PERKIN 2

Solid state nuclear bromination with *N*-bromosuccinimide. Part 1. Experimental and theoretical studies on some substituted aniline, phenol and nitro aromatic compounds†

Jagarlapudi A. R. P. Sarma * and Akula Nagaraju

Molecular Modeling Group, Organic Division-I, Indian Institute of Chemical Technology, Hyderabad 500 007, India

Received (in Cambridge, UK) 7th July 1999, Accepted 29th February 2000

Solid state bromination of a number of substituted phenol, aniline and nitro aromatic compounds with *N*-bromosuccinimide yields exclusively the nuclear brominated products. Reactivity in the solid state depends on the reaction time, temperature and nature of the substituent on the substrate. The reaction apparently proceeds by an electrophilic aromatic substitution pathway. Molecular orbital and reaction free energy calculations also support such a view. Thermal analysis and video microscopic observation reveal the nature of the solid state reaction. Crystallinity is required for the reactivity and product selectivity. Product yield decreases with loss of selectivity when the reaction is carried out in a melt or in solution. Unlike the topochemical solid state reactions wherein molecular packing is more important than the intrinsic reactivity, these reactions demonstrate the importance of both these factors.

Introduction

Even though solid state organic reactions are nearly 100 years old, their utility in industry is fairly restricted because of the limitation of generality of such reactions.[1–3] Solid state organic reactions are governed by the topochemical principles wherein minimum molecular motion is one of the significant criteria and the intrinsic reactivity of the molecule is not often very crucial.[4,5] Well studied solid state 2 + 2 dimerisation, thermal and gas–solid reactions represent some examples of topochemical reactions. The majority of these reactions belong to a single-component system wherein two or more similar molecules react to yield products.[6,7] However, solid–solid reactions involving mixtures, *i.e.*, two-component systems, are very scarce. Nevertheless, when reactions are carried out in such solid–solid mixtures, reactivity usually differs from the normal solution reaction. Increased concern about pollution of the environment caused by industrial effluents has triggered a resurgence in the study of solid state reactions.[8–15]

N-Bromosuccinimide (NBS) is an important reagent not only for bromination but also for a host of other reactions.[16] Depending upon the nature of the reactant and reaction conditions, in solution, NBS reacts differently with many aromatic compounds. Being a constant source of Br_2 at very low concentrations, NBS is used extensively in bromination reactions involving radical substitution, electrophilic addition and substitution pathways while oxidation reactions are not that uncommon.[17] However, many of these reactions lead to multiple products. Product selectivity is generally not observed in the solution reactions. Recently, solid state NBS bromination of phenols and hydroquinones has been reported wherein multiple nuclear bromination products along with some oxidation products were obtained.[17] However, these products were different from those formed in a solution phase reaction. Notably, in spite of the presence of active benzylic hydrogens, benzyl bromides were not formed, indicating a sort of regioselectivity. Thus, this study is aimed at understanding the utility and generality of the solid state bromination reactions of a number of substituted hydroxy, amino and nitro aromatic compounds.

Computational methodology

Semi-empirical calculations

Using AM1 methods in MOPAC, molecular structures were optimised until the gradients were less than 0.01 or the heat of formation test was satisfied.[18] Molecular orbital energies, electrostatic potential charges, transition state locations and free energies for the reactions at different temperatures were also calculated based on these optimised molecular geometries. In the calculation of free energies, while the enthalpy of formation, ΔH_f, was directly obtained from the calculations, the entropy of formation, ΔS_f, was obtained based on the difference between the calculated entropy contribution, S°_{cal}, and the sum of the elemental entropies of formation, ΔS°_{ele}.[19] All the calculated energies and partial charges of the ring C-atom, where bromination is effective, and its associated hydrogen are given in Table 2.

