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Homolytic bond dissociation energies of 4-substituted bicyclo[2.2.2]octanyl compounds: inductive/field effects on the stabilities of organic radicals

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ABSTRACT: The inductive/field effects on homolytic bond dissociation energies (BDEs) were studied for the first time using substituted 4-X-bicyclo[2.2.2]octane-Y—Z systems. A variety of very different chemical bonds (i.e. Z—Y: Z = CH_2, NH, O, SiH_2, PH, S; Y = H, F, Li) were considered, and popular substituents including H, CH_3, F, OH, NH_2, SH, CN and NO_2 were utilized. High-quality BDE values were obtained for the first time for many bicyclo[2.2.2]octane systems from carefully calibrated G3B3/B3LYP calculations. Significant effects of the substituents at the 4-position of bicyclooctane were found for the Z—Y BDEs of bicyclooctanyl-Z—Y systems. Nice Hammett-type correlations were obtained for these substituent effects using the inductive/field F constants. It was found that the reaction constants (i.e. ρ values) of the Hammett correlations varied dramatically from -1.96 to $+23.01\,\mathrm{kJ\,mol^{-1}}$ for different Z—Y systems: The ρ values for the Z—H BDEs were about ~ 1.0–$5.0\,\mathrm{kJ\,mol^{-1}}$; the ρ values for the Z—F BDEs were about -2.0 to $-1.0\,\mathrm{kJ\,mol^{-1}}$; the ρ values for the Z—Li BDEs were ~ 13.0–$23.0\,\mathrm{kJ\,mol^{-1}}$. The substituent effects on both the stability of the parent molecules before homolysis and the stability of the radical products after homolysis were demonstrated to be important for the BDEs. It was shown that the inductive/field substituent effects on BDEs could not be explained by the electronegativity or bond polarity theories. Nevertheless, we developed a theoretical model on the basis of the classic electrostatic theories for the inductive/field effects. This model successfully explained the intriguing inductive/field substituent effects on BDEs. Copyright © 2004 John Wiley & Sons, Ltd.

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KEYWORDS: substituent effect; inductive/field effect; bond dissociation energy; bicyclooctane; *ab initio*

INTRODUCTION

The Hammett relationship shows that the effect of a substituent on the property of an aromatic molecule is proportional to the effect of the same substituent on the acidity of benzoic acid.[1] This elegant model has been utilized extensively to understand or predict the reactivities of neutral, cationic and anionic organic species.[2] Two substituent effects, i.e. the electronic effect and the steric effect, have been demonstrated to be mechanistically important for the Hammett relationship (although the steric effect is only important for *ortho* substituent effects). The electronic substituent effects are considered to be the product of two components: the inductive/field effect and the resonance effect.[3]

Despite the tremendous success of the Hammett relationship for closed-shell organic species, there is much less consensus about the application of the Hammett relationship to radical systems.[4] This is mainly caused by the fact that radicals are highly unstable and usually difficult to handle in experiments. Also, theoretical work in the past could not provide much help to attain trustworthy energies for radical systems because the traditional HF and MP2 methods suffer severely from spin contamination effects. Owing to the lack of reliable data for radical systems, very few have been able to study the quantitative structure–activity relationships (QASR) associated with radicals.[4]

Luckily the very recent advance in the composite *ab initio* methods has made it possible to attain sufficiently accurate energies for radical systems.[5] Although there is still a strong limitation in the size of the systems handled by the composite *ab initio* methods, one can use a composite *ab initio* method to obtain the energy of a smaller model system and then employ a density functional theory (DFT) method to calculate the energy difference between the model system and the real system. It has been demonstrated that by adding the composite *ab initio* energy of the model system and the DFT energy difference one can obtain a sufficiently accurate energy for the real system.[6]

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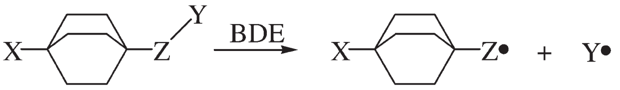
Using the above approach, we and several other groups recently have studied the QSARs of various radical systems.[7–11] It was found in a number of cases that the Z—Y homolytic bond dissociation energies (BDEs) of compounds X—C_6H_4—Z—Y could follow the Hammett relationship. Both the substituent effects on the stability of the parent compounds and the substituent effects on the stability of the radicals were found to be important for the overall homolysis process. For benzene systems, it was demonstrated that the reaction constant (i.e. the ρ value) for homolysis of the Z—Y bond in X—C_6H_4—Z—Y could be predicted quantitatively using the change in acidity from HOOC—C_6H_4—Z—Y to HOOC—C_6H_4—$Z^{\cdot}$.[11]

In the present study we extend our research to the 4-substituted bicyclo[2.2.2]octane system. This system is very important in physical organic chemistry because it fully eliminates the conjugation and steric interactions, guaranteeing operation of the pure inductive/field effect. Using the solution-phase acidities of 4-substituted bicyclo[2.2.2]octane-1-carboxylic acids Roberts and Moreland determined the substituent σ_I constants.[12] The gas-phase acidities of a number of these acids have been determined more recently by Koppell *et al.*[13] Despite the importance of this system, there have been relatively few computational studies of its substituent effects, and even fewer that make use of flexible basis sets and correction for electron correlation.

Very recently, Wiberg used the MP2/6–311++G** method to calculate the acidities of 4-substituted bicyclo[2.2.2]octane-1-carboxylic acids.[14] He found that these acidities were linearly dependent on the C—X bond dipoles. He also found that the substituent effects on acidities could be reproduced by the Kirkwood–Westheimer model. At about the same time Exner and Bohm studied the energies of various 4-substituted bicyclo[2.2.2]octane-1-carboxylic acids and their anions using the B3LYP/6–311+G(d,p) method.[14] These authors found that the substituent effects were proportional and opposing (that in the anion being eight times greater) but for their effect on acidity they were summed. These authors also stressed that the inductive effect should receive more attention in fundamental textbooks.

