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Relationship between Superelectrophilicity and the Electrophilicity Index of Isolated Species

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We report a relationship between the superelectrophilicity of a series of dications and the electrophilicity index of isolated species. The enhanced electrophilicity is described by global and local reactivity indexes. Alkyloxonium and carboxonium dications and diprotonated carboxylic acids have been used as simple benchmark systems to discuss this relationship on a qualitative and quantitative basis. The theoretical scale of electrophilicity roughly reproduces the experimental superelectrophilicity hierarchy established on the basis of the ^{17}O and ^{13}C NMR chemical shifts in alkyloxonium and carboxonium ions and diprotonated carboxylic acids.

1. Introduction

The presence of carbocation intermediates in molecular rearrangements was first suggested by Meerwein and van Emster in 1922.[1] These authors studied the Wagner rearrangement of camphene hydrochloride to isobornyl chloride. They found that the rate of the reaction was enhanced with the dielectric constant of the solvent. They also observed that in the presence of Lewis acids such as $SbCl_5$, $FeCl_3$, $AlCl_3$, and $SbCl_3$, as well as dry HCl, the rate of the Wagner rearrangement increased.[1] The authors traced the enhancement in the reaction rate to the rearrangement of a cationic intermediate instead of the migration of the chlorine atom.[1] In the 1930s, carbocations were considered to be unstable and short-lived, because they could not be directly observed. In the 1950s, increasing attention was paid to the development of modern carbocationic chemistry.[2−4] Olah et al. reported the first observation of alkyl cations and long-lived carbocation species in highly acidic solutions (superacids).[2,5−7] The presence of counteranions of low nucleophilicity such as SbF_6^- contributed to the stability of these long-lived carbocations, which could even be isolated as crystalline salts. The development of the superacidic media to obtain stable cations permitted the isolation of different intermediate species such as nitronium, oxonium, and carboxonium ions. They were found to participate in a wide variety of reactions.[8−10] Olah et al.'s studies on superacidic systems concluded that superacids, apart from being highly ionizing, low nucleophilicity media, in some cases were capable of producing electrophilic activation by further protolytic (or electrophilic) interaction (coordination and/or solvation).[11] In a recent account, Olah and Klumpp discuss superelectrophilic solvation involving the interaction of electron-donating groups (ligands) of overall electron-deficient species (electrophiles) with strongly electron-acceptor superacids.[12] This electrophilic activation has been observed in liquid superacids, on solid acids, and even in enzymatic biological systems.[12] Electrophiles capable of further interactions by coordination or solvation with strong Brönsted or Lewis acids can be activated in this way. The resulting enhancement of reactivity is very significant compared to that of their parent compounds under conventional conditions and indicates the formation of a new species named superelectrophiles.[11] Concerning the nature of superacid-activated reactions, it should be recognized that they may proceed through superelectrophilic solvation without necessarily forming limiting dicationic (doubly electron-deficient) intermediates**.** However, there is abundant literature about the structure and reactivity of dications[13] describing the role of cations and dications as intermediates in acid-catalyzed reactions.[11,14] Although the preparation of carbocations under superacidic conditions and the technique for the manipulation and X-ray measure-

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ment of crystals at low temperatures have been known for decades, the single-crystal X-ray diffraction of reactive carbocations has successfully been applied only within the past few year.[15]