Results and discussion

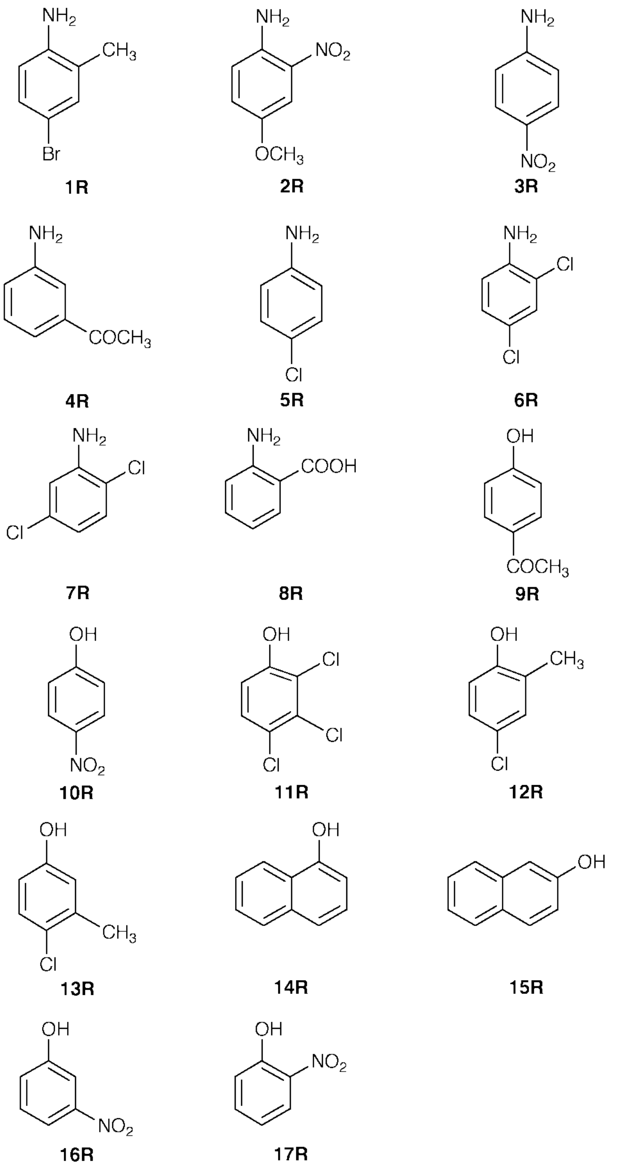
Solid state reaction of substituted phenols with NBS, bromine or chlorine gas is very rapid and almost goes to completion. Out of these three types of reactions, only the reaction with NBS is seemingly a solid–solid reaction. However, this could also be considered as a solid–gas reaction because the Br_2 liberated by the NBS decomposition diffuses into the reactant crystal and undergoes the reaction. This was exemplified by the similar reactivity observed in a number of NBS or chlorine gas reactions of substituted phenols which form halocyclohexadienones and halocyclohexenones.[2,17] Nuclear halogenation in preference to benzylic halogenation in some of these studies is an indication of the difference in the reaction process in the solid state compared to that in solution. Thus the study of solid state NBS reaction with some substituted phenols, anilines and nitro aromatics should improve the understanding of the generality of this reaction. The nature of the substituents has been chosen in such a way that the activity of the ring can be reasonably controlled from active to inactive (Charts 1 and 2).

Apart from the nature of the substituents, there are other parameters that govern the activity and product selectivity. Two important factors that control the solid state bromination

---

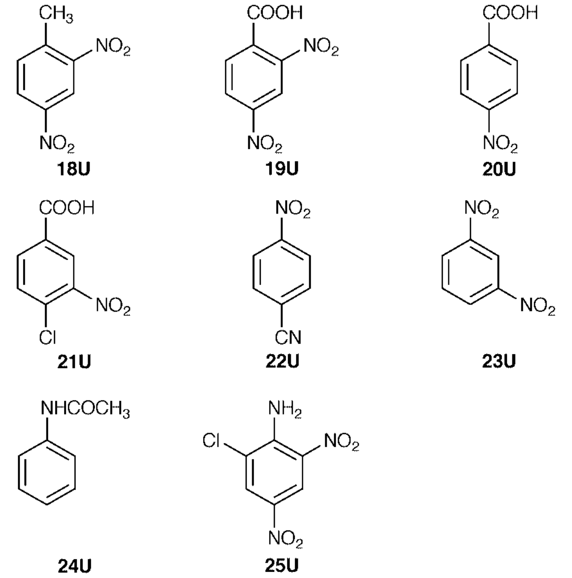
† IICT Communication No. 4324.

DOI: 10.1039/a905466i



1R **2R** **3R** **4R** **5R** **6R** **7R** **8R** **9R** **10R** **11R** **12R** **13R** **14R** **15R** **16R** **17R**

Chart 1 Reactive compounds.



