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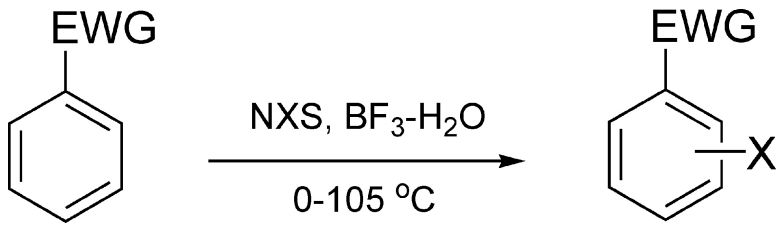

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N-Halosuccinimide/BF_3-H_2O, Efficient Electrophilic Halogenating Systems for Aromatics

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Contribution from the Donald P. and Katherine B. Loker Hydrocarbon Research Institute and Department of Chemistry, University of Southern California, Los Angeles, California 90089-1661, and Instituto de Química, Departamento de Química Orgânica, Universidade Federal do Rio de Janeiro, Cidade Universitária CT Bloco A, 21949-900 Rio de Janeiro, Brazil

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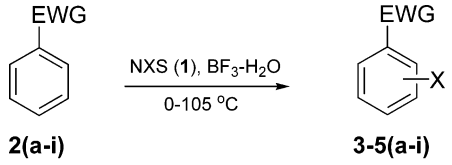
Abstract: *N*-Halosuccinimides (NXS, **1**) are efficiently activated in trifluoromethanesulfonic acid and BF_3-H_2O, allowing the halogenations of deactivated aromatics. Because BF_3-H_2O is more economic, easy to prepare, nonoxidizing, and offers sufficiently high acidity ($-H_0 \approx 12$, only slightly lower than that of trifluoromethanesulfonic acid), an efficient new electrophilic reagent combination of NXS/BF_3-H_2O has been developed. DFT calculations at the B3LYP/6-311++G**//B3LYP/6-31G* level suggest that protonated *N*-halosuccinimides undergo further protosolvation at higher acidities to reactive superelectrophilic species capable either in the transfer of X^+ from the protonated forms of NXS to the aromatic substrate or in forming a highly reactive and solvated X^+ which would readily react with the aromatic substrates. Structural aspects of the BF_3-H_2O complex have also been investigated.

Introduction

Haloarenes are compounds of high practical utility. There are many known methods for the preparation of haloarenes from aromatics especially from electron-rich systems. However, severe experimental conditions are required for the halogenation of deactivated aromatics. During our study of various superacidic systems for acid-catalyzed synthetic transformations, we found that boron trifluoride monohydrate (BF_3-H_2O) is a very effective acid catalyst for varied synthesis such as for the preparation of nitrite free alkyl nitrates, thioacetalization of ketones, preparation of sulfides from carbonyl compounds, nitration of aromatics using potassium nitrate, etc., under relatively mild conditions.[1,2]

Even though *N*-halosuccinimides (NXS, **1**) have been extensively studied as halogenating agents for alkanes as well as electron-rich aromatics, few examples of halogenation of deactivated aromatics with NXS have been reported. During the past decade, Olah et al. have carried out extensive experimental as well as theoretical studies on superelectrophilic activation of electrophiles by protosolvation with superacidic systems, allowing electrophilic reactions to take place with weakly nucleophilic substrates.[3] Our previous study revealed that iodination of deactivated arenes could be easily achieved in high yields with *N*-iodosuccinimide (NIS) in trifluoromethanesulfonic acid.[4] This suggested that NXS could be in general readily activated to allow the halogenation of deactivated arenes. Because BF_3-H_2O is more economic than trfluoromethanesulfonic acid, easier to prepare, and offers reasonably high acidity ($-H_0 \approx 12$),[2] we undertook a study of the combination of NXS with BF_3-H_2O as new halogenating systems. Our present study shows that the combinations indeed act as very effective reagents for the halogenations (chlorination, bromination, and iodination) of various deactivated aromatics under mild conditions (Scheme 1).

Scheme 1



Results and Discussion

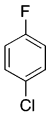
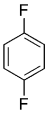
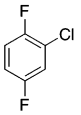
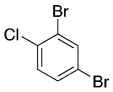
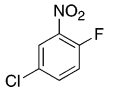
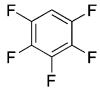
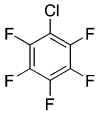
(a) Chlorination Using *N*-Chlorosuccinimide (NCS). Apart from conventional Friedel−Crafts chlorination, many other types of reactions were reported for the chlorination of aromatics. Use of hypochlorites (or hypochlorous acid) can result in chlorination following either a radical pathway or a Friedel−Crafts-type

† University of Southern California.
‡ Universidade Federal do Rio de Janeiro.

