2 PERKIN

Substituent effects on the S–H bond dissociation energies of thiophenols †

Yao Fu, Bo-Lin Lin, Ke-Sheng Song, Lei Liu *‡ and Qing-Xiang Guo

Department of Chemistry, University of Science and Technology of China, Hefei 230026, P.R. China. E-mail: leiliu@chem.columbia.edu

Received (in Cambridge, UK) 28th January 2002, Accepted 30th April 2002

Density function UB3LYP/6-311++g(d,p) and perturbation theory ROMP2/6-311++g(d,p) calculations were performed on 4-substituted thiophenols and their corresponding radicals. It was found that although UB3LYP and ROMP2 methods underestimated the absolute S–H bond dissociation energies, they could predict almost as good relative S–H bond dissociation energies as a method of a considerably higher level, UCCSD(T)/6-311++g(d,p). From the calculation results it was determined that the S–H bond dissociation energies of thiophenols should have a positive correlation with the substituent σ_p^+ constants whose slope was *ca.* 2.5 kcal mol^{-1}. Such a slope indicated that the experimental S–H bond dissociation energies obtained from a previous solution phase measurement were reasonably accurate for *para* H, CH_3, OCH_3, Cl, and NO_2 substituted thiophenols. However, the solution phase bond dissociation energy for 4-aminothiophenol was too low, which was found by the calculation in this study to be caused by the hydrogen bonding between the amino group and the solvent molecules. Finally, through the studies on the isodesmic reactions it was found that the substituent effects on the stability of neutral thiophenols had a fair and positive correlation with the substituent σ_p^+ constants; the slope was 0.5 kcal mol^{-1}. On the other hand, the substituent effects on the stability of thiophenol radicals had an excellent and negative correlation with the substituent σ_p^+ constants and gave a slope of -1.8 kcal mol^{-1}. Therefore, the major source of the substituent effects on S–H bond dissociation energies of thiophenols was the stability of the homolysis products, namely, thiophenol radicals.

Introduction

The interesting chemistry of sulfur-centered radicals in diverse fields such as organic synthesis, biochemistry, and environmental science has attracted considerable attention recently.[1] For example, thiyl radicals derived from cysteine, homocysteine, and glutathione are directly involved in the mechanism of a number of enzymes such as pyruvate formate–lyase and ribonucleotide reductase, which are clearly important for normal biological functions.[2] On the other hand, unnecessary thiyl radicals in the body created by ultraviolet radiation or other oxidation pathways are able to abstract a hydrogen atom intra- or intermolecularly from the α-carbon center of peptide residues, which causes oxidative damage to proteins as implicated in numerous pathological disorders and the process of aging.[3]

The importance of thiyl radicals has stimulated researchers to study the thermochemistry of these species including the heats of formation and combustion, electron affinities, ionization potentials, and more importantly, homolytic bond dissociation energies.[4] Herein, the homolytic bond dissociation energy (BDE) of a chemical bond X–Y is defined as the gas-phase enthalpy change of following reaction, (1).

$$\text{X–Y} \longrightarrow \text{X}^{\bullet} + \text{Y}^{\bullet} \qquad (1)$$

It should be mentioned that the zero-point energy must be taken into consideration in the calculation of BDEs. Clearly, for thiyl radicals the most relevant BDE is that of the S–H bond.

However, it must be mentioned that direct measurement of BDEs in the gas phase is not a simple exercise. Usually, obtaining a single BDE datum requires considerably sophisticated experimental work. In addition, for those relatively large compounds which are hard to vaporize, gas-phase BDEs are even more difficult to obtain. Therefore, so far the experimental gas-phase S–H BDEs are only known for a limited number of small thiols such as H_2S, CH_3SH, and CH_3CH_2SH.

Since 1986, Bordwell and coworkers have developed a simple solution-phase method to determine the BDEs of the acidic H–A bonds in weak organic acids by measuring the equilibrium acidities (pK_a) and the oxidation potentials of the conjugate anions (ΔE_{ox}). Using a thermodynamic cycle and correlation with the gas-phase data, they were able to obtain an empirical equation relating the BDEs with the pK_a and ΔE_{ox} values.[5] This wonderful achievement makes it possible to fairly rapidly estimate the BDEs of a series of relatively large compounds such as substituted phenols, anilines, and thiophenols.[6,7] From such studies, the interesting remote substituent effects on the O–H, N–H, and S–H BDEs have been better understood.

Unfortunately, it has been found that sometimes the Bordwell method provides overestimated or underestimated BDEs for certain groups of compounds (*e.g.* phenols and anilines), usually because of the complication of the solvation effect in the measurement.[8] Such an overestimation or underestimation means that we should be cautious about the absolute BDEs from the solution-phase measurement. However, if the overestimation or underestimation is systematic we would still be able to use the solution-phase method to investigate the relative BDEs to each other in a closely related series of compounds. Clearly, such relative BDEs are often more important than the absolute BDE values. From relative BDEs, we could understand the substituent effects on the corresponding bond strength and thereby, radical stability.

---

† Electronic supplementary information (ESI) available: detailed results of the bond lengths, charge and spin distributions, and vibration frequencies. See http://www.rsc.org/suppdata/p2/b2/b201003h/

‡ *Present address*: Department of Chemistry, Columbia University, New York, NY 10027, USA.

DOI: 10.1039/b201003h

Nevertheless, it should be noted that so far it actually remains unclear whether the overestimation or underestimation of the solution-phase measurement of BDEs is indeed systematic. Therefore, it is highly recommended that the BDEs as well as the relative BDEs from the solution-phase measurement should be critically evaluated with other methods such as theoretical calculations. Indeed, this has been done, for instance, on the BDEs of substituted toluenes and phenols.[9] Generally, it was found that the calculated substituent effects on BDEs are in reasonable agreement with those found using solution-phase measurements.

In this paper we report our recent theoretical results on the S–H BDEs of *para*-substituted thiophenols. Such a study has only been conducted with semiempirical methods before.[10] Clearly, the major purpose of the present study is to evaluate the experimental results of the substituent effects on thiophenol BDEs; the origin of the substituent effects is also an interesting area.

Methods

All the calculations were performed with GAUSSIAN 98.[11] Geometry optimization was done at UB3LYP/6-31g(d) level without any constraint. The optimized structures were confirmed to be real minima by UB3LYP/6-31g(d) frequency calculations (no imaginary frequency).