18U **19U** **20U** **21U** **22U** **23U** **24U** **25U**

Chart 2 Unreactive compounds.

are the reaction time and temperature. In contrast to earlier studies,[17] only nuclear bromination products and no oxidation or other products are observed.

Reaction conditions and substituent effects

In general, solid state NBS brominations are highly exothermic. If the reactant has a low melting point, usually the reaction mixture turns into paste when allowed to rest for long. As to the general nature of the exothermic reactions, even in these bromination reactions, controlling the reaction temperature (Table 1) is an important factor that determines the activity and product selectivity. The reaction is complete or optimum yield is obtained when the reaction temperature is well below the melting point of the reaction (preferably below by ~30 °C). This is in tune with one of the important postulates for any solid state reaction. When well-grown crystals of NBS and the reactant are kept under a microscope in contact with each other, reaction propagation can be monitored in terms of colour change. In general, in a solid state reaction, as the product is formed, it breaks away from the parent crystals and a new microcrystalline phase of product begins to grow.[7] When such an analogy is applied here, formation of mono and/or multiple bromination products could be a reality depending on the activity and crystallinity of the first product.

The reaction temperature is varied based on the substituents and melting point of the reactants. If too many or too strong activating groups are present on the aromatic ring, bromination is very fast and the temperature is lowered to control the reaction. If the melting point of the reactant is low, the reaction temperature is again lowered to avoid melting and even the reaction time is also sometimes reduced to obtain better product selectivity (see the values for **5R**–**7R**, **11R**–**13R** in Table 1). If either the melting point of the reactant is high or any deactivating groups are present, the reaction temperature and/or time are increased to accelerate the reaction (**2R**, **9R**, **14R**, **15R**). This indicates the importance of diffusion of Br_2 from the reactivity in the form of control exerted in the solid state.

When very active substituents such as hydroxy, alkoxy or alkyl groups are considered in phenols or anilines, multiple bromination and/or oxidation products are observed.[17] Reducing the activity in the form of a milder chloro substitution improves the product selectivity to some extent. Chlorophenols and chloroanilines have good activity and selectivity as **1R**, **6R**, **11R** and **12R** produce a single monobromo product while **5R**, **7R** and **13R** yield dibromo products. But in no case are the oxidation products observed. When phenols/anilines are substituted with slightly stronger electron-withdrawing groups such as acetyl, carboxy and nitro groups (**2R**, **3R**, **4R**, **8R**–**10R**) activity is further reduced, however reactivity and selectivity are still maintained. Anthranilic acid, **8R**, forms two different monobromo products and these different products could arise either from the reaction of different polymorphic forms or for different reasons such as electronic or thermal effects. A similar situation may prevail with **16R** which is also dimorphic. However, in **17R**, the very low melting point of the reactant could be the reason for the formation of multiple products. In fact, multiple bromo products could also be obtained if the unsubstituted positions in the monobrominated product have an equal propensity to reaction as the initial reactant. Thus many of these factors need to be considered when multiple nuclear bromination (a mixture of two or more of mono-, di- or tribromo) products are obtained. However, the selectivity can be considered to be partly retained in view of the fact that either benzylic (in possible cases) or oxidation products are not formed. When the reactant contains stronger deactivating groups such as nitro, along with only some moderately active groups such as chloro or methyl, bromination is rather difficult and these compounds remain unreactive. In fact, the situation is much worse when only electron-withdrawing groups are present with no reactivity at all. Many of the compounds given in Chart 2 fall into these last two categories. However, this sort of qualitative analysis does not contribute significantly to the

Table 1 Reaction conditions and yields of the observed and expected products in a solid state bromination reaction. In most of the reactive compounds the melting points of the products are comparable to those of the reactants and the reaction temperature is well below both of them

