters (Hammett constant σ of X, Hammett constant σ of Y, excited-state substituent constant $\sigma_{\text{CC}}^{\text{ex}}$ of X, and the substituent specific cross-interaction effect $\Delta\sigma_{\text{CC}}^{\text{ex}2}$ between X and Y) was obtained. The results show that the factors affecting the $E_{(\text{Red})}$ of 3,4'/4,3'/3,3'-substituted XBAYs are different from those of 4,4'-substituted XBAYs. For 3,4'/4,3'/3,3'-substituted XBAYs, $\sigma(\text{X})$ and $\sigma(\text{Y})$ must be employed, and the contribution of $\Delta\sigma_{\text{CC}}^{\text{ex}2}$ is important and not negligible. Compared with 4,4'-substituted XBAYs, X group contributes less to 3,4'/4,3'/3,3'-substituted XBAYs, while Y group contributes more to them. Additionally, it was observed that either para-substituted XBAYs or meta-substituted XBAYs, the substituent effects of X are larger than those of Y on the $E_{(\text{Red})}$ of substituted XBAYs.

Key words: 3,4'/4,3'/3,3'-substituted benzylideneanilines, Substituent effects, Electrochemical reduction potentials, Cyclic voltammetry, Excited-state substituent constant

I. INTRODUCTION

In the molecule of benzylideneanilines (abbreviated as XBAYs, XPhCH=NPhYs), CH=N is a bridge linking two aromatic rings, in which one ring carries substituent X and another ring carries substituent Y. Changes of X and Y in XBAY can affect its molecular overall electron distribution and its properties. Therefore, the substituent effects play an important role in the studies of this kind of compounds, and attain great interest in recent years [1–3]. In addition, substituent effects are also the focus of quantitative structure property/activity relationship (QSPR/QSAR) [4–6].

Based on the mechanism of electrochemical reduction, the reduction progress of title compounds and their derivatives firstly carried out on the carbon atom of CH=N , and the more positive charge the carbon atom has, the easier the XBAY is to be reduced and the more positive its potential value is [7–10]. So,

the electrochemical reduction potentials $E_{(\text{Red})}$ values of XBAYs can be determined by the charge of the carbon atoms which is affected by the substituents of X and Y. In previous reports, the substituent effects on the reduction potentials of XBAYs or the analogous compounds were studied [11–13]. For example, Celik *et al.* ever analyzed the effects of para-substituents on the half-wave potentials of several substituted benzaldehyde oximes and acetophenone oximes, and pointed out that their half-wave potentials could be correlated well with Hammett substituent constant σ [12]. Their work promotes the studies of the substituent effects on the analogous compounds in the field of electrochemistry [12]. The previous studies mostly placed emphasis on the substituent effects by changing the kind of substituents. However, there are few quantitative structure property/activity relationship studies about the substituent effects by changing the position of the substituents.

Recently, Cao *et al.* analyzed the substituent effects on the $E_{(\text{Red})}$ for 52 samples of 4,4'-disubstituted XBAYs, and obtained a four-parameter equation [14], as shown in Eq.(1), in which $\sigma_{\text{F}}(\text{X})$ is the inductive ef-

* Author to whom correspondence should be addressed. E-mail: czcao@hnust.edu.cn

fect of X, $\sigma_R(X)$ and $\sigma_R(Y)$ are the conjugative effect of X and Y respectively, $\sigma_{CC}^{ex}(X)$ is the excited-state substituent constant of X.

$$E_{(Red)} = -2.23 + 0.35\sigma_F(X) + 0.52\sigma_R(X) + 0.11\sigma_R(Y) - 0.15\sigma_{CC}^{ex}(X) \quad (1)$$

$$R = 0.9756, R^2 = 0.9518,$$

$$S = 0.052, n = 52, F = 232.07$$

In Ref.[14], the $E_{(Red)}$ values of the 52 samples of 4,4'-disubstituted XBAYs were not corrected by ferrocene. In this work, their $E_{(Red)}$ values were corrected by ferrocene [15], and a modified regression equation was obtained (shown as Eq.(2)).