^{13}C NMR spectroscopy has extensively been used to study the structure of oxonium, carboxonium, and oxycarbenium ions and diprotonated carboxylic acids,[16,17] because it allows the direct monitoring of the cationic center and the chemical shifts and coupling constants can be correlated with the geometry and hybridization of the cation. This technique has also been used by Olah et al. to provide evidence about the intermediacy of pentaphenyl and heptaphenyl cations in the reaction of triphenylmethyl cation with diphenyldiazomethane or diphenylketene.[18] Olah et al.[17] have applied ^{17}O NMR spectroscopy to study a series of oxonium and carboxonium ions. These authors observed a 240−250 ppm ^{17}O shielding effect for ketones upon protonation, showing a decrease in the carbon−oxygen π bond order by about 40%. A similar effect was observed for protonated carboxylic acids.[17] Protosolvation (further protonation of electrophiles) of oxonium and carboxonium ions leading to doubly electron-deficient or dicationic species results in an enhancement of reactivity with respect to their oxonium or carboxonium ions. For instance in 1975 Olah et al.[19] reported that in superacidic media the acetyl cation (CH_3CO^+) and nitronium ion (NO_2^+) display enhanced reactivity promoted by their protolytic activation through the dications CH_3COH^{2+} and $HONO^{2+}$. Schwarz et al.[20] reported the experimental evidence for the existence of the protonitronium dication ($HONO^{2+}$) in the gas phase and ab initio calculations of its potential energy surface. Protonated ketones or aldehydes[21] are involved in the acid-catalyzed hydration, nucleophilic addition, and ketal-forming reactions of the carbonyl group, as well as in the formation of semicarbazones, hydrazones, and Schiff bases. Acyl cations are intermediates in the formation and hydrolysis of esters and Friedel−Crafts acylation reactions.[22] For instance, Ohwada et al.[23] have highlighted the role of superacid media on the prototype Pictet−Spengler reactions catalyzed by superacids. They found that the yields were dependent on the acidity of the media. A linear relationship was found between the rate of the cyclization and the acidity of the reaction media in kinetic studies of substituted amines and related imines.[23,24] In this case, the reaction between nitronic acids and benzene requires a strong acid such as trifluoromethanesulfonic acid to form the O,O-diprotonated aci-nitro superelectrophilic species.[24] On the other hand, IR studies on acetyl cation also showed significant shifts of the CO frequency, depending on the acidity of the system, thereby indicating protolytic activation of acetyl cation leading to protoacetyl dication.[25]

From a theoretical point of view, superelectrophilic species have been studied in terms of theirs electronic structures, energies, and gas-phase proton affinities.[9] Lammerstma et al. presented an excellent review about organic dications.[26] The relationship between gas-phase experiments and ab initio molecular orbital studies (on isolated species) are emphasized to provide an understanding of the structures and energies of these doubly charged species. An important theoretical result concerns the thermodynamic stability of dications in superacid media. For instance, the stability of the H_4O^{2+} was computationally studied by Olah et al.[8] These authors concluded that H_4O^{2+} is thermodynamically unstable toward deprotonation to H_3O^+, yet the dication has a significant kinetic stability.[8] Despite the kinetic stability, calculations performed on the isolated systems showed that the protonation of H_3O^+ was thermodynamically unfavorable. However, it must be recognized that these computational data may not be related to the condensed phase conditions.[11] On the basis of thermodynamic arguments, Lammertsma and Schleyer showed that not all small organic dications are stable in superacid media.[27] Further studies by Lammertsma et al.[28] reported ab initio protonation enthalpies in fluorosulfonic acid for several small neutral bases and their conjugated acids. The model allowed these authors to predict protonation enthalpies for weak bases that are incompletely protonated in superacids. The possible existence of FOH_3^{2+} and $F_2OH_2^{2+}$ in either superacidic media or gas phase has been recently discussed.[29]

High-level calculations on the other hand are particularly useful to theoretically compute NMR chemical shifts. For instance, Olah et al.[30−34] have reported numerous studies on ab initio calculations of NMR, GIAO,[35] and IGLO[36] indexes. Both GIAO and IGLO methods are used for the calculations of magnetic susceptibility and chemical shifts tensors. Whereas the GIAO (gauge including atomic orbital) method[35] transforms the gauge of the basis set functions to the position of their nuclei,