Compound	Mp/°C	Reaction conditions		Yield (%)	Observed/expected[a] in a solid state reaction	Mp/°C
		Temp/°C[b,c]	Time/min			
1R	56	15	3	80	6-Br	205
2R	128	40	4	75	6-Br	119
3R	149	20	4	80	2-Br	102
4R	98	10	2	30	2,4,6-Br	169
5R	68	15	0.3	45	2,6-Br	96
6R	60	10	0.4	90	6-Br	85
7R	56	10	0.5	20:10	4-Br	105
					4,6-Br (1:1)	89
8R	145	25	1.5	25:25	4-Br	220
					6-Br (1:1)	178
9R	108	35	5	45	2,6-Br	68
10R	114	30	4	50	2,6-Br	144
11R	58	15	1	85	6-Br	82
12R	48	5	0.1	60	6-Br	43
13R	62	5	0.1	50	2,6-Br	40
14R	96	35	3	50	2,4-Br	97
15R	122	35	2	60	1-Br	84
16R	95	5	0.1	—	Multiple products	—
17R	43	5	0.1	—	Multiple products	—
18U	70	25	10	—	6-Br	95
19U	180	100	15	—	6-Br	210
20U	240	120	15	—	2-Br	166
21U	182	120	15	—	6-Br	—
22U	148	50	10	—	2-Br	—
23U	90	40	10	—	5-Br	77
24U	114	40	10	—	3-Br	87
25U	248	120	15	—	5-Br	—

[a] While **1R**–**6R** and **9R**–**15R** reactants gave single products (observed), **7R** and **8R** gave two products whereas **16R** and **17R** gave multiple products. **18U**–**25U** are unreactive and in these cases, products are expected based on the electronic behaviour of reactants. [b] Compounds with low melting points melt during the progress of the solid state reaction and to retain the crystallinity the reaction temperature was lowered. [c] Some compounds are not reactive at room temperature (~ 27 °C) and in these cases the reaction mixture was heated, though to a temperature well below their melting point.

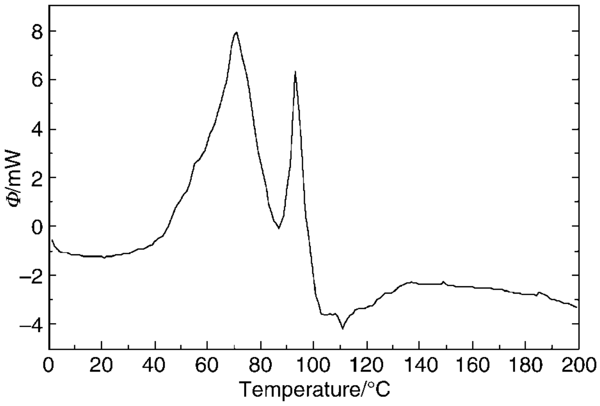


Fig. 1 DSC trace of a 1 : 1 (mol equiv.) mixture (6.3 mg) of *p*-nitrophenol with NBS. Note the two exothermic peaks with onset temperatures 43 and 60 °C (shoulder) and a third exothermic peak at 89 °C. The first two correspond to the formation of mono- and dibromo products while the third is probably due to the formation of any of the other products or decomposition of NBS. A tiny endothermic peak at 110 °C is due to the melting of the reactant whose melting point is 114 °C.

understanding of the intricacies involved in the generality of this reaction if it is to have any industrial applications.

Thermal analysis and crystal morphology

As a representative example, thermal analysis studies were carried out on a 1 : 1 mixture of NBS and *p*-nitrophenol, **10R**. Fig. 1 is the differential scanning calorimeter (DSC) trace showing two exothermic peaks below 80 °C indicating the two bromination stages. Both DTA and TGA traces also reveal similar results. In the DSC trace, the onset temperature of the first peak is at 43 °C which is closely followed by another at ~60 °C (shoulder). These two peaks are due to the two stages involved in the formation of the dibromo product. A third peak with onset at 89 °C indicates another bromination reaction. A small endothermic peak with onset at 109.3 °C refers to the melting of the reactant. In fact, when the reaction was carried out either in the melt (at ~120 °C) or in acetonitrile solution at least three products were obtained while the solid state reaction yields only one dibromo product.

Crystal morphological changes during reaction were observed by video microscopy on a single crystal of *p*-nitrophenol, **10R**, in contact with NBS. In Fig. 2a, freshly ground NBS powder and a reactant crystal of **10R** are kept at a distance; later they were brought into contact with each other. Within a few minutes (<5), the change in the colour of the reactant crystal is perceptible (Fig. 2b). Even though the crystal morphology remains almost unchanged, the reaction is complete in the crystal. During the reaction, crystallinity is lost and the product is transformed into polycrystalline material. Lack of any significant morphological changes such as melting and conversion into the product proves beyond doubt the nature of the solid state bromination reaction. Thus crystallinity is used effectively to control the diffusion of Br_2 and enhance the selectivity compared to the melt or solution.