(1) (a) Olah, G. A.; Wang, Q.; Li, X.-Y.; Bucci, I. *Synthesis* **1992**, 1085. (b) Olah, G. A.; Wang, Q.; Li, X.-Y.; Prakash, G. K. S. *Synthesis* **1993**, 207. (c) Olah, G. A.; Wang, Q.; Trivedi, N.; Prakash, G. K. S. *Synthesis* **1992**, 465. (d) Olah, G. A.; Wang, Q.; Prakash, G. K. S. *Catal. Lett*. **1992**, 465.
(2) Farcasiu, D.; Ghenciu, A. *J. Catal*. **1992**, *134*, 126.
(3) (a) Olah, G. A.; Mathew, T.; Marinez, E. R.; Esteves, P. M.; Etzkorn, M.; Rasul, G.; Prakash, G. K. S. *J. Am. Chem. Soc*. **2001**, *123*, 11556. (b) Olah, G. A. *Angew. Chem., Int. Ed. Engl*. **1993**, *32*, 767. (c) Olah, G. A.; Prakash, G. K. S.; Lammerstma, K. *Res. Chem. Intermed*. **1989**, *123*, 141.
(4) Olah, G. A.; Wang, Q.; Sandford, G.; Prakash, G. K. S. *J. Org. Chem*. **1993**, *58*, 3194.

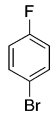
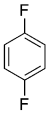
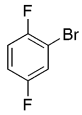
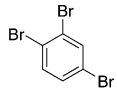
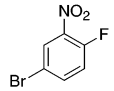
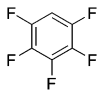
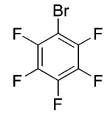
10.1021/ja0465247 CCC: $27.50

Table 1. Chlorination of Deactivated Aromatics with NCS/BF_3-H_2O

Starting Material	Time (h)	Product	Yield (%)
2a 	1	3a 	95
2b 	24	3b  *o,p* ratio 46:54	86
2c 	24	3c  *o,p* ratio 40:60	90
2d 	8	3d  *o,p* ratio 38:62	60
2e 	24	3e 	82
2f 	72	3f 	90
2g 	24[a]	3g 	69
2h 	18[a]	3h 	81
2i 	5[b]	3i 	83

[a] at 100−105 °C, [b] at 75 °C, all in a pressure tube.

Table 2. Bromination of Deactivated Aromatics with NBS/BF_3-H_2O

Starting Material	Time (h)	Product	Yield (%)
2a 	1	4a 	96
2b 	18	3c  *o,p* ratio 29:71	92
2c 	16	4c  *o,p* ratio 10:90	90
2d 	3	4d  *o,p* ratio 18:82	77
2e 	6	4e 	96
2f 	36	4f 	85
2g 	6[a]	4g 	92
2h 	7[a]	4h 	95
2i 	1	4i 	96

[a] at 100−105 °C in a pressure tube.

electrophilic substitution with Cl^+ depending on the acidity of the medium. Chlorination with calcium hypochlorite,[5] *tert*-butyl hypochlorite[6] or benzoyl hypochlorite,[7] sodium chlorate-chlorotrimethylsilane, etc.[8] were also extensively studied. However, in all of these cases, reactions with deactivated aromatics were extremely sluggish. When chlorination of deactivated aromatics was attempted with NCS/BF_3-H_2O, we found that it provided monochloro derivatives in good yields. In some cases, longer reaction times or higher temperatures were required when compared to corresponding brominations and iodinations (vide supra). Depending on the degree of substrate deactivation, the reaction mixture was either stirred at room temperature or heated to indicated temperatures for the required time. In the case of 2-nitrofluorobenzene and nitrobenzene, the systems were heated to 105−110 °C in a closed pressure tube to obtain 4-chloro-2-nitrofluorobenzene (81%) and 3-nitrochlorobenzene (69%) over 24 and 18 h, respectively. Pentafluorobenzene gave 83% of chloropentafluorobenzene in 5 h at 75 °C.