$$E_{(Red)} = -1.96 + 0.35\sigma_F(X) + 0.52\sigma_R(X) + 0.11\sigma_R(Y) - 0.15\sigma_{CC}^{ex}(X) \quad (2)$$

$$R = 0.9756, R^2 = 0.9518,$$

$$S = 0.052, n = 52, F = 232.20$$

Then we want to know if Eq.(2) will still be applicable in the case of X and/or Y changed from para-position to meta-position. If not, what are the difference and the reasons? To answer above questions, 49 samples of 3,4'/4,3'/3,3'-substituted benzylideneanilines (as shown in Fig.1) were synthesized and the substituent effects on their $E_{(Red)}$ values were analyzed, and meaningful results were obtained.

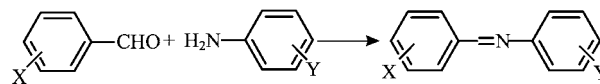
II. EXPERIMENTS

A. Preparation of XBAYs

The substituted benzylideneanilines were all synthesized with the solvent-free method according to Fig.1 [24, 25]. They were purified with anhydrous alcohol, and were confirmed with 1H NMR and ^{13}C NMR. The NMR spectra were recorded with Bruker AV 500 MHz in $CDCl_3$ at room temperature at an approximate concentration. The detailed data of the synthesized compounds are available in the supplementary materials.

B. Measurement of redox potentials

The electrochemical experiments were carried out by cyclic voltammetry (CV) and using a CS300 electrochemical apparatus in deaerated acetonitrile under nitrogen atmosphere at 298 K. $n-Bu_4NPF_6$ (0.1 mol/L) in acetonitrile was employed as the supporting electrolyte. A standard three-electrode cell consists of a glassy carbon disk as work electrode, a platinum wire as a counter electrode, and 0.01 mol/L $AgNO_3/Ag$ (in 0.1 mol/L $n-Bu_4NPF_6$ /acetonitrile) as reference electrode. The scanning speed was 50 mV/s. Ferrocene was taken as an external reference. For example, Fig.2 is the cyclic voltammetric curve of m -FBANMe₂- p .



X (p or m) = NMe₂, OMe, Me, H, F, Cl, CF₃, CN, NO₂ or Br
Y (p or m) = NMe₂, OMe, Me, H, F, Cl, CN, or Br

FIG. 1 Target compounds used in this work.

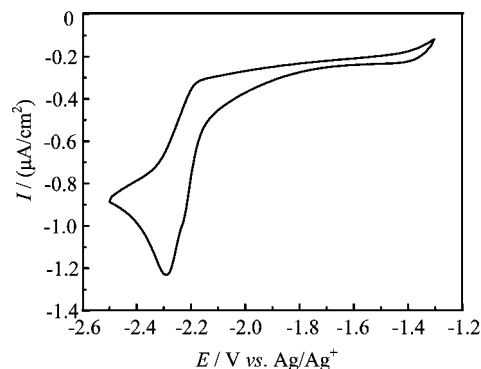


FIG. 2 Cyclic voltammetric curve of m -FBANMe₂- p .

III. RESULTS AND DISCUSSION

Forty-nine samples of 3,4'/4,3'/3,3'-substituted benzylideneanilines were synthesized and their $E_{(Red)}$ were measured by CV method. Their $E_{(Red)}$ values corrected by ferrocene were summarized in Table I.