Our own interest is the effect of substituents on the homolytic BDEs of 4-substituted bicyclo[2.2.2]octanyl compounds (see Scheme 1). We believe that this subject warrants a careful investigation because it is generally believed that the resonance effect is important for the stability of radicals but very little is known about the field/inductive effect on the stability of radicals. Can the field/inductive effect significantly stabilize or destabilize a radical? How is the direction of the stabilization or destabilization effect predicted? What is the driving force for the stabilization or destabilization? Unfortunately, none of these questions has been answered before.

Herein we report our study concerning the above questions. Appropriate isodesmic reactions are designed to separate the overall effect on homolysis into the effect on the stability of the parent compounds and the effect on the stability of the radicals. Different radical centres, including $CH_2^{\cdot}$, $NH^{\cdot}$, $O^{\cdot}$, $SiH_2^{\cdot}$, $PH^{\cdot}$ and $S^{\cdot}$, and different leaving moieties, including $H^{\cdot}$, $F^{\cdot}$ and $Li^{\cdot}$, are considered in order to embrace as many different types of electron demand as possible. Furthermore, because the α-position bonding strengths of the 4-substituted bicyclo[2.2.2]octanyl compounds are largely unknown, we combine the composite *ab initio* and DFT methods to provide high-quality estimates for these BDE values.



X = H, CH_3, F, OH, NH_2, SH, CN, NO_2
Z = CH_2, NH, O, SiH_2, PH, S
Y = H, F, Li

Scheme 1

METHOD

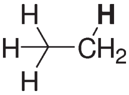
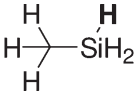
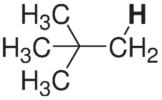
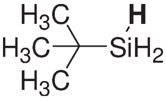
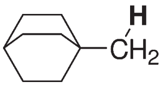
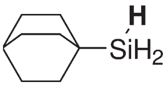
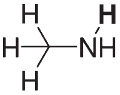
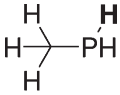
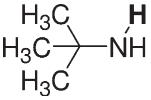
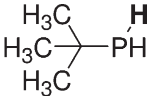
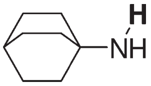
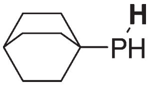
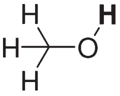
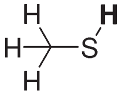
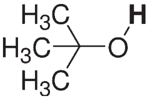
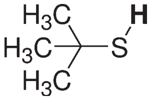
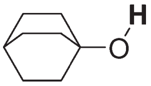
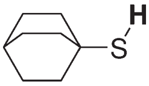
All the calculations were done using Gaussian 03.[16] The geometry of a neutral molecule or radical was optimized using the UB3LYP/6–31+G* method and each final structure was checked by UB3LYP/6–31+G* frequency calculation to be a real minimum without any imaginary frequency. Single-point calculations were performed at the UB3LYP/6–311++G(2df,p) level. These results were corrected by the zero point energies and thermal corrections calculated at the UB3LYP/6–31+G* level to get the enthalpies at 298 K and 1 atm in the gas phase. The BDEs were then calculated as enthalpy changes of the homolysis reaction A—B → $A^{\cdot}$+$B^{\cdot}$ at 298 K and 1 atm in the gas phase. In addition to the UB3LYP/6–311++G(2df,p)//UB3LYP/6–31+G(d) method, we also used the G3B3 method to calculate some BDEs.

RESULTS AND DISCUSSION

Bond dissociation energies

Table 1 shows the C—H BDE values of a number of systems related to bicyclo[2.2.2]octanes. Comparing the experimental BDEs with the G3B3 data (see Fig. 1(a)), one can see that the G3B3 method predicts the BDEs very accurately. The mean error of the G3B3 method is 0.8 kJ mol^{-1} for the compounds in Table 1, and the root-mean-square (RMS) error is 3.8 kJ mol^{-1}. On the other hand, the UB3LYP/6–311++G(2df,p)//UB3LYP/6–31+G(d) method (abbreviated as B3LYP below) always underestimates the BDEs (see Fig. 1(b)). The mean error of the B3LYP method is −14.4 kJ mol^{-1} and the RMS error is 15.2 kJ mol^{-1}.

Table 1. Comparison of experimental and theoretical BDEs (kJ mol^{-1})

Compound	Exp.	G3B3[a]	B3LYP[b]	Compound	Exp.	G3B3[a]	B3LYP[b]
	420.5 (Ref. 17)	422.5	410.8		386.2 (Ref. 23)	387.3	379.2
	423.0 (Ref. 18)	428.7	415.6		—	387.1	378.3
	—	—	414.0		—	—	377.7
	418.4 (Ref. 19)	415.9	400.3		—	337.2	329.4
	418.4 (Ref. 20)	421.5	404.5		—	340.3	331.2
	—	—	403.3		—	—	330.8
	436.0 (Ref. 21)	438.3	414.5		364.0 (Ref. 24)	359.8	348.9
	441.4 (Ref. 22)	446.5	421.4		370.7 (Ref. 25)	365.6	353.8
	—	—	415.8		—	—	352.8

[a] G3B3 BDEs.

[b] UB3LYP/6–311++G(2df,p)//UB3LYP/6–31+G(d) BDEs.

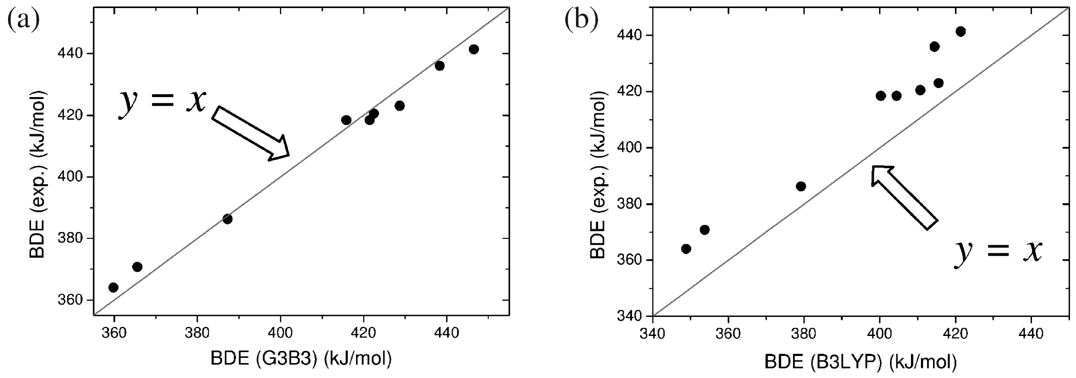


Figure 1. Correlation of the experimental BDEs with the G3B3 (a) and B3LYP (b) results