Single-point energy calculations were done at the UB3LYP/6-31g(d), UB3LYP/6-311++g(d,p) and ROMP2/6-311++g(d,p) levels. It should be mentioned that such levels of methods represent a good compromise between the accuracy and CPU-cost of the calculation. Clearly, higher levels of methods such as CCSD(T), G3, or CBS-Q are not practical now for a systematic study of a number of di-substituted benzenes which individually has about ten heavy atoms. On the other hand, other similar levels of theoretical methods including UMP2 and PMP2 are known to be much less reliable in dealing with radical species because of the spin contamination.[12]

Bond dissociation energies were calculated as the enthalpy change of the reactions in (eqn. (2))at 298 K.

$$X–C_6H_4–SH \rightarrow X–C_6H_4–S^{\bullet} + H^{\bullet} \qquad (2)$$

The results were corrected with zero point energies and finite temperature (0–298 K) corrections calculated at the UB3LYP/6-31g(d) level scaled by 0.9806.[13]

Results and discussion

Geometry

Fig. 1 shows the UB3LYP/6-31g(d) optimized thiophenol and thiophenol radical and it can be seen that in thiophenol there is almost no C–C bond length alteration, because all the C–C bonds are about 1.394–1.400 Å long. In comparison, in the thiophenol radical the C–C bond length alternation is significant. In particular, the two C–C bonds adjacent to sulfur are about 1.420 Å long, which is *ca.* 0.020 Å longer than the corresponding bonds in thiophenol.

The C–H bond length in thiophenol is 1.087 Å, compared to the corresponding value in the thiophenol radical of 1.086 Å. The C–S bond length in thiophenol is 1.789 Å, which is considerably shortened after–S–H bond cleavage to 1.728 Å. Clearly, the contraction of the C–S bond should be caused by the stronger conjugation effect between the sulfur radical and the phenyl ring than that between the –SH group and phenyl ring. This stronger conjugation effect makes the C–S bond in the thiophenol radical have a considerable double-bond character.

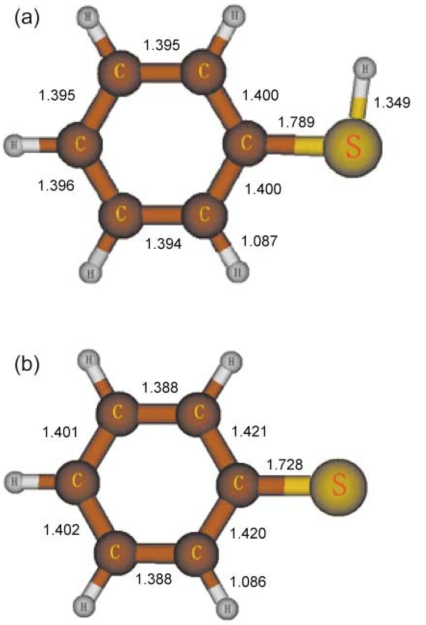

Fig. 1 The UB3LYP/6-31g(d) optimized geometry of (a) thiophenol and (b) thiophenol radical.

Given the fact that the C–S bond length changes the most from thiophenol to thiophenol radical, we collected the C–S bond lengths of all the *para* substituted thiophenols and thiophenol radicals optimized at the UB3LYP/6-31g(d) level (see the supplementary information †). It was found that the C–S bond is always significantly shortened after S–H bond cleavage due to the enhanced conjugation effect.

Interestingly, plotting the C–S bond lengths *versus* the substituent σ_p^+ constants give two straight lines as shown in Fig. 2. The correlation coefficients (r) are 0.92 and 0.94 respectively, indicating that both the correlations are fairly strong. Presumably, such correlations are caused by the fact that the C–S bond is polarized, sulfur being the negative end. Therefore, changing the electron demand of the substituent should affect the ionic bond character of the C–S bond and therefore, its length.

Nevertheless, the two straight lines have opposite slopes. Our tentative explanation for this interesting behavior is that in thiophenol the carbon atom should be better conjugated with the *para* substituent than the sulfur atom. Consequently, an electron-withdrawing group would remove more electron density from the carbon than from the sulfur. In the C–S bond carbon is the positive end of the polarity, removing more electron density from the carbon than from the sulfur means that the ionic bond character of the C–S bond is actually enhanced, resulting in contraction of the C–S bond. On the other hand, an electron-donating substituent should supply more electron density to the carbon than to the sulfur, which would weaken the ionic character of the C–S bond and thereby, lengthen the C–S bond. Clearly, the above effects should lead to the negative slope observed for thiophenols.

In comparison, in the thiophenol radicals it would be expected that the sulfur atom in the C–S bond should be better conjugated with the *para* substituents than the carbon atom. As a result, an electron-withdrawing substituent would remove more electron density from the sulfur than from carbon, weakening the C–S ionic character and thereby, elongating its length. An electron-donating group, on the other hand, does the opposite and therefore, shortens the C–S bond.

Bond dissociation energies

Table 1 summarizes the experimental and theoretical S–H BDEs of a number of *para*-substituted thiophenols. It is worth mentioning that the experimental measurements were conducted using the Bordwell solution-phase method in DMSO.[7]

Table 1 Experimental and theoretical S–H BDEs of substituted thiophenols (values given in kcal mol^{-1})

X	Exp.[a]	UB3LYP/6-31g(d)	UB3LYP/6-311++g(d,p)	ROMP2/6-311++g(d,p)
H	79.1	73.8	76.0	75.5
CH_3	78.3	72.8	74.8	74.7
$N(CH_3)_2$	—	68.1	70.3	72.7
NH_2	69.8	68.9	71.2	73.1
OCH_3	76.9	70.3	72.5	73.2
OH	—	70.5	72.9	73.5
SCH_3	—	71.0	72.9	73.9
F	—	72.6	75.0	74.7
Cl	79.2	73.6	75.5	75.1
CN	—	75.6	77.7	76.6
$COCH_3$	—	75.3	77.4	76.3
$SOCH_3$	—	74.5	76.7	76.0
COOH	—	75.7	77.9	76.5
NO_2	81.4	77.2	79.5	77.5
CF_3	—	75.5	77.9	76.8

[a] Taken from ref. 7.