Firstly, the parameters in Eq.(2) were assumed to be applicable with the $E_{(Red)}$ of the 3,4'/4,3'/3,3'-substituted XBAYs. So the correlation between the experimental $E_{(Red)}$ values of Table I with the parameters $\sigma_F(X)$, $\sigma_R(X)$, $\sigma_R(Y)$ and $\sigma_{CC}^{ex}(X)$ was carried out, and Eq.(3) was obtained.

$$E_{(Red)} = -1.89 + 0.47\sigma_F(X) + 0.39\sigma_R(X) + 0.24\sigma_R(Y) - 0.05\sigma_{CC}^{ex}(X) \quad (3)$$

$$R = 0.8869, R^2 = 0.7866,$$

$$S = 0.091, F = 40.54, n = 49$$

As seen from Eq.(3), its correlation result is not good enough and worse than that of Eq.(2). The coefficients of the parameters in Eq.(2) were different from those of corresponding parameters in Eq.(3), as well as their intercepts. It implies that the factors affecting the $E_{(Red)}$ of 3,4'/4,3'/3,3'-substituted XBAYs may be different from those of para-substituted XBAYs. Therefore, we used the parameters listed in Table I to make regression analysis against the $E_{(Red)}$ values of the 49 samples once again, and obtained the optimality equation (Eq.(4)).

$$E_{(Red)} = -1.96 + 0.46\sigma(X) + 0.29\sigma(Y) - 0.05\sigma_{CC}^{ex}(X) + 0.03\Delta\sigma_{CC}^{ex,2} \quad (4)$$

$$R = 0.9461, R^2 = 0.8951, S = 0.064, F = 93.83, n = 49$$

In Eq.(4), $\sigma(X) = \sigma_F(X) + \sigma_R(X)$, $\sigma(Y) = \sigma_F(Y) + \sigma_R(Y)$, and $\Delta\sigma_{CC}^{ex,2} = [\sigma_{CC}^{ex}(X) - \sigma_{CC}^{ex}(Y)]^2$. Obviously, the cor-

TABLE I The corrected $E_{(\text{Red})}$ values of 49 samples of 3,4'/4,3'/3,3'-substituted benzylideneanilines.