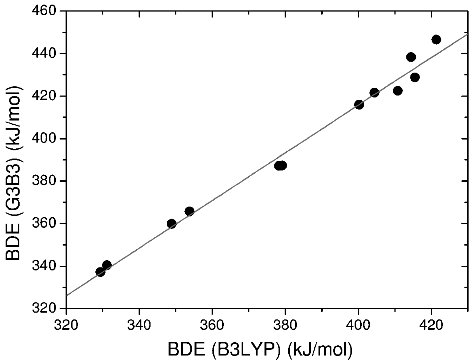


Figure 2. Correlating the B3LYP BDEs with the G3B3 results reveals that the error of the B3LYP method is systematic

It is clear from the above analysis that the B3LYP method cannot accurately predict the absolute BDEs. Nevertheless, we find that the B3LYP BDEs correlate nicely with the G3B3 data (see Fig. 2). This suggests that the underestimation of BDE by the B3LYP method is largely systematic and therefore we can combine the G3B3 and B3LYP method to calculate the absolute BDEs. For the bicyclo[2.2.2]octane systems, we choose $Me_3C—Z—Y$ as the reference system. The Z—Y BDEs of the bicyclo[2.2.2]octanyl-Z—Y molecules are then estimated using the following equation

$$\begin{aligned}\mathrm{BDE_{calc.}}\ &(\text{bicyclo[2.2.2]octanyl-Z}-\text{Y})\\ &= \mathrm{BDE_{G3B3}}\ (\mathrm{Me_3C}-\mathrm{Z}-\mathrm{Y})\\ &\quad + \mathrm{BDE_{B3LYP}}\ (\text{bicyclo[2.2.2]octanyl-Z}-\text{Y})\\ &\quad - \mathrm{BDE_{B3LYP}}\ (\mathrm{Me_3C}-\mathrm{Z}-\mathrm{Y})\end{aligned} \tag{1}$$

Using the above G3B3/B3LYP method, we calculate the Z—Y BDEs for the $Me_3C—Z—Y$ and bicyclo[2.2.2]octanyl-Z—Y systems, where $Z = CH_2$, NH, O, SiH_2, PH and S and Y = H, F and Li. The results are listed in Table 2 and it is clear that all the Z—Y BDEs of $Me_3C—Z—Y$ are very close to the corresponding Y—Z BDEs of bicyclo[2.2.2]octanyl-Z—Y.

Substituent effects on bond dissociation energies

The substituent effects on the Z—Y BDEs of the bicyclo[2.2.2]octanyl-Z—Y systems are evaluated by the relative BDEs of the substituted molecules compared with the parent species (Eqn (2)) using the B3LYP method

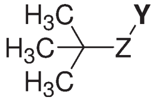
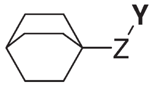
$$\begin{aligned}\Delta\mathrm{BDE} = \ &\mathrm{BDE}(\text{X-bicyclo[2.2.2]octanyl}-\text{Z}-\text{Y})\\ &- \mathrm{BDE}(\text{bicyclo[2.2.2]octanyl}-\text{Z}-\text{Y})\end{aligned} \tag{2}$$

The results are listed in Table 3. It is worth mentioning that the ΔBDE values can be very accurately calculated by the B3LYP method directly, owing to the cancellation of errors within a closely related family of compounds.[7–11]

From Table 3 one can see that there are noticeable substituent effects on the Z—Y BDEs of the bicyclo[2.2.2]octanyl-Z—Y systems. Although the magnitude of the substituent effects on the Z—H and Z—F BDEs is usually small (about -1.0 to $3.0\,\mathrm{kJ\,mol^{-1}}$ for many cases), all the data in Table 3 can be reproduced easily and therefore are reliable. Compared with the Z—H and Z—F cases, the magnitude of the substituent effects on the Z—Li BDEs is fairly large ($\sim$0–$15\,\mathrm{kJ\,mol^{-1}}$). It is worth noting that in a very recent study by Exner and Böhm the authors reported small (0–$4\,\mathrm{kJ\,mol^{-1}}$) but significant substituent effects on the stability of neutral 4-substituted bicyclo[2.2.2]octane-1-carboxylic acids.[15]

Because we are interested in the inductive/field effects on the BDEs, we plot the ΔBDE values against the substituent F constants for each combination of Z and Y.[26] It is found that all the Z—Y BDEs show nice correlations with the substituent F constants (see Fig. 3 for the C, N and O cases). The correlation coefficients are mostly higher than 0.90 and the slope of the correlation (i.e. the reaction constant ρ) indicates the direction and magnitude of the substituent effects on the Z—Y BDEs. It is clear from Table 3 that the ρ values vary dramatically from -1.96 to $23.01\,\mathrm{kJ\,mol^{-1}}$ for different Z—Y systems.

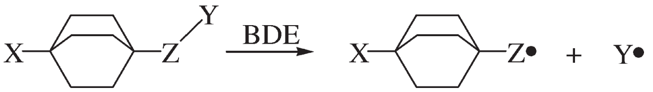
Table 2. Recommended Z—Y BDEs for $Me_3C—Z—Y^a$ and bicyclo[2.2.2]octanyl-Z—Y^b systems ($\mathrm{kJ\,mol^{-1}}$)

						
BDE	Y = H	Y = F	Y = Li	Y = H	Y = F	Y = Li
$Z = CH_2$	428.7	479.5	186.6	427.1	476.4	187.0
Z = NH	421.5	301.3	284.7	420.3	297.7	284.9
Z = O	446.5	196.7	393.7	440.9	189.3	389.9
$Z = SiH_2$	387.1	646.1	211.6	386.5	645.4	211.4
Z = PH	340.3	483.9	202.3	339.9	482.7	203.3
Z = S	365.6	362.0	311.9	364.7	359.3	315.9

[a] Calculated using the G3B3 method.