Free energy of the reaction

Dibromination and tribromination reaction free energies are nearly twice and thrice that of monobromination reactions respectively (Table 2). Also, the monobromination reaction free energies vary little with the substituents. Even though the reaction free energy calculations predict an exothermic reaction correlating well with the experimental observation, they fall short in distinguishing the reactive and unreactive compounds. Even in the case of unreactive compounds, the reaction free energies of the expected monobromo products (based on the

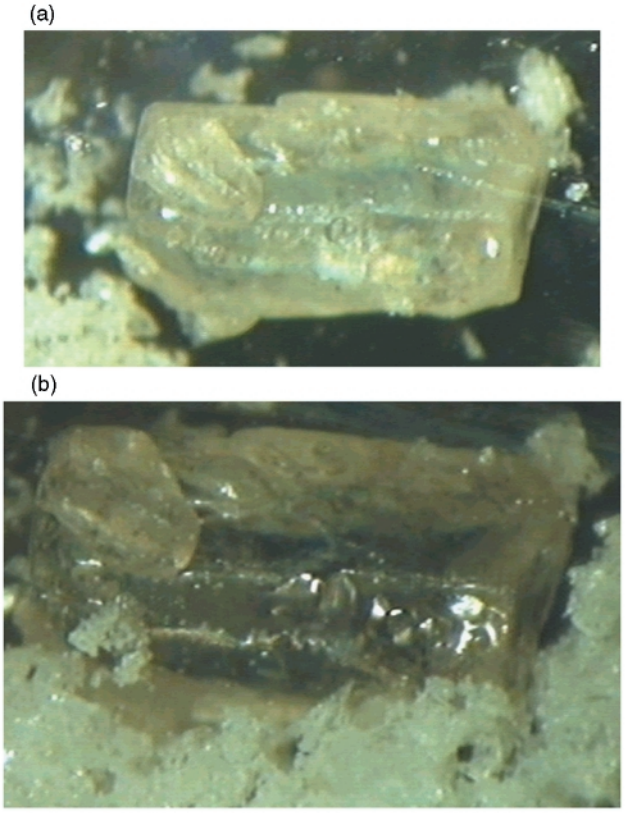


Fig. 2 (a) A single crystal of *p*-nitrophenol (**10R**) in the vicinity of NBS powder before the start of the reaction. (b) Note the colour change in the same single crystal when it is in contact with NBS powder for a few minutes. The reaction is complete with only dibromo product formation within this time. Even though the morphological identities are maintained during the reaction, the crystallinity is lost and the product becomes polycrystalline.

electronic effects) are comparable to those of reactive compounds. However, no reaction was observed in them. To determine the reasons for the lack of reactivity in some of the unreactive compounds a reaction coordinate analysis study involving transition state location was carried out.

Reaction coordinate analysis

Reaction coordinate analysis was performed for reactive *p*-nitroaniline, **3R**, and unreactive 2,4-dinitrotoluene, **18U**, as a case study. For this analysis, the starting geometry consists of a neutral molecule and a bromonium ion separated by 4.5 Å from the ring C-atom lying on the axis passing through that C-atom and normal to the aromatic ring. The product structure is the brominated product and a proton situated on the opposite side to that of the initial bromonium ion and separated by 3.5 Å from the C-atom. Transition state location (saddle point) calculations have been performed in MOPAC with a default approach rate of 0.15. In Fig. 3, the transition state in **3R** is more flat (possibility of a few intermediate stages) and it is much sharper and higher in energy in **18U**. Thus, though ΔG_f is nearly the same for reactive and unreactive compounds, the activation energy is far less for the reactive compounds compared to the unreactive compounds. This is a general result observed in most of the electrophilic substitution reactions.

Electrostatic potential (ESP) charges

Absence of any side chain bromination in either alkyl phenols or anilines, nuclear bromination in all reactive cases, and the variation in the reactivity with respect to the nature of the substituents, indicate an electrophilic substitution pathway. If this is indeed the case, then the partial atomic charges on the ring C-atoms should correlate with the bromination selectivity. In all compounds, it is invariably observed that bromination is effective on the most electron-rich ring C-atom. Thus, the partial ESP charge of the ring C-atom where bromination is effective is given in Table 2 along with the ESP charge of the associated H-atom. In the reactive compounds, in general, the ESP charge on the C-atom for all reactive compounds is high and the associated H-atom is also more acidic compared to the unreactive compounds. Even among the reactive substrates, in compounds with high activating groups such as **5R**, **6R**, **7R**, **11R**, **12R** and **13R**, the ring C-atom where bromination is effective is relatively more electron-rich (−0.5 to −0.7) compared to some other compounds such as **2R**, **3R**, **4R** and **8R** where either the negative charge on the C-atom or the positive charge on the associated H-atom is less. Thus the compounds in the first set are more reactive than those in the second set.