X	Y	$\sigma_{\text{F}}(\text{X})$ [16]	$\sigma_{\text{F}}(\text{Y})$ [16]	$\sigma_{\text{R}}(\text{X})$ [16]	$\sigma_{\text{R}}(\text{Y})$ [16]	$\sigma_{\text{CC}}^{\text{ex}}(\text{X})^{\text{a}}$	$\sigma_{\text{CC}}^{\text{ex}}(\text{Y})^{\text{a}}$	$E_{(\text{Red})\text{expt.}}^{\text{b}}$	$E_{(\text{Red})\text{calcd.}}^{\text{b}}$
<i>m</i> -F	<i>p</i> -NMe ₂	0.34	0.15	0.00	-0.98	0.02	-1.81	-1.94	-1.95
<i>m</i> -F	<i>p</i> -OMe	0.34	0.29	0.00	-0.56	0.02	-0.50	-1.88	-1.88
<i>m</i> -F	<i>p</i> -Me	0.34	0.01	0.00	-0.18	0.02	-0.17	-1.86	-1.86
<i>m</i> -F	<i>p</i> -Cl	0.34	0.42	0.00	-0.19	0.02	-0.22	-1.71	-1.74
<i>m</i> -Br	<i>p</i> -NMe ₂	0.39	0.15	0.00	-0.98	-0.03	-1.81	-2.03	-1.93
<i>m</i> -Br	<i>p</i> -OMe	0.39	0.29	0.00	-0.56	-0.03	-0.50	-1.81	-1.86
<i>m</i> -Br	<i>p</i> -Me	0.39	0.01	0.00	-0.18	-0.03	-0.17	-1.79	-1.83
<i>m</i> -Br	<i>p</i> -F	0.39	0.45	0.00	-0.39	-0.03	0.06	-1.87	-1.77
<i>m</i> -Br	<i>p</i> -Cl	0.39	0.42	0.00	-0.19	-0.03	-0.22	-1.86	-1.72
<i>m</i> -CN	<i>p</i> -NMe ₂	0.56	0.15	0.00	-0.98	0.56	-1.81	-1.85	-1.82
<i>m</i> -CN	<i>p</i> -OMe	0.56	0.29	0.00	-0.56	0.56	-0.50	-1.73	-1.78
<i>m</i> -CN	<i>p</i> -Me	0.56	0.01	0.00	-0.18	0.56	-0.17	-1.76	-1.77
<i>m</i> -CN	<i>p</i> -Cl	0.56	0.42	0.00	-0.19	0.56	-0.22	-1.66	-1.65
<i>m</i> -CN	<i>p</i> -CN	0.56	0.51	0.00	0.15	0.56	-0.70	-1.48	-1.50
<i>m</i> -OMe	<i>p</i> -NMe ₂	0.12	0.15	0.00	-0.98	0.10	-1.81	-1.99	-2.05
<i>p</i> -NMe ₂	<i>m</i> -Me	0.15	-0.07	-0.98	0.00	-1.81	-0.03	-2.16	-2.18
<i>p</i> -OMe	<i>m</i> -Me	0.29	-0.07	-0.56	0.00	-0.50	-0.03	-2.09	-2.08
<i>p</i> -Cl	<i>m</i> -Me	0.42	-0.07	-0.19	0.00	-0.22	-0.03	-1.88	-1.87
<i>p</i> -CF ₃	<i>m</i> -Me	0.38	-0.07	0.16	0.00	-0.12	-0.03	-1.71	-1.73
<i>p</i> -CN	<i>m</i> -Me	0.51	-0.07	0.15	0.00	-0.70	-0.03	-1.53	-1.64
<i>p</i> -NO ₂	<i>m</i> -Me	0.65	-0.07	0.13	0.00	-1.17	-0.03	-1.58	-1.53
<i>p</i> -NMe ₂	<i>m</i> -F	0.15	0.34	-0.98	0.00	-1.81	0.02	-2.00	-2.05
<i>p</i> -OMe	<i>m</i> -F	0.29	0.34	-0.56	0.00	-0.50	0.02	-1.93	-1.95
<i>p</i> -Me	<i>m</i> -F	0.01	0.34	-0.18	0.00	-0.17	0.02	-1.89	-1.93
<i>p</i> -Cl	<i>m</i> -F	0.42	0.34	-0.19	0.00	-0.22	0.02	-1.76	-1.75
<i>p</i> -NMe ₂	<i>m</i> -Br	0.15	0.39	-0.98	0.00	-1.81	-0.03	-2.04	-2.04
<i>p</i> -OMe	<i>m</i> -Br	0.29	0.39	-0.56	0.00	-0.50	-0.03	-2.09	-1.94
<i>p</i> -Me	<i>m</i> -Br	0.01	0.39	-0.18	0.00	-0.17	-0.03	-1.92	-1.92
<i>p</i> -Cl	<i>m</i> -Br	0.42	0.39	-0.19	0.00	-0.22	-0.03	-1.71	-1.73
<i>p</i> -CN	<i>m</i> -Br	0.51	0.39	0.15	0.00	-0.70	-0.03	-1.43	-1.50
<i>p</i> -NMe ₂	<i>m</i> -OMe	0.15	0.12	-0.98	0.00	-1.81	0.10	-2.13	-2.11
<i>p</i> -CN	<i>m</i> -OMe	0.51	0.12	0.15	0.00	-0.70	0.10	-1.53	-1.57
<i>p</i> -NO ₂	<i>m</i> -OMe	0.65	0.12	0.13	0.00	-1.17	0.10	-1.47	-1.47
<i>p</i> -Cl	<i>m</i> -CN	0.42	0.56	-0.19	0.00	-0.22	0.56	-1.53	-1.67
<i>p</i> -CN	<i>m</i> -CN	0.51	0.56	0.15	0.00	-0.70	0.56	-1.50	-1.42
<i>m</i> -OMe	<i>m</i> -CN	0.12	0.56	0.00	0.00	0.10	0.56	-1.59	-1.75
<i>m</i> -Me	<i>m</i> -OMe	-0.07	0.12	0.00	0.00	-0.03	0.10	-1.96	-1.96
<i>m</i> -Me	<i>m</i> -Me	-0.07	-0.07	0.00	0.00	-0.03	-0.03	-1.99	-2.02
<i>m</i> -Me	<i>m</i> -F	-0.07	0.34	0.00	0.00	-0.03	0.02	-1.98	-1.90
<i>m</i> -F	<i>m</i> -Me	0.34	-0.07	0.00	0.00	0.02	-0.03	-1.84	-1.83
<i>m</i> -F	<i>m</i> -F	0.34	0.34	0.00	0.00	0.02	0.02	-1.74	-1.71
<i>m</i> -F	<i>m</i> -Br	0.34	0.39	0.00	0.00	0.02	-0.03	-1.76	-1.70
<i>m</i> -CN	<i>m</i> -OMe	0.56	0.12	0.00	0.00	0.56	0.10	-1.66	-1.70
<i>m</i> -CN	<i>m</i> -Me	0.56	-0.07	0.00	0.00	0.56	-0.03	-1.72	-1.75
<i>m</i> -CN	<i>m</i> -F	0.56	0.34	0.00	0.00	0.56	0.02	-1.62	-1.63
<i>m</i> -CN	<i>m</i> -CN	0.56	0.56	0.00	0.00	0.56	0.56	-1.61	-1.58
<i>m</i> -Br	<i>m</i> -Me	0.39	-0.07	0.00	0.00	-0.03	-0.03	-1.86	-1.81
<i>m</i> -Br	<i>m</i> -CN	0.39	0.56	0.00	0.00	-0.03	0.56	-1.69	-1.61
<i>m</i> -Br	<i>m</i> -Br	0.39	0.39	0.00	0.00	-0.03	-0.03	-1.68	-1.67