[b] Calculated using Eqn (1).

Table 3. Substituent effects on the Z—Y BDEs of the bicyclo[2.2.2]octanyl-Z—Y systems (kJ mol^{-1})



	$Z = CH_2$			Z = NH			Z = O		
ΔBDE[a]	Y = H	Y = F	Y = Li	Y = H	Y = F	Y = Li	Y = H	Y = F	Y = Li
X = H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X = Me	0.24	0.33	0.18	0.07	0.28	0.16	−0.03	0.21	0.28
$X = NH_2$	0.34	0.16	1.65	0.47	0.06	1.41	0.02	0.16	1.93
X = SH	0.63	0.04	3.89	1.30	−0.10	4.77	1.04	−0.18	6.31
X = OH	0.49	0.24	2.83	1.24	−0.05	4.13	0.34	−0.15	4.41
X = F	0.61	−0.71	4.58	1.27	−0.53	6.00	1.60	−0.56	8.43
X = CN	1.03	−0.92	7.94	2.39	−0.54	10.10	3.18	−0.19	13.82
$X = NO_2$	1.01	−1.05	8.68	2.85	−0.44	11.08	3.06	−0.46	14.99
ρ[b]	**1.38**	**−1.96**	**13.00**	**4.10**	**−1.10**	**16.98**	**5.04**	**−0.96**	**23.01**
r[c]	0.937	−0.850	0.960	0.966	−0.883	0.973	0.909	−0.859	0.963

	$Z = SiH_2$			Z = PH			Z = S		
	Y = H	Y = F	Y = Li	Y = H	Y = F	Y = Li	Y = H	Y = F	Y = Li
X = H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X = Me	0.35	0.29	0.36	−0.01	0.16	0.42	−0.13	0.14	0.09
$X = NH_2$	0.19	0.05	1.56	−0.08	0.12	1.06	0.05	0.13	1.45
X = SH	0.45	0.04	3.89	0.30	−0.3	3.43	0.22	−0.32	3.56
X = OH	0.36	−0.14	2.78	0.27	0.04	1.82	0.18	0.17	2.75
X = F	0.42	−0.25	4.77	0.10	−0.67	4.32	0.48	−0.44	4.66
X = CN	0.43	−0.55	8.10	0.46	−0.68	7.51	0.91	−0.68	8.10
$X = NO_2$	0.62	−0.72	8.53	0.46	−0.85	7.93	0.67	−0.89	8.67
ρ[b]	**0.64**	**−1.25**	**12.87**	**0.76**	**−1.53**	**11.97**	**1.33**	**−1.46**	**13.18**
r[c]	0.831	−0.906	0.959	0.864	−0.909	0.942	0.904	−0.866	0.960

[a] Calculated as the relative value between the substituted and unsubstituted cases.

[b] The slope of the correlation between ΔBDEs and the substituent F constants.

[c] The correlation coefficient of the correlation between ΔBDEs and the substituent F constants; the substituent F constants are: $F(H) = 0.00$; $F(Me) = 0.01$; $F(NH_2) = 0.08$; $F(SH) = 0.30$; $F(OH) = 0.33$; $F(F) = 0.45$; $F(CN) = 0.51$; $F(NO_2) = 0.65$.

For the Z—H BDEs, the ρ values are 1.38, 4.10, 5.04, 0.64, 0.76 and 1.33 kJ mol^{-1} for Z = C, N, O, Si, P and S. Thus a stronger electron-withdrawing group such as CN and NO_2 will lead to a higher Z—H BDE compared with a less electron-withdrawing substituent. On the other hand, the ρ values for the Z—F BDEs are −1.96, −1.10, −0.96, −1.25, −1.53 and −1.46 kJ mol^{-1} for Z = C, N, O, Si, P and S. Thus a stronger electron-withdrawing group will lead to a lower Z—F BDE compared with a less electron-withdrawing case. Furthermore, the ρ values for the Z—Li BDEs are 13.00, 16.98, 23.01, 12.87, 11.97 and +13.18 kJ mol^{-1} for Z = C, N, O, Si, P and S. These ρ values are all positive values, as with the ρ values for the Z—H BDEs, but the former are much higher in magnitude than the latter (see Fig. 3).

It appears from the above analysis that the sign and magnitude of the ρ values may have some dependence on the polarity of the Z—Y bonds. Thus we plot the ρ values against the difference between the Pauling electronegativity differences for the bonding atoms, i.e. $\Delta X = X(Z) - X(Y)$ (see Fig. 4) (the electronegativity constants are: C, 2.5; N, 3.0; O, 3.5; Si, 1.8; P, 2.1; S, 2.5; H, 2.1; F, 4.0; Li, 1.0). One can see from Fig. 4 that the plot does not provide a straight line. Although there is a positive dependence between the ρ values and the electronegativity difference when $\Delta X > 0$, the ρ value surprisingly remains almost the same for all the negative ΔX values, therefore it is not adequate to use the bond polarity or electronegativity difference to explain the substituent effects on the Y—Z BDEs.