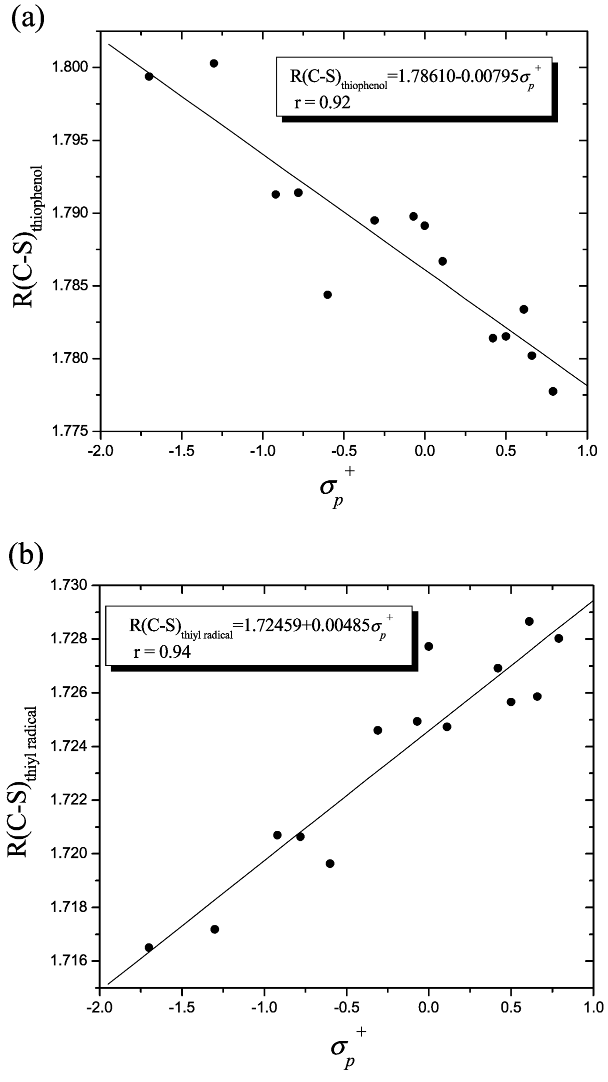

Fig. 2 Dependence of the C–S bond lengths of *para*-substituted (a) thiophenols and (b) thiophenol radicals on the substituent σ_p^+ constants.

From Table 1, it can be seen that all the theoretical methods predict smaller S–H BDEs than the experiment values. The reason for this disagreement might be that the experimental values are overestimated. However, from many former studies it has been shown that the UB3LYP and ROMP2 methods tend to underestimate the BDEs regardless of the basis sets being used.[9,12] Therefore, with UB3LYP and ROMP2 methods we cannot evaluate the accuracy of the experimentally measured absolute S–H BDEs.

Nevertheless, it should be mentioned that we are most concerned with the substituent effects on the S–H BDEs. Therefore, the calculated absolute BDEs are less important. However, from many studies it has been shown that the error in the calculated BDEs by a certain theoretical method is highly systematic in nature. As a consequence, if we calculate the relative bond dissociation energies (ΔBDE) according to the following eqn. (3),

$$\Delta BDE(S\text{–}H)_X = BDE(X\text{–}C_6H_4\text{–}SH) - BDE(C_6H_5\text{–}SH) \quad (3)$$

the corresponding results are expected to be fairly accurate. In addition, corrections for the S–H BDEs of all the substituted thiophenols using only one known experimental BDE value and theoretical ΔBDEs can be made.

In Table 2 are listed the ΔBDEs calculated at UB3LYP/6-31g(d), UB3LYP/6-311++g(d,p) and ROMP2/6-311++g(d,p) levels together with the experimental ΔBDEs.

From Table 2, it can be seen that generally ΔBDEs calculated with different theoretical methods are qualitatively in agreement with each other. In particular, UB3LYP/6-31g(d) and UB3LYP/6-311++g(d,p) methods almost predict identical magnitudes of ΔBDEs, as the largest difference between their results is only 0.3 kcal mol^{-1}. This finding is in agreement with the general opinion that the basis set effects on B3LYP calculations are fairly small. Nevertheless, it is clear that the UB3LYP method always predicts a larger magnitude of ΔBDE than ROMP2/6-311++g(d,p).

In order to find out which method tends to give a better magnitude of ΔBDE between UB3LYP and ROMP2, we performed UCCSD(T)/6-311++g(d,p) calculations on a number of relatively small thiols as listed in Table 3. This high level of calculation has been shown to be able to predict fairly accurate ΔBDE[12] and therefore, we used its results to evaluate the performances of UB3LYP and ROMP2.

According to Table 3, the ROMP2/6-311++g(d,p) and UB3LYP/6-311++g(d,p) BDEs are in good agreement with the UCCSD(T)/6-311++g(d,p) values. Plotting the former two groups of BDEs *versus* the latter gives two straight lines as shown in Fig. 3. From Fig. 3, it is clear that both the ROMP2 and UB3LYP BDEs correlate excellently with the UCCSD(T) value ($r > 0.995$). This observation clearly validates the assumption that a relatively cheap theoretical method can be used to study the relative bond dissociation energies among a series of closely related compounds.

The intercepts of the regressions show that the UB3LYP method (intercept = −12.9 kcal mol^{-1}) underestimates the S–H BDE more than the ROMP2 method (intercept = −4.8 kcal

Table 2 Relative bond dissociation energies of substituted thiophenols (values given in kcal mol^{-1})

X	Exp.[a]	UB3LYP/6-31g(d)	UB3LYP/6-311++g(d,p)	ROMP2/6-311++g(d,p)
H	0.0	0.0	0.0	0.0
CH_3	−0.8	−1.0	−1.2	−0.8
$N(CH_3)_2$	—	−5.7	−5.7	−2.8
NH_2	−9.3	−4.9	−4.8	−2.4
OCH_3	−2.2	−3.5	−3.5	−2.3
OH	—	−3.3	−3.1	−2.0
SCH_3	—	−2.8	−3.1	−1.6
F	—	−1.2	−1.0	−0.8
Cl	0.1	−0.2	−0.5	−0.4
CN	—	1.8	1.7	1.1
$COCH_3$	—	1.5	1.4	0.8
$SOCH_3$	—	0.7	0.7	0.5
COOH	—	1.9	1.9	1.0
NO_2	2.3	3.4	3.5	2.0
CF_3	—	1.7	1.9	1.3

[a] Taken from ref. 7.