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in the IGLO (individual gauges for localized orbitals) method[36] the gauges of the final wave functions are transformed to their centers of charge. Good comparisons between the experimental NMR chemical shifts and the ab initio ones for both electrophilic cations and dications have been reported.[30−32] The relationship between electrophilicity and NMR chemical shift is based on a model where a downfield NMR shift is interpreted as a decrease of the electron density at the electrophilic (positively charged) site. However, the relationship between electrophilicity and electronic charge deficiency may not be as general as believed. For instance, it has been recently reported that the electrophilicity power of a molecule presents an unexpected inverse relationship with the positive charge at the electrophilic center in Michael reagents.[37] These authors concluded that a better hierarchy of electrophilicity could be formulated in terms of the electrophilic Fukui function at the active site.[37] Because the Fukui function encompasses information about local softness[38] (i.e., local electronic polarizability), it seems that both electron deficiency and polarizability at the active sites of electrophiles may contain relevant information about the propensity of these systems to acquire additional electronic charges from the environment.[39,40]

A complete theoretical discussion about the origin of electrophilicity concept was proposed by Parr et al.[41] This definition is based on a second-order energy model, introducing the maximum charge-transfer amount from the environment that stabilizes the electrophile in a quantity $\omega = -\Delta E$, where ω is defined as electrophilicity. The charge transfer is variationally obtained as $\Delta N_{\max} = -\mu/\eta = \chi S$, in terms of the electronic chemical potential μ (the negative of the global electronegativity χ) and the chemical hardness η (the inverse of the global softness S).[38] Within this model, a good electrophile will be characterized by a high value of electronegativity (or a high value of electronic chemical potential), and a low value of the chemical hardness. This model conveniently stresses the role of the electronic chemical potential as a descriptor of charge transfer and the role of the chemical hardness as a measure of the resistance of the system to exchange electronic charge with the environment. Note, however, that in the present case the positively charged superelectrophiles are expected to be hard species, and therefore the superelectrophilicity pattern is expected to be mostly driven by the electronegativity (or the electronic chemical potential) of the electron acceptors.

In this article we present a relationship between superelectrophilicity and the electrophilicity index of isolated species of some neutral, mono-, and dication reagents using Parr's definition[41] of electrophilicity for isolated species. We further study the effect of chemical substitution on the electrophilicity pattern of these systems by looking at the variation in regional electrophilicity at the active site induced by electron-releasing groups.

Model Equations and Computational Details

The global electrophilicity index ω is defined by[41]

$$\omega = \frac{\mu^2}{2\eta} \tag{1}$$

in terms of the electronic chemical potential μ and the chemical hardness η, which may be approached in terms of the one-electron energies of the frontier molecular orbital HOMO and LUMO, ϵ_H and ϵ_L, as $\mu \approx (\epsilon_H + \epsilon_L)/2$ and $\eta \approx \epsilon_L - \epsilon_H$, respectively.[38,42]

The local electrophilicity index may also be expressed as[39,40]

$$\omega_k = \omega f_k^+ \tag{2}$$

thereby showing that the maximum electrophilicity power in a molecule will be developed at the k site where the Fukui function for a nucleophilic attack f_k^+ (electrophilic Fukui function) displays its maximum value, i.e., at the active site of the electrophile.[38] This site does not coincide in general with the site having the highest positive charge.[43] Full geometry optimization for different dications, monocations, and the neutral parent were performed at B3LYP/6-31G(d) level of theory using the Gaussian98 package.[44] The global electrophilicity index, ω, was evaluated using eq 1. The electronic chemical potential, μ, and the chemical hardness, η, were evaluated using the frontier molecular orbital model described above. Electrophilic Fukui functions at site k (f_k^+) were obtained from single point calculations at the optimized structures in their ground states, by a method described elsewhere.[45,46] With these values at hand, the local electrophilicity (ω_k) is obtained from eq 2.