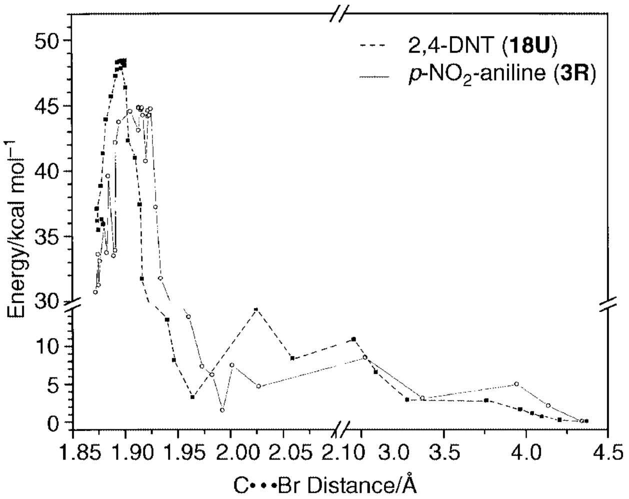


Fig. 3 Saddle point calculations showing the reaction coordinate analysis. The relative energies of **3R** and **18U** are shown on the ordinate while the C · · · Br distance that transforms from non-bonded to a bond during the reaction is indicated on the abscissa.

HOMO–LUMO energies

The molecular orbital energies have been computed in order to distinguish the reactive and unreactive compounds more explicitly. If the reaction follows a well-defined electrophilic substitution pathway, the HOMO and LUMO levels should be able to give an insight into the reactivity and assist in predicting the feasibility of such a reaction. From these calculations it is observed that the lower the HOMO, the greater is the difficulty for the bromination. In fact, most of the unreactive compounds have relatively lower HOMO values compared to the reactive compounds. Not surprisingly, the greater the difference between the HOMO and LUMO levels, the lower is the reactivity. When this difference is lower (7.9 to 9.1 eV) the reaction is feasible and as the LUMO–HOMO gap widens (9.1 to 9.8 eV), the reaction is more difficult. Thus both factors, namely, lower HOMO and larger separation of HOMO from LUMO, affect the bromination reaction as seen in Fig. 4. However, it is interesting to note that among the many solid–solid and solid–gas reactions studied so far in the literature, this is one of the few studies where a molecular property contributes significantly to the solid state reactivity. In fact, here the solid medium is effectively used only to control the reactivity and diffusion, but the intrinsic reactivity plays a vital role in the overall reactivity.

Experimental

Solid state reactions

In general the substrate (~1.0 g) and freshly powdered NBS (1 : 1 molar equivalents) were mixed very gently for a few seconds. After the specified reaction time the mixture was

Table 2 Data on the free energy of the reaction, some electrostatic potential (ESP) charges, the energy of HOMO, and the energy difference between LUMO and HOMO levels are given