(b) Bromination Using *N*-Bromosuccinimide (NBS). Synthetic utility of bromoarenes as flame retardants, herbicides, and biocides in agriculture[9] and as reactive intermediates in synthetic reactions necessitate their convenient synthesis. Although many Lewis acids are effective bromination catalysts, their susceptibility to any adventitious water and frequently needed large amounts make their use less desirable. Highly electron-rich substrates can be brominated with molecular bromine even without catalysts. Durene and mesitylene are brominated in 67−78% yields with elemental bromine.[10] However, for direct bromination of deactivated nitrobenzene or dinitrobenzene with molecular bromine, the reactions were carried out in the presence of silver trifluoromethanesulfonate in concentrated H_2SO_4.[11] Other reagents suitable for such bromination were shown to be dibromoisocyanuric acid in sulfuric acid,[12] $BrNO_3$ in sulfuric acid, elemental bromine with mercurous oxide or HF and SbF_5,[13] and a mixture of benzoyl peroxide and lithium bromide.[14]

In reported bromination reactions, it was difficult to selectively obtain monobrominated products of moderately deactivated aromatic compounds. Studies have shown that NBS can

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(9) Rozen, S.; Lerman, O. *J. Org. Chem.* **1993**, *58*, 239.
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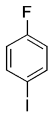
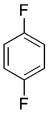
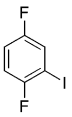
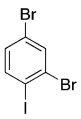
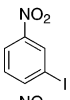
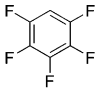
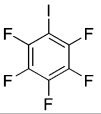
Table 3. Iodination of Deactivated Aromatics with NIS/BF_3-H_2O

Starting Material	Time (h)	Product		Yield (%)
2a 	0.5	5a 		98
2b 	20	3d 	*o,p* ratio 24:76	77
2c 	1	4d 	*o,p* ratio 20:80	68
2d 	3	5d 	*o,p* ratio 30:70	74
2e 	0.25[a]	5e 		87
2f 	24	5f 		84
2g 	20	5g 		95
2h 	4	5h 		92
2i 	1	5i 		90

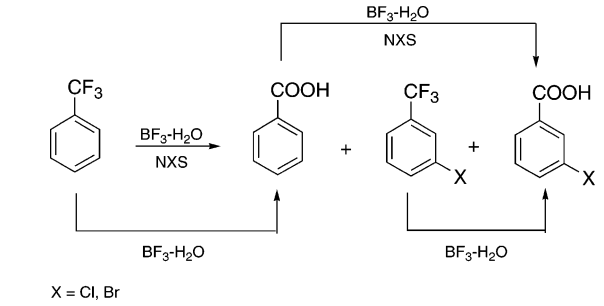
[a] at 0−5 °C.

be used as a source of Br^+ in the electrophilic aromatic bromination of activated aromatics, most frequently in nonpolar solvents, in the presence of acids or chlorides of aluminum, zinc, or iron.[15] Such brominations were also studied in polar media such as propylene carbonate and in *N*,*N*-dimethylformamide at room temperature.[16] Activated aromatic compounds such as phenol, guaiazulene, and polyalkylbenzenes could be brominated by NBS in the presence of catalytic quantities of Koser's reagent {[hydroxy(tosyloxy)iodo] benzene}.[10] Chlorination and bromination of some deactivated systems have been carried out with NCS and NBS, respectively, in H_2SO_4 under vigorous conditions.[17]

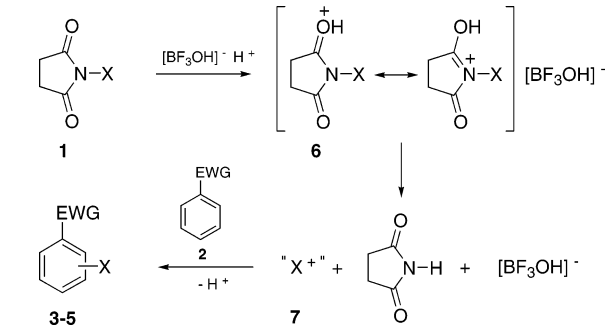
Our present study shows that NBS/BF_3-H_2O is a very convenient and mild reagent for aromatic bromination, providing monobrominated products in high yields. Most of the reactions were fast and complete in less than 10 h, giving monobrominated products in 77−96% yields. Because the yield in the case of nitrobenzene was very low at room temperature, increasing the reaction temperature enhanced the yields. Usually reactions were carried out by adding an excess of BF_3-H_2O to stoichiometric amounts of the substrate and NBS without any organic solvent present.