^a The para-substituent were taken from Ref.[17], the meta-substituent were taken from Refs.[18, 19].

^b $E_{(\text{Red})\text{expt.}}$ were measured by CV method and $E_{(\text{Red})\text{calcd.}}$ were calculated by Eq.(4).

TABLE II The relative and fraction contribution (Ψ_r and Ψ_f) of parameters in Eq.(2) and Eq.(4).

	Parameters	$\sigma(X)$		$\sigma(Y)$		$\sigma_{CC}^{ex}(X)$	$\Delta\sigma_{CC}^{ex,2}$
		$\sigma_F(X)$	$\sigma_R(X)$	$\sigma_F(Y)$	$\sigma_R(Y)$		
Eq.(2)	Ψ_r	0.1068	0.1482		0.0343	0.0917	
	Ψ_f	0.2669	0.3703		0.0857	0.2291	
			0.6372		0.0857		
Eq.(4)	Ψ_r		0.1092	0.0272		0.0108	0.0256
	Ψ_f		0.5657	0.1411		0.0559	0.1324

relation of Eq.(4) is much better than that of Eq.(3), and its standard deviation S is down to 0.064 from 0.091 of Eq.(3). And the number of variables employed in Eq.(4) is equal to that in Eq.(3). Furthermore, the intercept of Eq.(4) is equal to that of Eq.(2). It can be explained as follows: in case X and Y groups all are H atom, both of 4,4'-substituted XBAYs and 3,4'/4,3'/3,3'-substituted XBAYs all returned to the parent molecule, benzylideneaniline (HBAH). Thus, the intercepts of Eq.(4) and Eq.(2) should be equal to each other, which express the reduction potential of HBAH.

In addition, the plot of the $E_{(Red)calcd.}$ values calculated by Eq.(4) vs. the experimental $E_{(Red)expt.}$ values for 3,4'/4,3'/3,3'-substituted XBAYs of Table I was made and shown in Fig.3.