Compound	ΔG_{f}[a]	ESP charges Carbon[b]	ESP charges Hydrogen[b]	HOMO/eV	Δ(LUMO − HOMO)/eV
1R	−33.1, (1.99)	−0.536	0.215	−8.56	8.78
2R	−26.8, (−13.14)	−0.345	0.215	−7.44	8.88
3R	−33.1, (4.12)	−0.276	0.149	−9.27	8.48
4R	−94.1, (−6.53)	−0.306[c]	0.208	−8.80	8.51
5R	−65.5, (−3.04)	−0.495[c]	0.215	−8.58	8.87
6R	−32.4, (1.24)	−0.658	0.234	−8.67	8.69
7R	−32.8,[d] (−3.26)	−0.598[c,e]	0.098	−8.80	8.73
	−63.2, (−7.63)				
8R	−35.5, (4.60)	−0.395[e]	0.188	−8.63	9.00
	−36.4, (3.83)	−0.279	0.168		
9R	−61.2, (−9.83)	−0.473[c]	0.197	−10.10	9.01
10R	−57.5, (−12.28)	−0.340[c]	0.229	−9.43	9.05
11R	−30.3, (−0.85)	−0.637	0.217	−9.36	8.89
12R	−31.3, (−0.09)	−0.477	0.244	−9.01	9.14
13R	−58.1, (−19.3)	−0.731[c]	0.240	−9.05	9.14
14R	−62.2, (−3.14)	−0.470[c]	0.201	−8.49	8.12
15R	−28.9, (1.15)	−0.527	0.263	−8.57	8.22
16R	—	−0.373[f]	0.227	−9.95	8.93
17R	—	−0.423[f]	0.213	−9.95	8.94
18U	−28.6, (2.13)	−0.223	0.201	−11.03	9.20
19U	−32.7, (8.44)	0.003	0.183	−11.69	9.92
20U	−24.7, (2.59)	−0.021	0.165	−10.90	9.17
21U	−26.2, (−2.92)	0.205	0.092	−10.70	9.12
22U	−30.1, (3.56)	−0.163	0.205	−10.94	9.21
23U	−31.4, (2.78)	−0.089	0.176	−11.45	9.51
24U	−32.4, (−0.36)	−0.096	0.105	−9.12	9.18
25U	−23.5, (2.29)	−0.336	0.408	−9.96	8.30

[a] ΔG_{f} is the difference in free energy of formation between products and reactants at the reaction temperature. The values in parentheses indicate the entropy contributions expressed in cal deg^{-1} mol^{-1} (1 kcal = 4.184 kJ). [b] ESP charges of the ring C-atom and its associated H-atom where bromination is observed or expected. [c] These compounds undergo multiple bromination to form dibromo, tribromo products. However, the ESP charge of the most electron-rich ring C-atom is given. [d] The upper value is for the monobromo product while the lower is for the dibromo product. [e] In **7R**, the ESP charge of the C-atom where monobromination is effective is given. **8R** produces two monobromo products and the ESP charges of both the ring C-atoms are given. [f] Mixture of products is obtained. The ESP charge of the most electron-rich ring C-atom is given.

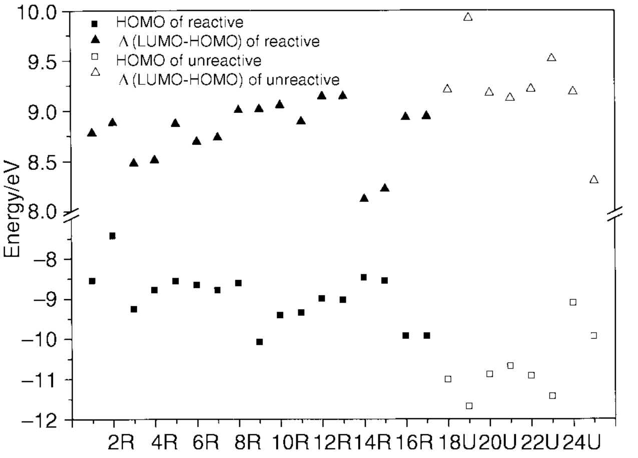


Fig. 4 The HOMO (squares) and LUMO–HOMO separation (triangles) energies of reactive (solid symbols) and unreactive (open symbols) compounds.

dissolved in petroleum ether and ethyl acetate (10 : 1) and the mixture was separated using column chromatography. Either grinding of the mixture or monitoring the reaction for a longer time usually resulted in a paste, especially if very low melting reactants or products were involved. The reaction being highly exothermic, reaction temperature and time were varied not only to ensure crystallinity but also to optimise the selectivity and yield. All products were characterised with NMR (Varian 400/200 MHz) and mass spectra (Micromass 7070h operating at 70 eV). In the case of unreactive substrates, reaction time and temperature were altered suitably, however no products were observed and the substrates were recovered almost completely. Thermal analyses were carried out on a Mettler Toledo 851E Star system.

Conclusions

Solid state NBS bromination reactions are regioselective and exclusively nuclear brominating. The reactivity depends upon the nature of the substituents, and product selectivity depends on the reaction time and temperature. The reaction proceeds by an electrophilic substitution pathway rather than by any free radical mediated mechanism, which is normally associated with NBS bromination in solution. These reactions exemplify the importance of intrinsic reactivity of the molecular system along with the importance of crystallinity. The solid state diffusion reaction presents an alternative to NBS solution chemistry in terms of product selectivity and could have potential industrial applications as it deals with cleaner and greener technologies devoid of any solvent sand hazardous effluents.