Table 3 S–H BDEs of relatively small compounds calculated at different levels of methods (values in kcal mol^{-1})[a]

XS–H	UB3LYP/6-311++g(d,p)	ROMP2/6-311++g(d,p)	UCCSD(T)/6-311++g(d,p)
HS–H	86.9	83.1	85.0
CH_3–S–H	82.4	80.1	81.9
NH_2–S–H	65.4	64.0	67.1
HO–S–H	72.7	70.5	72.7
F–S–H	79.1	76.0	78.4
SH–S–H	69.6	69.1	70.5
Cl–S–H	77.6	75.8	77.6

[a] All the geometry optimization are done at the UB3LYP/6-31g(d) level. The final BDEs are corrected with the zero point energies calculated at the UB3LYP/6-31g(d) level scaled by 0.9806.

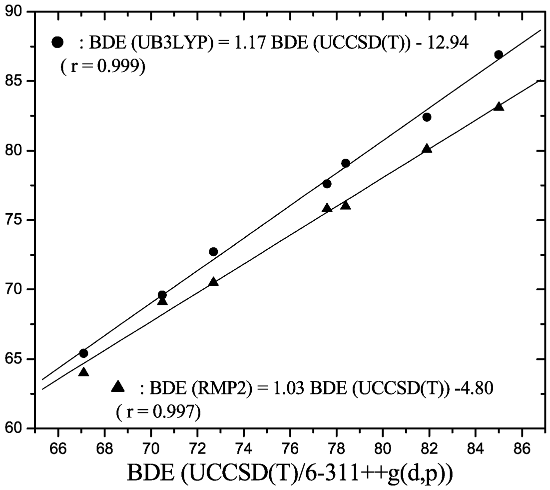

Fig. 3 The correlation between the BDEs calculated by UB3LYP/6-311++g(d,p), ROMP2/6-311++g(d,p), and UCCSD(T)/6-311++g(d,p) methods for a few relatively small thiols including H–SH, CH_3–SH, NH_2–SH, HO–SH, F–SH, HS–SH and Cl–SH.

mol^{-1}). Similar behavior was also observed in a recent study of the bond dissociation energies of simple sulfur-containing molecules.[14] The slopes of the regressions show that UB3LYP (slope = 1.17) overestimates the magnitude of ΔBDE more than ROMP2 (slope = 1.03). Therefore, it can be concluded that ROMP2 is better than UB3LYP at predicting the relative S–H bond dissociation energies. A similar conclusion was also made in a recent study of the H BDEs of a number of substituted methanes.[12]

Substituent effects on S–H BDEs

In Fig. 4 are plots of the ΔBDEs calculated at the UB3LYP/6-311++g(d,p) and ROMP2/6-311++g(d,p) levels *versus* the substituent σ_p^+ constants. Clearly, in these two plots the regressions are fairly good because both the correlation coefficients are over 0.97.

The slopes of the regressions reflect the substituent effects on the BDEs. According to UB3LYP/6-311++g(d,p) calculations, this slope should be 3.5 kcal mol^{-1} but according to ROMP2/6-311++g(d,p), this slope is 1.9 kcal mol^{-1}. It should be mentioned that from Fig. 4(b), it can be seen that the ΔBDEs corresponding to two groups, *i.e.* NH_2 and NMe_2, significantly deviate from the general trend. If we do not include them in the regression analysis, the slope for the ROMP2/6-311++g(d,p) BDEs is 2.3 kcal mol^{-1} ($r = 0.98$).

The experimental slope is 2.8 kcal mol^{-1} according to the BDEs of five thiophenols (*para* H, CH_3, OCH_3, Cl, and NO_2 substituted).[7,15] Therefore, the ROMP2 result agrees with the experimental value better than UB3LYP calculation. In addition, according to a former study using semiempirical methods on six thiophenols, the slope of UPM3 S–H BDEs is 2.0, the RPM3 slope is 2.1, the UAM1 slope is 2.3 and the RAM1 slope is 3.2 kcal mol^{-1}.[10]

Therefore, from all the above results it can be concluded that the slope of the substituent effects on the S–H BDE should be around 2.5 kcal mol^{-1}. This value was compared to the 7.3 kcal mol^{-1} found for the slope of *para* substituent effects on the O–H BDEs of phenols against the σ_p^+ constants.[6] The slope of *para* substituent effects on the N–H BDEs of anilines against the σ_p^+ constants was also reported to be 5.5 kcal mol^{-1}.[6] Given the fact that sulfur (2.5) has a smaller electronegativity than oxygen (3.5) and nitrogen (3.0), the smaller slope (~2.5 kcal mol^{-1}) found for the S–H BDEs of thiophenols is reasonable.

Detailed comparison of the theoretical results with the experimental ones also shows that ROMP2/6-311++g(d,p) is better than UB3LYP/6-311++g(d,p) in predicting the relative bond dissociation energies. For example, the *para* CH_3 substitution was found experimentally to reduce the thiophenol S–H BDE by as much as 0.8 kcal mol^{-1}. In comparison, the ROMP2

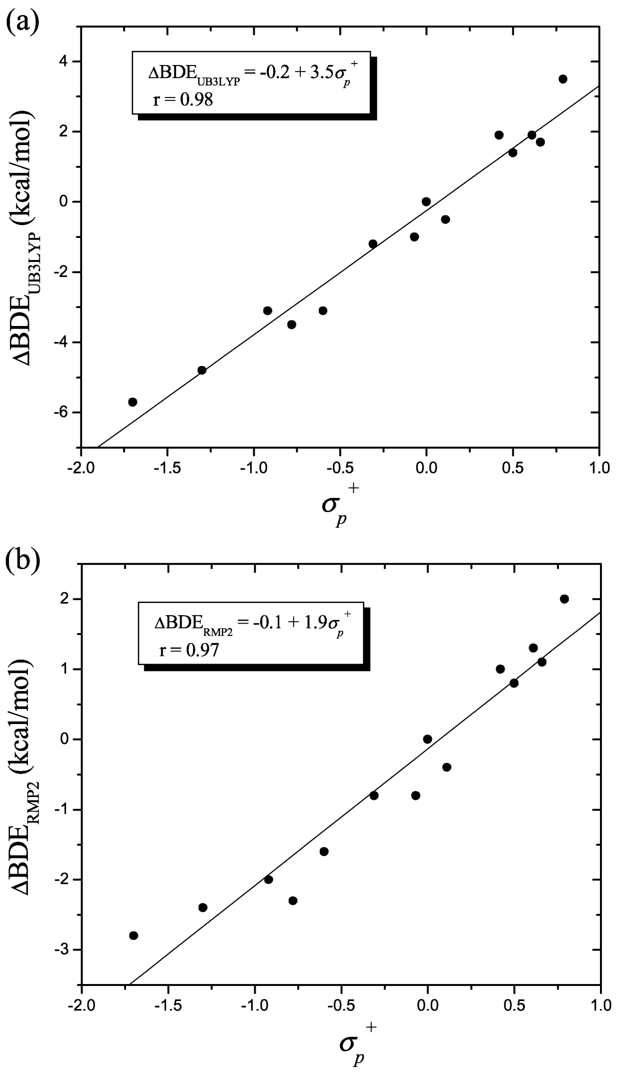

Fig. 4 Dependence of the ΔBDEs calculated at (a) UB3LYP/6-311++g(d,p) and (b) ROMP2/6-311++g(d,p) levels on the substituent σ_p^+ constants.

calculation predicts a reduction of 0.8 kcal mol^{-1}, while UB3LYP predicts a reduction of 1.2 kcal mol^{-1}.