(c) Iodination Using *N*-Iodosuccinimide (NIS). Iodoarenes are also important materials in various organic coupling reac-

Scheme 2



Scheme 3



tions,[18] as radiopharmaceuticals, etc.[19] Frequently, iodoaromatics show enhanced and uniquely high reactivity as compared to their bromo and chloro analogues.[20] They are also susceptible to photolytic cleavage at the carbon−iodine bond.[21] These properties make iodoaromatics convenient and useful in the synthesis of a wide range of aromatic compounds. However, elemental iodine is generally incapable of direct iodination of even electron-rich substrates under usual Friedel−Crafts conditions. Incorporation of iodine into the aromatic ring is achieved by indirect methods such as the Sandmeyer reaction. NIS activated by acids (including trifluoromethanesulfonic acid) in catalytic or stoichiometric quantities has been found to be useful for electrophilic iodinations.[4,22−25] Because the acidity of boron trifluoride monohydrate, as discussed, is close to that of trifluoromethanesulfonic acid ($-H_o = 14.1$),[26] NIS/BF_3-H_2O reagent was found suitable to achieve direct iodination of deactivated aromatics such as nitrobenzene under mild conditions. The reactions usually were faster than bromination, and only minor amounts of diiodinated products were observed in some cases. Results are summarized in Table 3.

With 1,1,1-trifluorotoluene, the iodination with NIS took place at room temperature, giving *m*-iodo-1,1,1-trifluorotoluene in 95% yield in 1 h. In contrast, chlorination and bromination required higher temperatures (100−105 °C), yielding mixtures of *m*-chloro/bromo-1,1,1-trifluorotoluene, benzoic acid, and *m*-chloro/bromobenzoic acid as major products. Prolonged

(15) Schmid, H. *Helv. Chim. Acta* **1946**, *29*, 1144.
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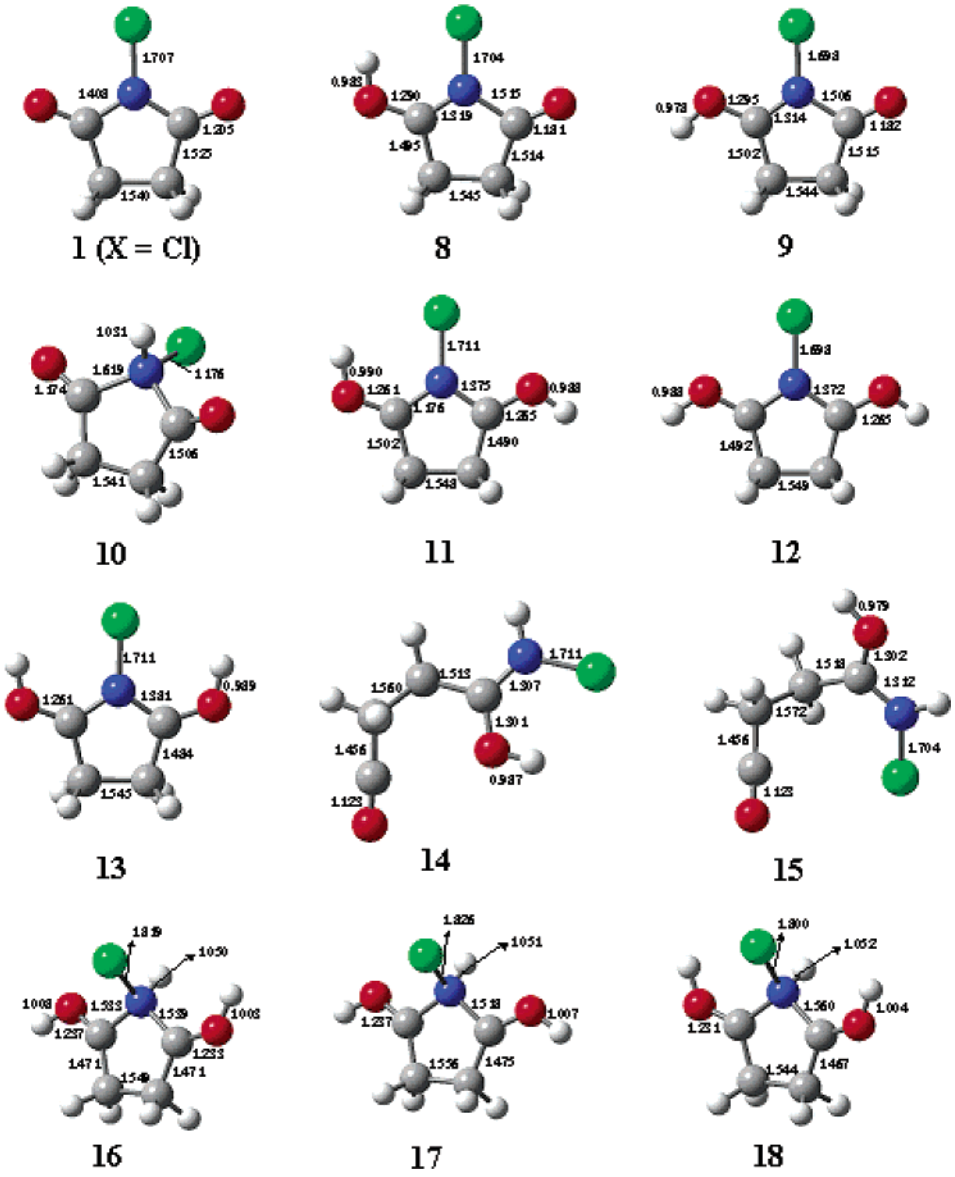