Substituent effects on the stability of the parent molecules and radicals

Because the bond polarity theory cannot explain the substituent effects on the Z—Y BDEs, we decide at this point to partition the substituent effects on the Z—Y BDEs into the effects of X on X-bicyclo[2.2.2]octanyl-Z—Y and the effects of X on X-bicyclo[2.2.2]octanyl-Z•

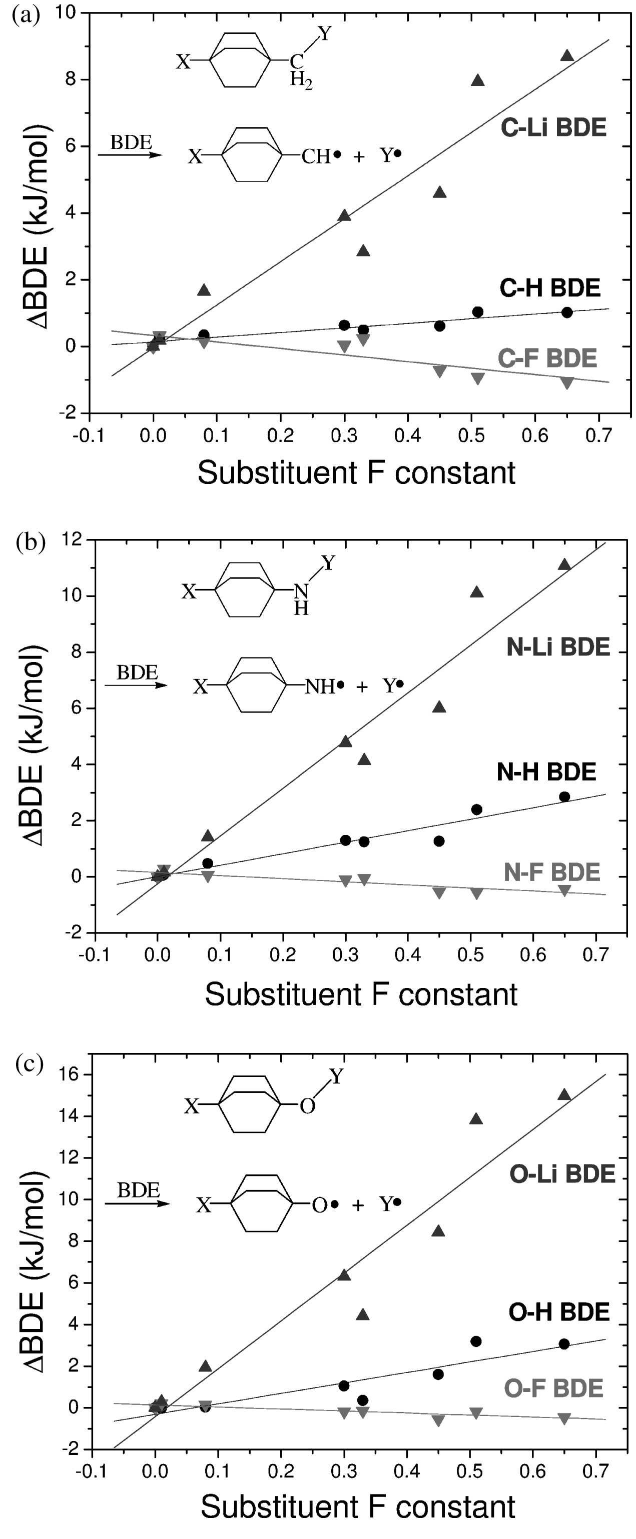


Figure 3. Correlations between the C—Y, N—Y and O—Y BDEs and the substituent *F* constants

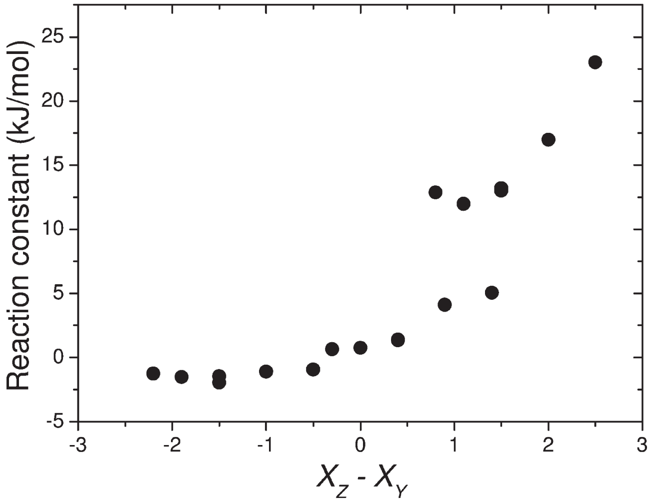
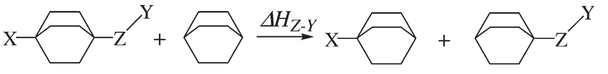
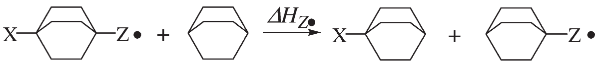


Figure 4. Correlations between the ρ values and Pauling electronegativity differences for the bonding atoms

(see Eqns (2) and (3)). We refer to the reaction enthalpy of Eqn (2) (i.e. $\Delta H_{Z—Y}$) as the molecule effect (ME) and the reaction enthalpy of Eqn (3) (i.e. $\Delta H_{Z^{\cdot}}$) as the radical effect (RE). Both ME and RE depict the energy cost to separate the Z—Y (or $Z^{\cdot}$) moiety from the X substituent. It is clear that ME − RE = ΔBDE. The detailed ME and RE values are listed in Table 4.



(2)



(3)

For each Z—Y (or $Z^{\cdot}$) case, we plot the ME or RE values against the substituent *F* constants. It is found that all the ME and RE values, except for the ME of CH_2—H, show good correlations with the substituent *F* constants (for a representative case, see Fig. 5). The slopes of the correlations (i.e. ρ values) vary dramatically from -12.02 to $+11.94\,\mathrm{kJ\,mol^{-1}}$). It is found that the ρ values for Z—H, Z—F, and $Z^{\cdot}$ are always negative and increase in the order ρ (Z—F) $< \rho$ ($Z^{\cdot}$) $< \rho$ (Z—H), whereas the ρ values for Z—Li are always positive, therefore for an electron-withdrawing group X it is energetically favourable to separate the Z—H, Z—F or $Z^{\cdot}$ moiety from X but it is energetically unfavourable to separate the Z—Li moiety from X.