Results and Discussion

To set up the appropriate scenery to discuss the enhanced electrophilicity of alkyloxonium and carboxonium dications and diprotonated carboxylic acids, let us mention that for instance electrophilic species participating in Diels−Alder reactions present electrophilicity numbers in the range 1.51 eV (methyl acrylate) to 8.97 eV (*N*-methylmethyleneammonium cation) within the ω scale.[47] Benzhydryl cations on the other hand, present electrophilicity values between 8.9 eV ((1,2,5,6-tetrahydro-4*H*-pyrrolo[3,2,1-*ij*]quinolin-8-yl)benzhydrylium ion)

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TABLE 1. Electronic Chemical Potential (μ), Chemical Hardness (η), and Electrophilicity (ω) Indexes[a]

	HOMO	LUMO	μ (eV)	η (eV)	ω (eV)
Alkyloxonium Mono- and Dications					
H_2O	−0.2911	0.0627	−3.11	9.63	0.50
H_3O^+	−0.7489	−0.2700	−13.86	13.03	7.37
H_4O^{2+}	−1.2954	−0.6021	−25.82	18.86	17.67
CH_3OH	−0.2645	0.0753	−2.57	9.24	0.36
$CH_3OH_2{}^+$	−0.6266	−0.2357	−11.73	10.64	6.47
$CH_4OH_2{}^{2+}$	−0.9205	−0.4922	−19.22	11.65	15.85
CH_3OCH_3	−0.2518	0.0923	−2.17	9.36	0.25
$CH_3(OH)CH_3{}^+$	−0.5594	−0.2066	−10.42	9.60	5.66
$(CH_3)_3O^+$	−0.5436	−0.1770	−9.80	9.98	4.81
$(CH_3)_3(OH)^{2+}$	−0.8357	−0.4766	−17.85	9.77	16.31
Carboxonium Mono- and Dications					
H_2CO	−0.2685	−0.0421	−4.23	6.16	1.45
H_2COH^+	−0.6727	−0.3773	−14.29	8.04	12.70
$H_2C(OH_2)^{2+}$	−1.0243	−0.6891	−23.31	9.12	29.79
CH_3COH	−0.2552	−0.0218	−3.77	6.35	1.12
$CH_3CH(OH)^+$	−0.6239	−0.3287	−12.96	8.03	10.46
$CH_3CH(OH_2)^{2+}$	−0.8654	−0.5988	−19.92	7.25	27.37
CH_3COCH_3	−0.2436	−0.0119	−3.48	6.30	0.96
$CH_3C(OH)CH_3{}^+$	−0.5955	−0.3002	−12.18	8.03	9.24
$CH_3C(OH_2)CH_3{}^{2+}$	−0.8147	−0.5562	−18.65	7.03	24.74
Mono- and Diprotonated Carboxylic Acids					
HCOOH	−0.2917	−0.0008	−3.98	7.92	1.00
$HC(OH)_2{}^+$	−0.6400	−0.3085	−12.90	9.02	9.22
$HC(OH)(OH_2)^{2+}$	−0.9377	−0.5899	−20.78	9.46	22.82
CH_3COOH	−0.2751	0.0094	−3.62	7.74	0.84
$CH_3C(OH)_2{}^+$	−0.6113	−0.2776	−12.09	9.08	8.05
$CH_3C(OH)(OH_2)^{2+}$	−0.8362	−0.5378	−18.69	8.12	21.51

[a] All properties were evaluated at the ground state of molecules optimized at the B3LYP/6-31G(d) level of theory. See text for details.

to 14.4 eV (4,4′-bis(dichloro)benzhydrylium ion).[48] Diazonium ions display an even higher pattern of electrophilicity ranging from 10.1 eV (*N*,*N*-dimethylbenzenediazonium ion) to 17.4 eV (2,4-dinitrodenzenediazonium ion).[43] It is worth emphasizing that the ω scale of electrophilicity has been extensively validated against kinetic[43,48,49] as well as spectroscopic scales[50] of electrophilicity. In Table 1 are displayed the global electrophilicity values for a series of alkyloxonium and carboxonium dications and diprotonated carboxylic acids. The values are presented in the order of increasing electrophilicity for each group, with reference to the neutral parent compounds. The values of electronic chemical potential (μ) and chemical hardness (η) needed to evaluate the global electrophilicity index (ω) through eq 1 are also included.