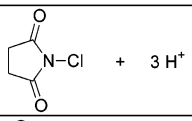
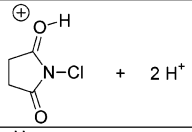
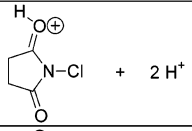
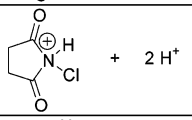
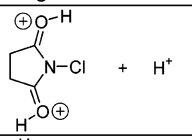
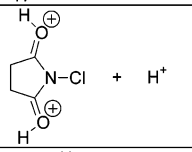
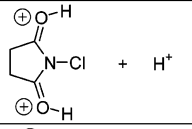
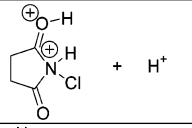
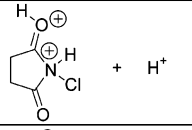
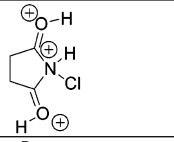
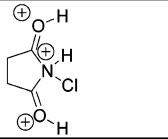
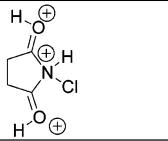
Figure 1. Minimum structures calculated for *N*-chlorosuccinimide (NCS, **1**) and its mono-, di-, and triprotonated forms.

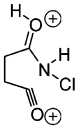
treatment of 1,1,1-trifluorotoluene and *m*-chloro/bromo-1,1,1-trifluorotoluene with BF_3-H_2O also afforded benzoic acid and *m*-chloro/bromobenzoic acid, respectively. This shows that the hydrolysis of CF_3 group competes with ring halogenation at more elevated temperatures. Benzoic acid also undergoes halogenation, although slowly, at 100−105 °C with large amounts of BF_3-H_2O. Large amounts of BF_3-H_2O also help in solubilizing the benzoic acid. However, the method has limited use in the case of highly insoluble substrates even with the addition of organic cosolvents or a large excess of BF_3-H_2O.

During our earlier studies[4] using trifluoromethanesulfonic acid, we suggested that the active species for iodination with NIS is either protonated NIS or more probably in situ formed iodine(I)trifluoromethanesulfonate in its protosolvated form (as shown by low-temperature ^{13}C NMR studies). The ^{13}C NMR spectrum of NIS in trifluoromethanesulfonic acid at −20 °C showed two carbonyl peaks at δ 189 and 192 ppm (the latter deshielded by ∼11 ppm from the corresponding carbonyl peak of NIS), indicating the presence of both protonated NIS and protonated succinimide. Similar mechanistic considerations can explain the reactions with BF_3-H_2O as shown in Scheme 2. Aromatic iodination under acid free conditions using iodine(I) trifluoromethanesulfonate prepared in situ from silver trifluoromethanesulfonate and iodine was found to be only moderately efficient for electron-deficient substrates.[27,28] Better yields found in present BF_3-H_2O-catalyzed reactions under mild conditions suggest the in situ formation of a superelectrophilic, protosolvated halogenating species such as **6**, which then can lead to the formation of protosolvated X^+, **7**. The presently studied halogenations definitely require strong acid, especially with deactivated aromatics. In relatively weak acids such as trifluoroacetic acid, deactivated aromatics do not react. In highly acidic medium, an alternate mechanism involving homolysis of NXS to radical halogen cations as the defacto halogenating agents is not possible. Furthermore, BF_3-H_2O is also a nonoxidizing system. The observed isomer distributions suggest a typical electrophilic aromatic substitution pathway (Scheme 3).