From experimental studies, OCH_3 should reduce the S–H BDE by as much as 2.2 kcal mol^{-1}. This value was compared to the ROMP2 prediction, 2.3 kcal mol^{-1}, and the UB3LYP prediction, 3.5 kcal mol^{-1}. Also, NO_2 was found experimentally to increase the S–H BDE by 2.3 kcal mol^{-1}. This value was compared to the ROMP2 prediction of 2.0 kcal mol^{-1} and the UB3LYP prediction of 3.5 kcal mol^{-1}.

Both ROMP2 and UB3LY levels predict that Cl substitution should lower the S–H BDE by *ca.* 0.4–0.5 kcal mol^{-1} which contrasts with the experimental observation that Cl increases the S–H BDE by 0.1 kcal mol^{-1}. We believe that such a magnitude of inconsistency is not serious if we notice the unavoidable errors of the experiment and calculation.

Nevertheless, it must be mentioned that there is disagreement between the theory and experimental values for the substituent effect of NH_2 on the S–H BDE. According to the experimental value, NH_2 should reduce the S–H BDE by 9.3 kcal mol^{-1}. On the contrary, the UB3LYP/6-311++g(d,p) method only predicts a reduction of 4.8 kcal mol^{-1}, whereas ROMP2 predicts an even smaller reduction of 2.4 kcal mol^{-1}. The difference of at least 4.5 kcal mol^{-1} between theory and experiment does not seem to come from the experimental or computational errors. Instead, we believe that it is caused by the solvent–solute hydrogen bonding effect on the NH_2 substituted thiophenol and thiophenol radical.

To support our proposal, we used the UB3LYP/6-31g(d) method to optimize the noncovalent molecular complex between 4-aminothiophenol (or its radical) and the solvent molecule used in the original experiment, *i.e.* DMSO. We only considered the hydrogen bonding between the NH_2 proton and the DMSO oxygen, so that the results should not be considered to be able to account for all the actual solvent–solute interactions. Nevertheless, the essential physical origin of the peculiar experimental BDE can be revealed from such a model study.

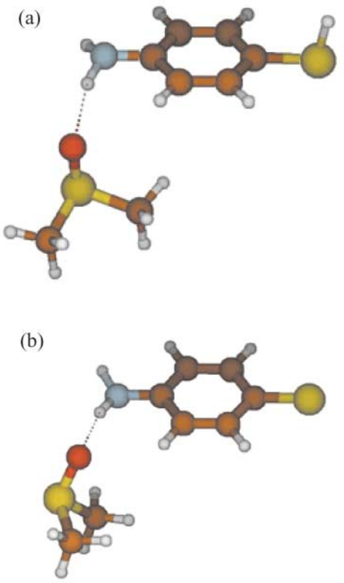

Fig. 5 UB3LYP/6-31g(d) optimized structures of the hydrogen-bonded complexes between DMSO and (a) 4-aminothiophenol and (b) the 4-aminothiophenol radical.

In Fig. 5 are shown the optimized structures of the complexes. The interaction energies of the two complexes are calculated using the UB3LYP/6-311++g(d,p) method as the difference between the total energy of the complex and the sum of those of the monomers. These interaction energies are corrected with the zero-point energies calculated at the UB3LYP/6-31g(d) level scaled by 0.9806. They are also corrected with the basis set superposition errors (BSSE) calculated using the standard Boys–Bernardi procedure.[16] Interestingly, from the calculations it was found that the 4-aminothiophenol radical ($\Delta E = -6.5$ kcal mol^{-1}) should interact with DMSO significantly more strongly than 4-aminothiophenol ($\Delta E = -4.8$ kcal mol^{-1}) through the hydrogen bonding between the NH_2 proton and the DMSO oxygen. The energetic difference between the two hydrogen bonds, *i.e.* 1.7 kcal mol^{-1}, although not being as large as that between the theoretical and experimental BDEs, is not a trivial value. Presumably, this energy difference is caused by the fact that the sulfur radical is more electron-deficient than the S–H group.

Therefore, the much lower ΔBDE found by experiment is actually caused by the stronger solute–solvent interaction of the thiol radical rather than that of the neutral thiol. Because not every thiophenol contains the amino group, the BDE lowering effect of such an interaction cannot be regarded as a systematic error at all. Clearly, this means that the BDE results from the solution-phase experimental measurement should be handled with considerable caution.

It should be mentioned that the theoretical BDEs should also be cautiously handled. This can be easily seen from the large difference between the ROMP2 (−2.4 kcal mol^{-1}) and UB3LYP ΔBDE (−4.8 kcal mol^{-1}) values for 4-aminothiophenol. Here, although we expected that the UB3LYP method to overestimate the value, the ROMP2 result cannot be accurate either.

In fact, the ROMP2 ΔBDE for NMe_2 and NH_2 groups deviate significantly from the general trend shown in Fig. 4.

Spin and charge distributions

We collected the Mulliken charge and spin density of the carbon and sulfur atoms in the C–S bonds of the thiophenols and thiophenol radicals calculated by the ROMP2/6-311++g(d,p) method (see the supplementary information†). From these results, we found that in the thiophenols and thiophenol radicals both the carbon and sulfur atoms of the C–S bonds carry negative charges. This observation does not contradict the previous assumption in this paper that the C–S bond is polarized with the carbon atom as the positive end and the sulfur as the negative end, because the charges here are net ones. Nevertheless, as these net charges are dependent not only on the C–S bond but also on the C–C and S–H bonds, there is no simple way to interpret the charges. Indeed, correlations between the charges and the substituent σ_p^+ constants are mostly very poor ($r < 0.80$).