The above findings suggest that the inductively electron-withdrawing groups destabilize the bicyclo[2.2.2]octanyl-$Z^{\cdot}$ radicals. Meanwhile the electron-withdrawing groups destabilize the bicyclo[2.2.2]octanyl-Z—H and bicyclo[2.2.2]octanyl-Z—F molecules but stabilize the bicyclo[2.2.2]octanyl-Z—Li systems. At this point, it is obvious that from Z—Li to $Z^{\cdot}$ the reaction constant must be positive. Because the electron-withdrawing groups destabilize the $Z^{\cdot}$ moiety more strongly than they do for the Z—H moiety, it is understandable that the reaction constant must be positive for the transformation from Z—H to $Z^{\cdot}$. Finally, because the electron-withdrawing groups destabilize the $Z^{\cdot}$ moiety

Table 4. Substituent effects on the stability of the parent molecule before homolysis and the radical product after homolysis (kJ mol^{-1})

	$Z = CH_2$				$Z = NH$				$Z = O$			
ΔBDE[a]	Y = H	Y = F	Y = Li	Y = ●	Y = H	Y = F	Y = Li	Y = ●	Y = H	Y = F	Y = Li	Y = ●
X = H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X = Me	0.08	0.17	0.02	−0.16	−0.25	−0.04	−0.16	−0.31	−0.45	−0.21	−0.14	−0.42
$X = NH_2$	−0.39	−0.56	0.92	−0.73	−0.82	−1.23	0.12	−1.29	−1.73	−1.60	0.18	−1.75
X = SH	−0.14	−0.73	3.12	−0.77	−0.93	−1.63	2.54	−2.23	−2.02	−3.25	3.25	−3.06
X = OH	−0.62	−0.87	1.72	−1.11	−1.41	−2.70	1.48	−2.65	−2.83	−3.31	1.24	−3.17
X = F	−0.44	−1.76	3.52	−1.05	−1.91	−3.71	2.81	−3.18	−3.38	−5.54	3.45	−4.98
X = CN	−0.45	−2.40	6.46	−1.48	−1.75	−4.68	5.96	−4.14	−3.46	−6.83	7.18	−6.64
$X = NO_2$	−0.40	−2.47	7.27	−1.41	−2.07	−5.37	6.16	−4.93	−4.34	−7.86	7.59	−7.40
ρ[b]	**−0.67**	**−4.03**	**10.86**	**−2.05**	**−3.03**	**−8.22**	**9.85**	**−7.14**	**−6.03**	**−12.02**	**11.94**	**−11.01**
r[c]	−0.664	−0.957	0.947	−0.925	−0.956	−0.978	0.939	−0.989	−0.966	−0.988	0.926	−0.982
Φ[d]	−0.28	0.55	−3.45	0.30	1.42	2.68	−2.00	1.79	3.07	4.63	−3.29	3.71
	$Z = SiH_2$				$Z = PH$				$Z = S$			
	Y = H	Y = F	Y = Li	Y = ●	Y = H	Y = F	Y = Li	Y = ●	Y = H	Y = F	Y = Li	Y = ●
X = H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X = Me	0.46	0.40	0.47	0.11	0.07	0.24	0.49	0.08	−0.18	0.08	0.03	−0.05
$X = NH_2$	0.18	0.04	1.54	−0.01	−0.63	−0.43	0.51	−0.55	−0.93	−0.85	0.47	−0.98
X = SH	−0.39	−0.80	3.05	−0.84	−1.04	−1.64	2.08	−1.34	−2.00	−2.54	1.33	−2.23
X = OH	−0.13	−0.63	2.29	−0.49	−0.99	−1.23	0.55	−1.26	−2.10	−2.11	0.48	−2.28
X = F	−0.49	−1.16	3.86	−0.91	−1.76	−2.52	2.47	−1.85	−3.08	−4.00	1.10	−3.56
X = CN	−2.01	−2.99	5.65	−2.44	−2.84	−3.98	4.21	−3.30	−4.35	−5.94	2.84	−5.26
$X = NO_2$	−1.35	−2.69	6.56	−1.97	−2.90	−4.20	4.58	−3.36	−4.83	−6.39	3.16	−5.50
ρ[b]	**−2.86**	**−4.75**	**9.37**	**−3.50**	**−4.55**	**−6.83**	**6.68**	**−5.31**	**−7.34**	**−10.13**	**4.50**	**−8.68**
r[c]	−0.840	−0.916	0.970	−0.897	−0.958	−0.967	0.909	−0.963	−0.985	−0.974	0.894	−0.978
Φ[d]	−1.30	−0.76	−4.06	−1.26	−0.50	−0.01	−3.52	−0.53	1.20	1.92	−2.04	1.43

[a] Relative value between substituted and unsubstituted cases.

[b] The slope of the correlation between ΔBDE and the substituent *F* constants.

[c] The correlation coefficient of the correlation between ΔBDE and the substituent *F* constants; the substituent *F* constants are: *F*(H) = 0.00; *F*(Me) = 0.01; *F*(NH_2) = 0.08; *F*(SH) = 0.30; *F*(OH) = 0.33; *F*(F) = 0.45; *F*(CN) = 0.51; *F*(NO_2) = 0.65.

[d] For the definition of Φ, see next section of text.

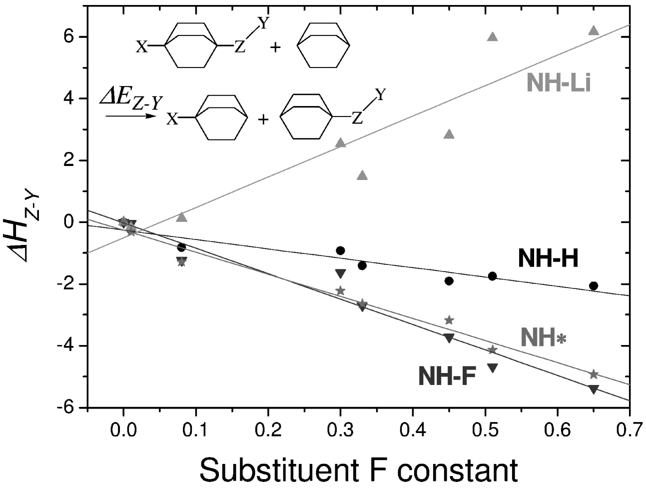
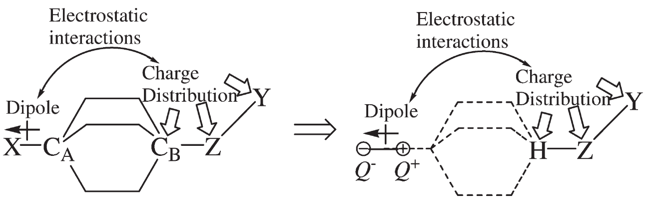


Figure 5. Correlations between the ME and RE values and the substituent *F* constants

less strongly than they do for the Z—F moiety, the reaction constant must be negative for the transformation from Z—F to Z˙. These findings explain the positive, negative and positive *ρ* values for the Z—H, Z—F and Z—Li BDEs, respectively.