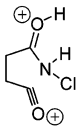
(27) Dalziel, J. R.; Aubke, F. *Inorg. Chem.* **1973**, *12*, 2707.
(28) Kobayashi, Y.; Kumadaki, I.; Yoshida, T. *J. Chem. Res., Synop.* **1977**, 215.

Table 4. B3LYP/6-311++G**//B3LYP/6-31G* Relative Enthalpies of Several Protonated *N*-Chlorosuccinimides at 298.15 K and 1 atm

Structure	ΔH (kcal/mol)
	275.8
	83.0
	84.0
	105.2
	1.5
	0.0
	4.2
	-1.6 [(a)]
	9.1 [(b)]
	87.3
	80.7
	94.2

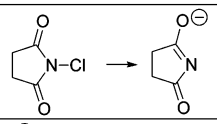
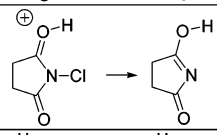
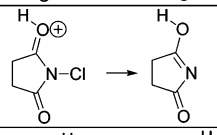
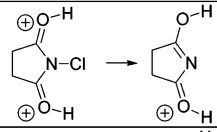
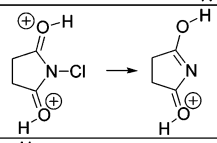
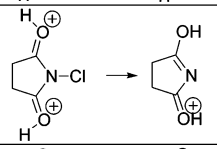
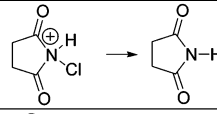
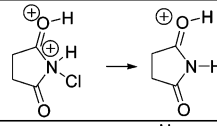
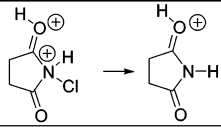
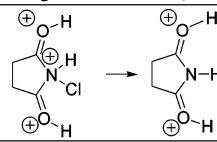
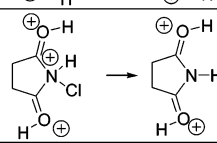
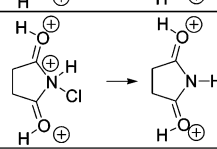


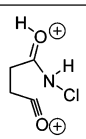
(a)



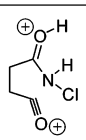
(b)

Table 5. B3LYP/6-311++G**//B3LYP/6-31G* Reaction Enthalpies for the Cl^+ Generation from Several Protonated *N*-Chlorosuccinimides at 298.15 K

Reaction	ΔH (kcal/mol)
	324.4
	192.2
	197.0
	82.8
	70.2
	76.8
	149.7
	68.3[(a)] (starting protonated succinimide is cleaved, see note (a))
	56.4[(b)] (starting protonated succinimide is cleaved, see note (b))
	-106.4
	-104.4
	-102.0



(a)



(b)

The beneficial role of fluorine in increasing the biological activity of many pharmaceutically active compounds is probably due to better cell penetration, better binding at lipophilic areas on the receptors, and better enzyme activation, This justified the preparation of many halofluoroaromatics. Preparation of the chloro, bromo, or iodo derivatives of fluorobenzene, 1,4-difluorobenzene, or 2-nitrofluorobenzene is found to be particularly convenient by our presently developed method. All reactions afforded the corresponding halogenated product in good to excellent yields (Tables 1−3).

Quantum Chemical Calculations. As an additional aspect of our work, we also carried out quantum chemical calculations of the studied systems. Figure 1 shows the geometries of the parent (**1**) and multiprotonated NCS as models (**8**−**14**) obtained after energy minimization at the B3LYP/6-31G* level. Structures **8**−**10** refer to monoprotonated species, whereas structures **11**−**15** and **16**−**18** correspond to di- and triprotonated species, respectively. Upon N-protonation of the monoprotonated species, ring opening takes place, affording an acylium ion, as shown in structures **14** and **15**. This takes place to reduce internal Coulombic repulsion between the adjacent positive charges in the molecule. Thus, ring opening allows a greater separation between the two charged moieties in the species. Nevertheless, the triprotonated species was also found to be a stable intermediate.

Table 4 contains the relative energies of the studied species at the B3LYP/6-311++G**/B3LYP/6-31G* level. These data show that the diprotonated species **12** is the most stable structure, wherein the ring structure is preserved. Actually, the open chain structure **14** is slightly more stable than **12**, which indicates that some decomposition of NCS can take place at high acidities. In the triprotonated species, the charge−charge repulsion becomes important, raising the energy of these intermediates in relation to the diprotonated species. However, if the medium is acidic enough, the triprotonated species can eventually be formed. It is noteworthy that proton transfer to form these species can be part of the process. Protosolvation due to the strongly acidic BF_3-H_2O can also play this role, leading to conclusions similar to those found in general and specific acid catalysis.