The only good correlation is that found between the charges at the sulfur atom in the thiophenol radicals and the substituent σ_p^+ constants (eqn. (4)).

$$\text{Charge at S in thiophenol radicals} = -0.06947 + 0.05256\sigma_p^+ \ (r = 0.98) \quad (4)$$

Such a good correlation is clearly related to the fact that in the thiophenol radicals sulfur should be directly conjugated to the *para* substituents. According to eqn. (4) an electron-withdrawing *para* substituent makes the sulfur carry less negative charge whereas an electron-donating one does the opposite.

The spin density at sulfur also has an appreciable correlation with the substituent σ_p^+ constants, although the correlation coefficient is quite low ($r = 0.86$). It is expected that the so-called spin-delocalization effect should also contribute to the pattern of spin distribution.[13b] Such an effect is the most significant in the *para* substituted $X–C_6H_4–CH_2^•$ radicals, where both the π-donor and π-acceptor substituents are found to reduce the spin at the benzyllic carbon effectively. To account for this effect, a number of scales of spin-delocalization (or sigma-dot, $\sigma^•$) substituent constants have also been established, among which the Jiang's σ_{JJ} scale is a typical one. Basically, except for F and CF_3 almost all the substituents were found to have positive spin-delocalization constants because they can delocalize the spin of a carbon radical to various extents.

In connection with the present study, we find that the spin density at sulfur indeed has an undeniable correlation with the substituent σ_{JJ} constants. However, the corresponding correlation coefficient is very low ($r = -0.61$). Therefore, we conducted the dual-parameter correlation for the spin density at sulfur using both the σ_p^+ and σ_{JJ} constants as variables. The result is shown in the eqn. (5).

$$\text{Spin at sulfur} = 0.77678 + 0.04363\sigma_p^+ - 0.0488\sigma_{JJ} \ (r = 0.90) \quad (5)$$

According to the above equation, the spin at sulfur should be increased by an electron-withdrawing group or reduced by an electron-donating group because the coefficient ahead of σ_p^+ is positive. Since a reduction of the spin at S should lead to a more stable radical, the positive coefficient ahead of σ_p^+ clearly means that the S–H homolysis should be become easier with an electron-donating substituent but harder with an electron-withdrawing group. Indeed, this is what has been observed.

On the other hand, the negative coefficient ahead of σ_{JJ} indicates that both the π-donor and π-acceptor substituents would reduce the spin at sulfur if all the other effects were the same. Clearly, this is exactly what the spin delocalization effect should mean.

Table 4 The ground (GE) and radical (RE) effects calculated at the ROMP2/6-311++g(d,p) level for substituted thiophenols (values in kcal mol^{-1})

X	GE	RE
H	0.0	0.0
CH_3	0.0	0.7
$N(CH_3)_2$	0.6	3.4
NH_2	0.2	2.4
OCH_3	−0.6	1.7
OH	−0.8	1.1
SCH_3	−0.1	1.5
F	−1.0	−0.2
Cl	−0.4	0.0
CN	0.0	−1.1
$COCH_3$	0.5	−0.3
$SOCH_3$	0.0	−0.4
COOH	0.4	−0.7
NO_2	0.3	−1.6
CF_3	0.0	−1.3

Origin of the substituent effects on bond dissociation energies

Magnitudes of BDEs are clearly related to the stabilities of both the starting materials and products of the bond homolysis. Therefore, we evaluated the *para* substituent effects on the stabilities of the thiophenol and thiophenol radical using the energy changes of the following isodesmic equations.

$$\text{Ground effect (GE): } X–C_6H_4–SH + C_6H_6 \longrightarrow C_6H_5–SH + X–C_6H_5 \quad (6)$$

$$\text{Radical effect (RE): } X–C_6H_4–S^• + C_6H_6 \longrightarrow C_6H_5–S^• + X–C_6H_5 \quad (7)$$

We call the energy change of the reaction depicted by eqn. (6) the ground effect because this energy change shows how the substituent × is going to stabilize the –SH group. In comparison, we call the energy change of the reaction depicted by eqn. (7) the radical effect because this energy change shows how the substituent X is going to stabilize the thiyl radical.[17] Clearly, ΔBDE is equal to the difference between the energy changes of eqns. (6) and (7).

In Table 4 are listed the GEs and REs calculated at the ROMP2/6-311++g(d,p) level. Plotting GE and RE values against the substituent σ_p^+ constants gave two straight lines as shown in Fig. 6. According to Fig. 6, the GEs do not have a good correlation with the substituent σ_p^+ constants; in particular, the GE values for two substituents, *i.e.* NMe_2 and NH_2, deviate markedly from the general trend. The reason for such deviations remains to be clarified later in this paper. Nevertheless, it can be seen from Fig. 6 that the GEs have a positive slope in the regression analysis (0.5 kcal mol^{-1}). This means that an electron-withdrawing group should favor $X–C_6H_4–SH$ in energy, presumably because in the C–S–H connection the net dipole moment should be pointing from H (electronegativity is 2.1) to C (electronegativity is 2.5). On the other hand, an electron-donating group should disfavor $X–C_6H_4–SH$ because it creates a local dipole moment anti-parallel to the C–S–H dipole when it is connected to the phenyl ring.

Contrary to the GE case, the REs have an excellent correlation with the substituent σ_p^+ constants ($r = -0.98$). The negative slope (−1.8 kcal mol^{-1}) is clearly related to the fact that in the C–S connection the local dipole moment must be pointing from C to S. Interestingly, it has been mentioned in this paper before that ROMP2/6-311++g(d,p) predicts a slope of 2.3 kcal mol^{-1} for the substituent effects on S–H BDEs. This number exactly equals the difference between the slopes for GEs (0.5 kcal mol^{-1}) and REs (−1.8 kcal mol^{-1}). Therefore,