Acknowledgements

Financial support from a UGC fellowship to A. Nagaraju is gratefully acknowledged. We thank Dr K. V. Raghavan (DIICT), Dr J. S. Yadav and Professor G. R. Desiraju, University of Hyderabad, for their constant support and interest in this work.

References

1 G. R. Desiraju, *Reactivity of Organic Solids in Solid State Organic Chemistry in the 21st Century*, ed. V. V. Boldyrev, IUPAC Publication, Oxford University, 1996.

2 R. Perrin, R. Lamartine, M. Perrin and A. Thozet, *Solid State Chemistry of Phenols and Possible Industrial Applications*, in *Organic Solid State Chemistry*, ed. G. R. Desiraju, Elsevier, Amsterdam, 1987, p. 271.

3 S. R. Byrn, *Solid State Chemistry of Drugs*, Academic Press, New York, 1982.

4 E. Hadjoudia, E. Kariv and G. M. J. Schmidt, *J. Chem. Soc.*, *Perkin Trans. 2*, 1972, 1056.

5 A. Gavezzotti and M. Simonetta, *Chem. Rev.*, 1982, **82**, 1.

6 V. Ramamurthy and K. Venkateshan, *Chem. Rev.*, 1987, **87**, 433.

7 (*a*) I. C. Paul and D. Y. Curtin, *Acc. Chem. Res.*, 1973, **6**, 217; (*b*) I. C. Paul and D. Y. Curtin, *Chem. Rev.*, 1981, **6**, 81; (*c*) I. C. Paul and D. Y. Curtin, *Gas Solid Reactions in Polar Crystals*, in *Organic Solid State Chemistry*, ed. G. R. Desiraju, Elsevier, Amsterdam, 1987, p. 331.

8 G. R. Desiraju, *Solid State Ionics*, 1997, **101**, 839.

9 G. Kaupp, J. Boy and J. Schmeyers, *J. Prakt. Chem.-Chem.-Ztg.*, 1998, **340**, 346.

10 N. J. Covilli and L. Cheng, *J. Organomet. Chem.*, 1998, **571**, 149.

11 J. Schmeyers, F. Toda, J. Boy and G. Kaupp, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 989.

12 Li Xl. Du., Y. M. Wang and J. B. Meng, *Sci. China*, *Ser. B*, *Chem.*, *Life Sci. Earth Sci.*, 1997, **40**, 205.

13 Li Xl. Du, Y. M. Wang and J. B. Meng, *Sci. China*, *Ser. B*, *Chem.*, *Life Sci. Earth Sci.*, 1997, **40**, 270.

14 Y. Ohashi, *Solid State Mater.*, 1996, 1522.

15 J. D. Dunitz, *Acta Crystallogr.*, *Sect. B*, 1996, **51**, 619.

16 L. A. Paquette, *Encyclopedia of reagents for organic synthesis*, John Wiley & Sons Inc., New York, 1997, pp. 768–772.

17 B. Satish Goud and G. R. Desiraju, *J. Chem. Res.* (*S*), 1995, 244.

18 MOPAC (version 6.0), M. J. S. Dewar, E. G. Zoebisch, E. F. Healy and J. J. P. Stewart, *J. Am. Chem. Soc.*, 1985, **107**, 3902.

19 For a given molecule of the formula: $C_mH_nN_oO_pBr_qCl_r$, $S°_{ele} = mS°(C) + n/2S°(H_2) + o/2S°(N_2) + p/2S°(O_2) + q/2S°(Br_2) + r/2S°(Cl_2)$. R. C. Reid and T. K. Sharewood, in *The Properties of Gases and Liquids*, McGraw-Hill, New York, 1966, p. 242. Elemental entropy values of individual atoms were taken from (*a*) *CRC Handbook of Physics and Chemistry*, R. C. Weast, 67th edn., CRC Press, Inc., Boca Raton, FL, USA, 1987; (*b*) *Handbook of Chemistry and Physics*, C. D. Hodgman, R. C. Weast and S. M. Selby, 42nd edn., The Chemical Rubber Publishing Co., Cleveland, OH, USA, 1961.