Table 5 contains the enthalpies for releasing a Cl^+ species from the parent and multiprotonated NCS. These values can be taken as an estimate of the electrophilicity of each of the species, as well as their ability to eventually release Cl^+. Electrophilic chlorination of aromatics can take place either by a Cl^+ species or by Cl^+ transfer from the protonated forms of NCS to the aromatic substrate. Due to the high reactivity of the Cl^+ species (it has never been observed in the free form in solution), the reaction probably goes through the Cl^+ transfer from the protonated NCS. By increasing the degree of protonation of NCS, the species becomes more activated (and thus destabilized) due to the presence of multiple positive charges, which results in a high degree of charge−charge repulsion. This intramolecular Coulombic repulsion can be relieved by transferring a positive Cl^+ moiety for any nucleophile present in the reaction media (such as an aromatic substrate). Thus, the multiple protonation of NCS in superacid media can cause a ground-state destabilization that acts as a driving force for the halogenation reaction because the activation barriers are lowered in this case as compared to the noncatalyzed reaction (Figure 2). Consequently,

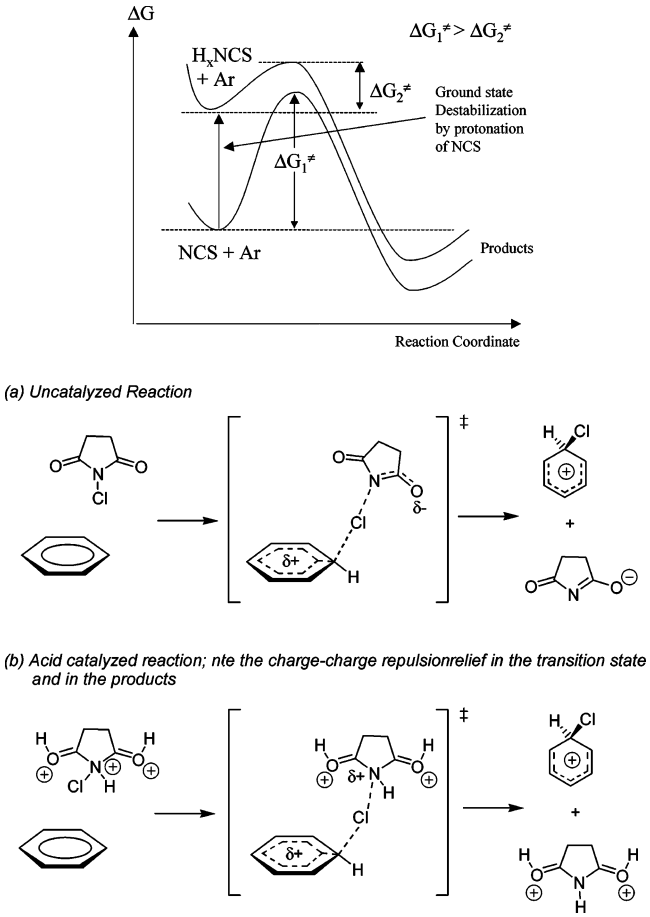


Figure 2. Ground-state destabilization effect and electrostatic relief as driving forces for electrophilic chlorination of aromatics.

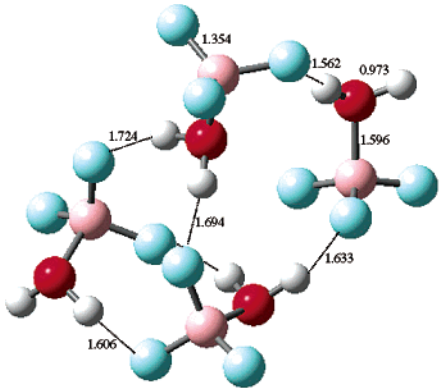


Figure 3. Global minimum structure calculated for the tetramer of BF_3-H_2O.

it is possible to perform electrophilic halogenation using NXS even with deactivated aromatics, the driving force being the acidity of the reaction medium. The present DFT calculations show that the increase in the degree of protonation of the NCS promotes a decrease in the enthalpy for Cl^+ release. The triprotonated species is very favorable to the release of a Cl^+ species, this being predicted to be an exothermic process, supporting the model above.

We did not carry out similar calculations for the NBS and NIS systems. However, we believe that their behavior upon protonation should be comparable to that predicted for the NCS system.