A classical electrostatic model for predicting the *ρ* values

At this point we wish to establish a predictive theoretical model to explain the *ρ* values of the MEs and REs listed in Table 4. Thus we employ the classical electrostatic approach[27] to quantify the inductive/field effects of the X substituent on the stability of the Z—Y or Z˙ moieties. Within the framework of this theory, the inductive/field effect of X on Y—Z is expressed as a Coulombic interaction of the charge distribution in the Y—Z moiety with a dipolar substituent located at the position of X (see Scheme 2).



Scheme 2

To apply mathematics to the above electrostatic model, we replace the X substituent with a pure dipole composed of a positive point charge ($+Q$) and a negative point charge ($-Q$). The distance between the positive and negative charges is 1.10 Å (equal to the C—H bond length). The distance between the positive charge and C_A (see Scheme 2) is 0.55 Å. We completely remove the carbon skeleton of bicyclooctane but we fix the positions of Z and Y in the space. To cap the Z—Y moiety, we put a hydrogen atom at the C_B position. This capping method should not significantly alter the electronic demand of the Z—Y moiety because the electronegativity of H is close to that of C.

Next we perform a single-point energy calculation for the isolated H—Y—Z moiety using the UB3LYP/6–311++G(2df,p) method. This calculation does not involve any geometry re-optimization because the positions of H, Z and Y are fixed. We choose the CHelpG (charges from electrostatic potentials using a grid-based method) method developed by Breneman and Wiberg[28] to get the charge distribution of the isolated H—Y—Z moieties. In this method, atomic charges are fitted to reproduce the molecular electrostatic potential at a number of points around the molecule. It is clear that this method is the most ideal for calculating the classical electrostatic interactions.

The electrostatic interaction between the dipole and the H—Y—Z moiety is then calculated using the classical Coulombic theory

$$E = \frac{Q}{4\pi\varepsilon_0}\sum_i \frac{q_i}{d_{i+}} - \frac{Q}{4\pi\varepsilon_0}\sum_i \frac{q_i}{d_{i-}} \tag{4}$$

where i runs through all the atoms in H—Z—Y, q_i is the CHelpG charge at atom i in H—Z—Y, d_{i+} is the distance between the positive point charge in the dipole and atom i in H—Z—Y, and d_{i-} is the distance between the negative point charge in the dipole and atom i in H—Z—Y. To simplify the above equation, we define

$$\Phi_{\mathrm{Z-Y}} = \frac{1}{4\pi\varepsilon_0}\sum_i \frac{q_i}{d_{i+}} - \frac{1}{4\pi\varepsilon_0}\sum_i \frac{q_i}{d_{i-}} \tag{5}$$

(Detailed Φ values are listed in Table 4). Thus we have

$$E = Q\Phi_{\mathrm{Z-Y}} \tag{6}$$

Now let us consider the reaction described in Eqn (2) for the definition of ME. We are interested in how to get the ρ value for ME when Z and Y are fixed. Thus we need to obtain the dependence of $\Delta H_{\mathrm{Z-Y}}$ on X. It is clear that the energies of non-substituted bicyclooctane and bicyclooctanyl-Z–Y do not make any contribution to the dependence of $\Delta H_{\mathrm{Z-Y}}$ on X because these two energy values are not affected by X. What do make contributions are the energies of X-bicyclooctanyl-Z—Y and X-bicyclooctanyl-H. Using Eqn (6) we can derive

$$\mathrm{ME} = \Delta H_{\mathrm{Z-Y}} = Q_X(\Phi_H - \Phi_{\mathrm{Z-Y}}) + \mathrm{constant} \tag{7}$$

In Eqn (7) Q_X corresponds to the dipolar charge produced by substituent X and Φ_{H} corresponds to the electrostatic field effect caused by H.

Let us assume that the ME follows the Hammett-type relationship, i.e.

$$\mathrm{ME} = \Delta H_{\mathrm{Z-Y}} = \rho_{Z-Y}F_X + \mathrm{constant}' \tag{8}$$

Using the ME values of two different substituents (i.e. X_1 and X_2) we can derive

$$\rho_{\mathrm{Z-Y}}(F_{X_1} - F_{X_2}) = (Q_{X_1} - Q_{X_2})(\Phi_H - \Phi_{Z-Y}) \tag{9}$$

Because $\rho_{\mathrm{Z-Y}}$, Φ_H and $\Phi_{\mathrm{Z-Y}}$ are fixed values, we have

$$\frac{\rho_{\mathrm{Z-Y}}}{\Phi_H - \Phi_{\mathrm{Z-Y}}} = \frac{Q_{X_1} - Q_{X_2}}{F_{X_1} - F_{X_2}} = k \tag{10}$$

where k is a constant. It is clear that k should not depend on Z—Y, because Q_X and F_X are independent of Z—Y. It is also clear that k should not depend on X, because $\rho_{\mathrm{Z-Y}}$, Φ_H and $\Phi_{\mathrm{Z-Y}}$ are independent of X.