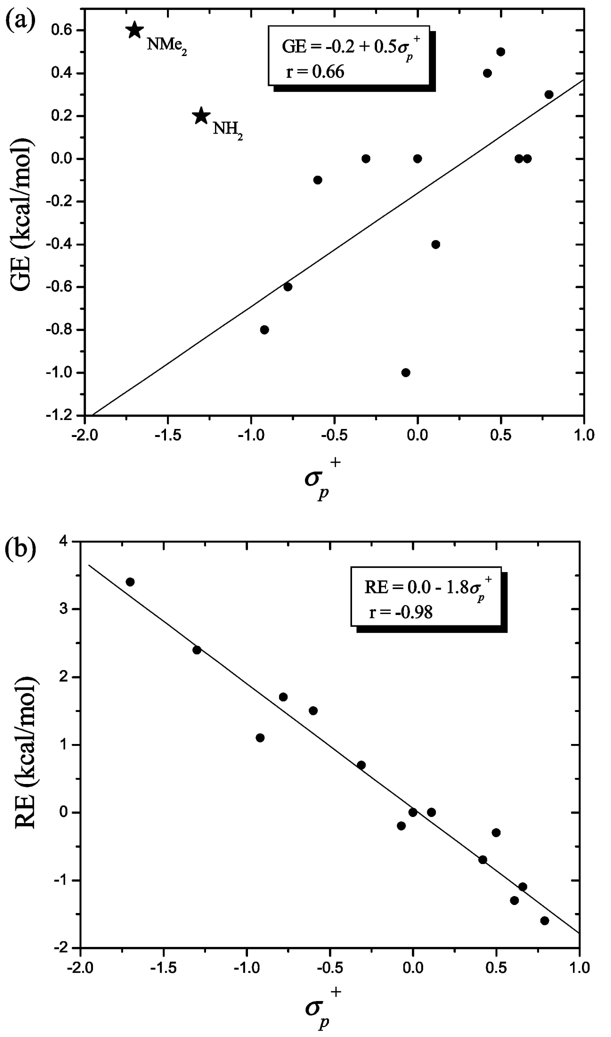

Fig. 6 Correlation of the (a) GEs and (b) REs values with the substituent σ_p^+ constants; in the correlation of GEs, the values for NMe_2 and NH_2 groups are not used because they deviate markedly from the general trend.

both the direct BDE-σ_p^+ and GE–RE analyses provide the same prediction for substituent effects.

Nevertheless, the GE–RE analysis reveals one more important aspect of the substituent effects on S–H BDEs, which is that the REs play a more important role than the GEs in dictating the net substituent effects on BDEs. This is not only shown by the better correlation of REs than GEs with the substituent σ_p^+ constants, but also the larger absolute slope of REs than GEs in the regression analysis.

Vibration frequencies

The C–S and S–H vibration frequencies are experimentally accessible quantities. Therefore, we calculated them using the UB3LYP/6-31g(d) method (see supplementary information†). The results revealed that the S–H vibration frequencies in the thiophenols are about 2700 cm^{-1}. However, it was found that the S–H vibration frequencies do not have any simple correlation with the substituent properties. Although it has been proposed before that the X–Y vibration frequency may correlate with its BDE for certain groups of compounds,[18] we find that such an empirical relationship cannot be applied to the S–H homolysis at all. In other words, there is no clear correlation between the S–H vibration frequencies and BDEs for the substituted thiophenols.

Nevertheless, it is found that the S–H vibration frequencies of 4-aminothiophenol (2636.6 cm^{-1}) and 4-(*N*,*N*-dimethylamino)thiophenol (2632.2 cm^{-1}) are about 75 cm^{-1} lower than the S–H vibration frequency of any other thiophenol. Detailed examination of the structures of all the thiophenols reveal that except for the two amino cases, all the thiophenols have their S–H moiety placed in the phenyl plane (Fig. 7). By contrast, in the two amino cases the S–H bond is actually perpendicular to the phenyl plane. Clearly, such differences in the S–H orientation must be related to different hyperconjugation effects of the amino groups *versus* that of the other substituents.

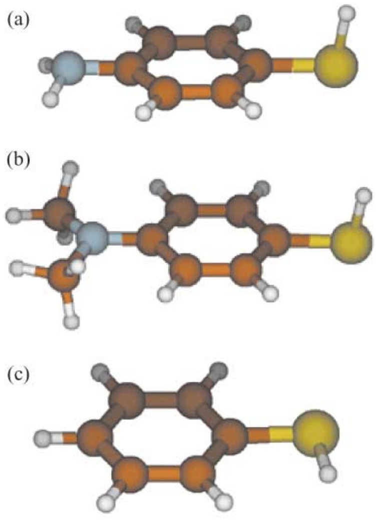

Fig. 7 The UB3LYP/6-31g(d) optimized geometry of (a) 4-nitrothiophenol, (b) 4-dimethylaminothiophenol and (c) thiophenol.

The different orientations of the S–H bond also explain the peculiar observations previously mentioned in this paper. These peculiar observations include the deviation of the ROMP2/6-311++g(d,p) ΔBDEs for 4-aminothiophenol and 4-(*N*,*N*-dimethylamino)thiophenol from the general trend. They also include the unexpectedly too high ground effect values found for 4-aminothiophenol and 4-(*N*,*N*-dimethylamino)thiophenol. Therefore, the S–H orientation is important for the studies on thiols, and further detailed study about the conformations of thiols is still needed.

The C–S vibration frequencies in thiophenols are about 1120 cm^{-1} and they do not exhibit any clear relationship with the substituent properties either. In comparison, the C–S vibration frequencies in the thiophenol radicals are around 1080 cm^{-1}, which are about 40 cm^{-1} lower than $\nu_{C\text{–}S}$ in thiophenols because of the C–S contraction in the radicals as observed previously in this paper. Interestingly, the C–S vibration frequencies in thiophenol radicals display good correlation with the substituent σ_p^+ constants eqn (8).

$$\nu_{C\text{–}S} = 1078.5 - 16.4\sigma_p^+ \ (r = -0.94) \qquad (8)$$

The negative slope means that an electron-withdrawing group weakens the C–S bond whereas an electron-donating group strengthens it.

Conclusion

In the present study, we performed density function and perturbation theory calculations on a number of 4-substituted thiophenols and their corresponding radicals. The geometry changes, bond dissociation energies, spin and charge distributions, and vibration properties associated with the thiophenol homolysis were obtained. From these data, we find that:

(1) The C–S bond length of thiophenol has a negative correlation with the substituent σ_p^+ constant, whereas the C–S bond length of the thiophenol radical has a positive correlation with the substituent σ_p^+ constant.

(2) The UB3LYP and ROMP2 methods underestimate the S–H bond dissociation energies so that they cannot be used to evaluate the accuracy of the absolute bond dissociation energies obtained experimentally. However, these two methods can predict almost as good relative bond dissociation energies as a much higher level of method, namely, UCCSD(T). In addition, ROMP2 is found to be better than UB3LYP in predicting the relatively bond dissociation energies.

(3) The S–H bond dissociation energies of thiophenols have a positive correlation with the substituent σ_p^+ constants; the slope is concluded to be *ca.* 2.5 kcal mol^{-1}.