The structure of BF_3-H_2O as its tetramer showing a global minimum was also investigated, using the same methodology employed for the study of the protonated NCS. Figure 3 shows the geometry obtained after optimization of the tetramer. One can see that the system is bound by hydrogen bonds involving the hydrogen atoms of water and the fluorine atoms of the neighboring BF_3 molecules. The enthalpy for deprotonation at 298.15 K and 1 atm, calculated at the B3LYP/6-311++G**//B3LYP/6-31G* level, was found to be of 286.3 kcal/mol.

Experimental Section

BF_3 (Matheson), *N*-chlorosuccinimide, *N*-bromosuccinimide, and *N*-iodosuccinimide and all of the substrates (Aldrich) were used as received. Analyses were carried out using GC (Varian 3000, 30m DB-5 capillary) and GC/MS (HP-5890 series II coupled with HP-5971 series MSD). ^1H and ^{13}C NMR spectra were obtained on a Varian VXR 300 MHz spectrometer in $CDCl_3$ using TMS as internal standard. The structures of the products were confirmed by comparison of their spectral data and physical constants with those of the authentic samples.

Preparation of Boron Trifluoride Monohydrate (BF_3-H_2O). BF_3 was passed carefully into a Nalgene bottle containing a weighed amount of distilled water (36 g, 2 mol) with cooling until a maximum weight increase was observed. The amount of BF_3 was found to be 134 g, which corresponds to a ratio of 1:1.01 in BF_3-H_2O.

Typical Procedure for Halogenation. BF_3-H_2O (4 mL) was added to a mixture of the deactivated aromatic compound (10 mmol) and *N*-halosuccinimide (10 mmol) in a 30 mL Nalgene bottle. The bottle was closed, and the mixture was stirred at the required temperature (room temperature for most reactions) for the specified period of time (Tables 1−3). For higher temperature reactions, pressure tubes were used. The progress of the reactions was monitored by GC/MS analysis. The reaction mixture was then completely transferred to a separatory funnel using water (30 mL) and dichloromethane (2 × 30 mL) and thoroughly shaken to extract the product into the organic layer. The organic layer was washed with saturated solution of sodium bisulfite or sodium thiosulfate (15 mL) to remove any free halogen present followed by saturated sodium bicarbonate solution (30 mL) and brine (30 mL). It was then washed with water (2 × 30 mL) and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the product was purified by fractional distillation or recrystallization from petroleum ether.

Computational Details. The geometries of several multiple protonated NCS species, their related nonchlorinated succinimide, a tetramer of BF_3-H_2O, and its anion were obtained, after an energy minimization procedure at the B3LYP/6-31G* level. The geometries obtained were characterized as minima on the potential energy surface by the absence of imaginary frequencies after vibrational analysis. Single-point energy calculations at the B3LYP/6-311++G** level were performed at the B3LYP/6-31G* geometries. Energy differences refer to enthalpy differences at 298.15 K and 1 atm that were computed at the B3LYP/6-311++G**//B3LYP/6-31G* level and consider zero-point energy and thermal expansion to 298.15 K. All calculations were carried out with the Gaussian 98 package.[29]

Summary

Aromatics including deactivated ones were found to be very efficiently halogenated using the NXS/BF_3-H_2O system at room temperature. Halogenation of more deactivated systems was also achieved by varying the reaction conditions, such as raising the temperature, prolonged reaction time, and increased amount of BF_3-H_2O. In all cases, the formation of monohalogenated product in high selectivity and good yield was observed under the reaction conditions. Halobenzenes afforded the *ortho* and *para* isomers along with minute amounts of dihalogenated products (from GC and GC/MS analyses). Therefore, this solvent-free system using NXS/BF_3-H_2O has an excellent ability for the halogenation of a wide variety of aromatic systems.

DFT theoretical calculations on the involved NCS system show that the driving force for the reaction is the activation of ground-state destabilization by multiple protonation of free NXS reagents, rendering them as superelectrophilic reagents.

Acknowledgment. Support by the Loker Hydrocarbon Research Institute and the National Science Foundation is gratefully acknowledged. P.M.E. acknowledges CNPq and FAPERJ (Brazil) for financial support.

Supporting Information Available: Table including absolute energies, ZPE, thermal corrections to 298.15 K and 1 atm, and absolute entropies for the species considered for quantum chemical calculations on this manuscript. This material is available free of charge via the Internet at http://pubs.acs.org.

JA0465247

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