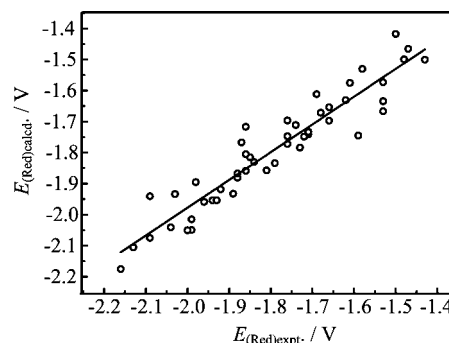
Comparing Eq.(4) and Eq.(2), it can be seen that the factors affecting the $E_{(Red)}$ of 3,4'/4,3'/3,3'-substituted XBAYs are different from those of 4,4'-substituted XBAYs. Here the relative importance of parameters in each equation is investigated from the relative contributions (ψ_r) or fraction contributions (ψ_f) of the corresponding parameters to $E_{(Red)}$ [20, 21].

$$\psi_r(i) = m_i \bar{X}_i \quad (5)$$

$$\psi_f(i) = \frac{R^2 |\psi_r(i)|}{\sum_i |\psi_r(i)|} \times 100\% \quad (6)$$

The m_i and \bar{X}_i are the coefficient and the average value of the i th parameter in each equation, and the R is the correlation coefficient of each equation. The sum is over the parameters in the equations. The contribution results for the corresponding parameters of the equations are all shown in Table II.

Table II shows that for the 4,4'-substituted XBAYs, the main contribution to the $E_{(Red)}$ is the X group, in which the total contribution of $\sigma_F(X)$, $\sigma_R(X)$ and $\sigma_{CC}^{ex}(X)$ is 86.63%. The contribution of Y group is only 8.57% and the contribution of $\sigma_F(Y)$ can be ignored. For the 3,4'/4,3'/3,3'-substituted XBAYs, the contribution of X group to the $E_{(Red)}$ is down to 62.16%, the contribution of Y group to the $E_{(Red)}$ rises to 14.11%, and the contribution of $\Delta\sigma_{CC}^{ex,2}$ is also important. In the 4,4'-substituted XBAYs, the contribution of σ_R of X or Y is larger than that of σ_F , while the contribution of σ_R of X or Y is equal to that of its σ_F in 3,4'/4,3'/3,3'-

FIG. 3 Plot of $E_{(Red)calcd.}$ values calculated by Eq.(4) vs. $E_{(Red)expt.}$ values for target compounds.

substituted XBAYs, so the $\sigma(X)$ and $\sigma(Y)$ were employed in Eq.(4).

It should be paid attention that the effects of X group on the $E_{(Red)}$ are larger than that of Y group in both 4,4'-substituted XBAYs and 3,4'/4,3'/3,3'-substituted XBAYs. The reasons may be as follows: the distance between X and carbon atom of CH=N is closer than that between Y and the carbon atom, and the aniline ring with Y group is twisted out of the C=C=N-C plane by 41° – 55° exhibited by crystal structures of XBAY molecules [22, 23], which may hinder the transmission of the conjugative effect some what from Y to the CH=N.

IV. CONCLUSION

An optimality equation (Eq.(4)) with four parameters was obtained for the electrochemical reduction potentials $E_{(Red)}$ of 49 samples of 3,4'/4,3'/3,3'-substituted XBAYs. The results indicated that the factors affecting the $E_{(Red)}$ of 3,4'/4,3'/3,3'-substituted XBAYs are different from those of 4,4'-substituted XBAYs. As regards the $E_{(Red)}$ of 3,4'/4,3'/3,3'-substituted XBAYs, the contributions of σ_F and σ_R of X (or Y) are equal to each other, so the parameters $\sigma(X)$ and $\sigma(Y)$ rather than σ_F and σ_R were employed, and the contribution of $\Delta\sigma_{CC}^{ex,2}$ is also important and not negligible. Compared with 4,4'-substituted XBAYs, X group contributes less to the $E_{(Red)}$ of 3,4'/4,3'/3,3'-substituted XBAYs, while Y group contributes more. Finally, X group contributes

more than Y group to the $E_{(\text{Red})}$ of substituted XBAYs wherever they are in para-position or meta-position.

V. ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No.21272063), the Scientific Research Fund of Hunan Provincial Education Department (No.14C0466), and the Natural Science Foundation of Hunan (No.14JJ3112).

- [1] A. Kawasaki, *J. Chem. Soc. Perkin Trans. 2*, **2**, 223 (1990).
- [2] K. Neuvonen, F. Fülöp, H. Neuvonen, A. Koch, E. Kleinpeter, and K. Pihlaja, *J. Org. Chem.* **68**, 2151 (2003).
- [3] H. Neuvonen, K. Neuvonen, and F. Fülöp, *J. Org. Chem.* **71**, 3141 (2006).
- [4] B. Hemmateenejad and M. Sanchooli, *J. Chemometrics.* **21**, 96 (2007).
- [5] M. Karelson, V. S. Lobanov, and A. R. Katritzky, *Chem. Rev.* **96**, 1027 (1996).
- [6] J. J. Sullivan, A. D. Jones, and K. K. Tanji, *J. Chem. Inf. Comp. Sci.* **40**, 1113 (2000).
- [7] X. Q. Zhu, Y. Tan, and C. T. Cao, *J. Phys. Chem. B* **114**, 2058 (2010).
- [8] A. J. Fry and R. G. Reed, *J. Am. Chem. Soc.* **91**, 6448 (1969).
- [9] C. P. Andrieux and J. M. Saveant, *J. Electroanal. Chem.* **33**, 453 (1971).
- [10] K. Polat, M. Uçar, M. L. Aksu, and H. Ünver, *Can. J. Chem.* **82**, 1150 (2004).
- [11] V. A. Sauro and M. S. Workentin, *J. Org. Chem.* **66**, 831 (2001).
- [12] H. Celik, G. Ekmekci, J. Ludvík, J. Piča, and P. Zuman, *J. Phys. Chem. B* **110**, 6785 (2006).
- [13] X. Q. Zhu, Q. Y. Liu, Q. Chen, and L. R. Mei, *J. Org. Chem.* **75**, 789 (2010).
- [14] C. Z. Cao, Y. K. Bi, and C. T. Cao, *Chin. J. Org. Chem.* **35**, 1302 (2015).
- [15] N. G. Connelly and W. E. Geiger, *Chem. Rev.* **96**, 877 (1996).
- [16] C. Hansch, A. Leo, and R. W. Taft, *Chem. Rev.* **91**, 165 (1991).
- [17] C. Z. Cao, G. F. Chen, and Z. Q. Yin, *J. Phys. Org. Chem.* **21**, 808 (2008).
- [18] C. Z. Cao, B. Sheng, and G. F. Chen, *J. Phys. Org. Chem.* **25**, 1315 (2012).
- [19] C. Z. Cao and Y. X. Wu, *Sci. China Chem.* **56**, 883 (2013).
- [20] D. E. Needham, I. C. Wei, and P. G. Seybold, *J. Am. Chem. Soc.* **110**, 4186 (1988).
- [21] F. P. Liu, Y. Z. Liang, C. Z. Cao, and N. Zhou, *Talanta* **72**, 1307 (2007).
- [22] H. B. Bürgi and J. D. Dunitz, *Helv. Chim. Acta.* **53**, 1747 (1970).
- [23] H. B. Bürgi and J. D. Dunitz, *Helv. Chim. Acta.* **54**, 1255 (1971).
- [24] C. Z. Cao, B. T. Lu, and G. F. Chen, *J. Phys. Org. Chem.* **24**, 335 (2011).
- [25] J. Schmeyers, F. Toda, J. Boy, and G. Kaupp, *J. Chem. Soc. Perkin Trans. 2* **4**, 989 (1998).