Because k is independent of Z—Y, we have

$$\rho_{\mathrm{Z-Y}} = k(\Phi_H - \Phi_{\mathrm{Z-Y}}) \tag{11}$$

With a similar treatment for RE, we can also derive

$$\rho_{\mathrm{Z}^{\cdot}} = k(\Phi_H - \Phi_{\mathrm{Z}^{\cdot}}) \tag{12}$$

Therefore, if we plot all the reaction constants (i.e. ρ values) of the MEs and REs against the corresponding $\Phi_{\mathrm{Z-Y}}$ or $\Phi_{\mathrm{Z}^{\cdot}}$ values, we should obtain a straight line whose slope and intercept are equal to $-k$ and $k\Phi_H$, respectively. Indeed, as shown in Fig. 6, all the ρ values do approximately fit in a line (i.e. $\rho_{\mathrm{Z-Y/Z}^{\cdot}} = -3.14\Phi_{\mathrm{Z-Y/Z}^{\cdot}} - 2.33$). The correlation is not perfect (correlation coefficient = 0.88) due to the following reasons: some ρ values are not obtained from perfect Hammett correlations (see Table 4); and use of H to cap the Z—Y moiety may introduce inaccurate descriptions

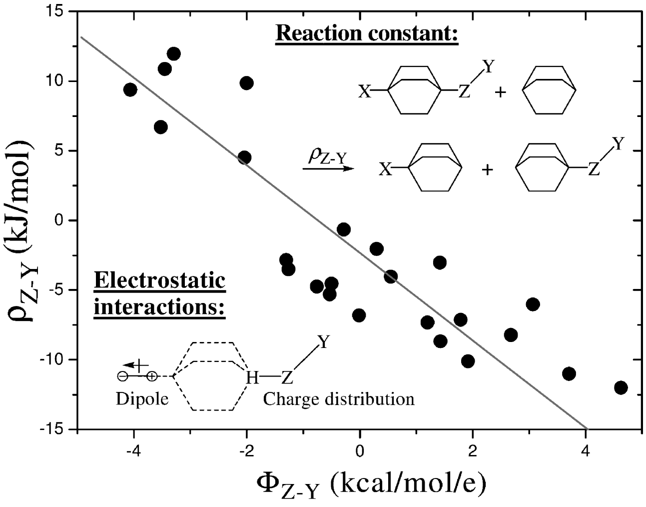


Figure 6. Correlations between the electrostatic interaction energies and the reaction constants (ρ) for the MEs and REs

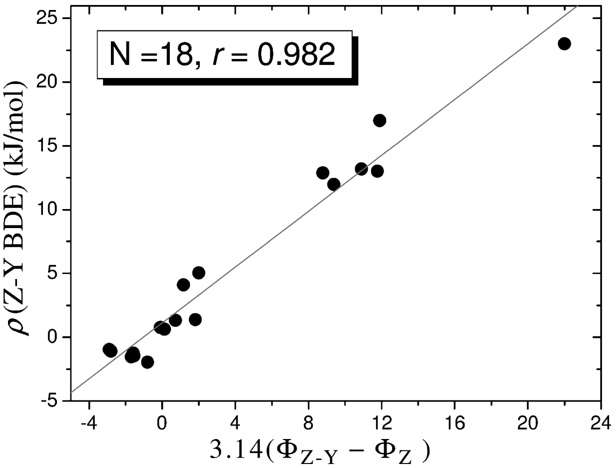


Figure 7. Correlations between the original ρ values listed in Table 3 and the values predicted by Eqn (13)

of the electrostatic effects. [We tried to use CH_3 to cap the Z—Y moiety, but this led to worse results. Using the CHelpG charges in the real X-bicyclooctanyl-Z—Y molecules also led to worse results because the local electrostatic field of C_B—Z—Y cannot be described by the CHelpG charges optimized for the electrostatic field of the whole molecule. Finally, we tried to use other charge distribution methods such as natural population analysis but this always led to worse results.]

Using the above results for ρ_{Z-Y} and $\rho_{Z\cdot}$, we now can predict the ρ values for the Z—Y BDEs. Because $\Delta BDE = ME—RE$, the ρ value for ΔBDE can be derived from the ρ values for ME and RE, i.e.

$$\begin{aligned}\rho(\mathrm{BDE}) &= \rho_{Z-Y} - \rho_{Z\cdot} = -k(\Phi_{Z-Y} - \Phi_{Z\cdot}) \\ &= 3.14(\Phi_{Z-Y} - \Phi_{Z\cdot})\end{aligned} \tag{13}$$

We show in Fig. 7 the correlation between the original ρ values listed in Table 3 and the values predicted by Eqn (13). For 18 different types of Z—Y bonds, our correlation coefficient is 0.982. It is clear that the prediction is fairly successful, and therefore the theoretical model we have developed correctly describes the inductive/field substituent effects on the homolytic bond dissociation energies.

CONCLUSIONS

In this study we investigated the inductive/field effects on the homolytic BDEs for the first time using substituted bicyclo[2.2.2]octane systems. A variety of very different chemical bonds, including Z—Y (Z = CH_2, NH, O, SiH_2, PH, S; Y = H, F, Li), were considered and several important conclusions can be made:

(i) High-quality BDE values are obtained for the first time for bicyclo[2.2.2]octane systems from calibrated G3B3/B3LYP calculations.

(ii) Significant effects of substituents at the 4-position of bicyclooctane are found for the Z—Y BDEs of bicyclooctanyl-Z—Y systems. Nice Hammett-type correlations can be obtained for these substituent effects using the inductive/field F constants.

(iii) The reaction constants (i.e. ρ values) of the Hammett correlations vary dramatically from -1.96 to $23.01\,\mathrm{kJ\,mol^{-1}}$ for different Z—Y systems: the ρ values for the Z—H BDEs are ~ 1.0–$5.0\,\mathrm{kJ\,mol^{-1}}$; the ρ values for the Z—F BDEs are about -2.0 to $-1.0\,\mathrm{kJ\,mol^{-1}}$; and the ρ values for the Z—Li BDEs are ~ 13.0–$23.0\,\mathrm{kJ\,mol^{-1}}$.

(iv) The substituent effects on the stability of the parent molecules before homolysis and the stability of the radical products after homolysis are important for the substituent effects on BDEs.

(v) The inductive/field substituent effects on BDEs cannot be explained by the electronegativity or bond polarity theories, but they can be explained successfully by a theoretical model on the basis of the classic electrostatic theories for inductive/field effects.

Supplementary material

Detailed relative bond dissociation energies and deprotonation enthalpies (PDF) are available in Wiley Interscience.

Acknowledgements

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