(4) The experimental S–H bond dissociation energies obtained from solution phase measurements are found to be reasonably accurate for *para* H, CH_3, OCH_3, Cl, and NO_2 substituted thiophenols. However, the solution phase bond dissociation energy for 4-aminothiophenol is complicated by the hydrogen bonding between the amino group and the solvent molecules.

(5) The substituent effects on the stability of neutral thiophenols have a fair and positive correlation with the substituent σ_p^+ constants; the slope is 0.5 kcal mol^{-1}. On the other hand, the substituent effects on the stability of thiophenol radicals have an excellent and negative correlation with the substituent σ_p^+ constants. The slope is -1.8 kcal mol^{-1}. Therefore, the major source of the substituent effects on S–H bond dissociation energies is the stability of the homolysis products, namely, thiophenol radicals.

Acknowledgements

We are grateful to the NSFC for financial support.

References

1 For excellent reviews about the sulfur-radicals see: *S-centered radicals*, ed. Z. B. Alfassi, John Wiley, Chichester, 1999.

2 (*a*) A. Graslund and M. Sahlin, *Ann. Rev. Biophys. Biomol. Struct.*, 1996, **25**, 259; (*b*) C. Parast, K. K. Wong and J. W. Kozarich, *Biochemistry*, 1995, **34**, 5712.

3 (*a*) A. Rauk, D. Yu and D. A. Armstrong, *J. Am. Chem. Soc.*, 1998, **120**, 8848; (*b*) A. Rauk, D. A. Armstrong and D. P. Fairlie, *J. Am. Chem. Soc.*, 2000, **122**, 9761.

4 A. G. Larsen, A. H. Holm, M. Roberson and K. Daasbjerg, *J. Am. Chem. Soc.*, 2001, **123**, 1723.

5 (*a*) F. G. Bordwell and M. J. Bausch, *J. Am. Chem. Soc.*, 1986, **108**, 1979; (*b*) F. G. Bordwell and X.-M. Zhang, *Acc. Chem. Res.*, 1993, **26**, 510; (*c*) Y.-Y. Zhao, F. G. Bordwell, J.-P. Cheng and D.-F. Wang, *J. Am. Chem. Soc.*, 1997, **119**, 9125; (*d*) J.-M. Lu, X.-Q. Zhu, Q. Li, J.-Q. He, M. Xian and J.-P. Cheng, *Chem. J. Chin. Univ.*, 2000, **21**, 570.

6 (*a*) F. G. Bordwell and J.-P. Cheng, *J. Am. Chem. Soc.*, 1991, **113**, 1736; (*b*) F. G. Bordwell, X.-M. Zhang and J.-P. Cheng, *J. Org. Chem.*, 1993, **58**, 6410.

7 F. G. Bordwell, X.-M. Zhang, A. V. Satish and J.-P. Cheng, *J. Am. Chem. Soc.*, 1994, **116**, 6605.

8 L. J. J. Laarhoven, P. Mulder and D. D. M. Wayner, *Acc. Chem. Res.*, 1999, **32**, 342.

9 For recent examples, see: (*a*) T. Fox and P. A. Kollman, *J. Phys. Chem.*, 1996, **100**, 2950; (*b*) Y.-D. Wu, C.-L. Wong, K. W. K. Chan, G.-Z. Ji and X.-K. Jiang, *J. Org. Chem.*, 1996, **61**, 746; (*c*) Y.-D. Wu and D. K. W. Lai, *J. Org. Chem.*, 1996, **61**, 7904; (*d*) T. Brinck, M. Haeberlein and M. Jonsson, *J. Am. Chem. Soc.*, 1997, **119**, 4239; (*e*) D. A. Pratt, J. S. Wright and K. U. Ingold, *J. Am. Chem. Soc.*, 1999, **121**, 4877; (*f*) J. S. Wright, E. R. Johnson and G. A. DiLabio, *J. Am. Chem. Soc.*, 2001, **123**, 1173; (*g*) D. A. Pratt, M. I. de Heer, P. Mulder and K. U. Ingold, *J. Am. Chem. Soc.*, 2001, **123**, 5518.

10 M. Jonsson, J. Lind, G. Merenyi and T. E. Eriksen, *J. Chem. Soc., Perkin Trans. 2*, 1994, 2149.

11 Gaussian 98, Revision A. 7, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, Jr., R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, A. G. Baboul, B. B. Stefanov, G. Liu A. Liashenko P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, J. L. Andres, C. Gonzalez, M. Head-Gordon, E. S. Replogle and J. A. Pople, Gaussian, Inc., Pittsburgh, PA, 1998.

12 (*a*) C. J. Parkinson, P. M. Mayer and L. Radom, *J. Chem. Soc., Perkin Trans. 2*, 1999, 2305; (*b*) D. J. Henry, C. J. Parkinson, P. M. Mayer and L. Radom, *J. Phys. Chem. A.*, 2001, **105**, 6750; (*c*) it should be noted that there are problems associated with the use of $\langle s^2 \rangle$ in the density function theory methods. On one hand, use of ROMP2 may result in an unrealistic spin distribution and therefore the results from the DFT and ROMP2 calculations must be treated with caution. The use of two or more different methods for the computation on open-shell systems is highly recommended to minimize the chance of obtaining an erratic result. For more details, see: J. F. Stanton, *J. Chem. Phys.*, 1994, **101**, 371.

13 A. P. Scott and L. Radom, *J. Phys. Chem.*, 1996, **100**, 16502.

14 N. Maung, *J. Mol. Struct. (THEOCHEM).*, 1999, **460**, 159.

15 It should be mentioned that the experimental S–H BDE for 4-aminothiophenol markedly deviates from the general trend so that it is not included in the regression analysis.

16 S. F. Boys and F. Bernardi, *Mol. Phys.*, 1970, **19**, 553.

17 It should be mentioned that the isodesmic reactions as in eqns. (6) and (7) may not fully reflect the substituent effects on the stabilities of the starting materials and products of bond homolysis. Controversy about eqns. (6) and (7) remains, but many authors, including us, prefer to use them as most researchers in this field can easily understand each other with these simple equations. For further discussion, see: (*a*) W. M. Nau, *J. Org. Chem.*, 1996, **61**, 8312; (*b*) W. M. Nau, *J. Phys. Org. Chem.*, 1997, **10**, 445.

18 E. I. Finkelshtein, *J. Phys. Org. Chem.*, 2001, **14**, 543.