The first group corresponds to the alkyloxonium dications, which are obtained as derivatives of the parent hydronium ion H_3O^+ by substituting one, two, or all three hydrogen atoms with alkyl groups. The second group includes carboxonium dications, i.e., alkylated carbonyl compounds, such as ketones and aldehydes. Finally, the third group corresponds to diprotonated carboxylic acids such as formic and acetic acids. It may be seen that the whole series of dications present a dramatic enhancement in electrophilicity. Note that their enhanced electrophilicity mainly results from their remarkable high electronegativity (the negative value of the electronic chemical potential, $\chi = -\mu$). Note also that, despite the fact that these species show very high values of hardness (an effect that according to eq 1 plays against the ability of the chemical species to accept further electronic charge from the environment), they still remain as powerful electron acceptors

The analysis within the individual groups shows that in the alkyloxonium series, the highest electrophilicity value is that associated with the H_4O^{2+} dication. Experimental studies have evidenced the presence of H_4O^{2+} (protohydronium dication) from hydrogen/deuterium exchange in isotopic hydronium ions with strong superacids.[11] Theoretical calculations in the gas phase have concluded that the diprotonation of water leads to an intermediate thermodynamically unstable with a considerable barrier to dissociation.[9,11] However, in superacidic solutions, clustering of these dications with their precursors could stabilize and delocalize the excess of charge.[9,11] For the methanol series, the charged derivatives are predicted to be less electrophilic than the water cation and dication. The dimethyl ether series shows an even lower electrophilic character as compared to the water and methanol series. Note that within this series protonation of dimethyl ether produces a more affective electrophilic activation than methylation ($\omega = 5.66$ and 4.81 eV, respectively).

The enhanced electrophilicity pattern in the series of carboxonium ions may reflect the stabilizing effects of the alkyl groups. Probably, the most common of these is the inductive effect, yet another source of alkyl group stabilization involves rehybridization energies, hyperconjugation, and other polarizability effects.[51] The increasing inductive effect by methyl substitution results in a progressive electrophilic deactivation. Compare for instance the series of formaldehyde, acetaldehyde, and acetone in Table 1. Finally, the series of carboxylic acids also show electrophilic deactivation induced by methyl substitution.

In Table 2 are depicted the electrophilic Fukui function at site k, f_k^+, the local electrophilicity ω_k, and the net charges on the atoms from Mulliken and natural bond orbital (NBO) analysis. The relevant electrophilic sites are the carbon atom in the series of the alkyloxonium ions and the carbonyl carbon atom in the carboxonium and diprotonated carboxylic acids. Also, we have incorporated in Table 2 the theoretical computed ^{13}C NMR and ^{17}O NMR chemical shifts available from the literature,[31,32] to compare to our results. Despite the fact that electrophilicity is not physically observable, the experimental hierarchy of electrophilicity may normally be associated to the NMR chemical shifts. Whereas upfield shifts are correlated with an increase in electron density at the electrophilic site and therefore with an electrophilic deactivation at that site, downfield chemical shifts are associated with electrophilic activation at the active

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TABLE 2. Electrophilic Fukui Function, f_k^+, Local Superelectrophilicity, ω_k, Net Charges on Atoms (Q_C, Q_H), and Calculated and Experimental NMR Chemical Shifts

	f_H^+	ω_H	Q_H[b]	Q_H[c]	NMR	IGLO(II) (δ)[a]	GIAO-MP2 (tzp/dz) (δ)[a]	expt (δ)[a]
				Alkyloxonium Mono- and Dications				
H_2O	0.5000	0.25	0.4668	0.3871	^{17}O	0.0	0.0	0.0
H_3O^+	0.3333	2.46	0.6060	0.5462	^{17}O	−2.2	28.2	10.2
H_4O^{2+}	0.2500	4.42	0.7304	0.6702	^{17}O	7.7	47.3	

	f_C^+	ω_C	Q_C[b]	Q_C[c]	NMR	IGLO(II) (δ)[a]	GIAO-MP2 (tzp/dz) (δ)[a]	expt (δ)[a]
CH_3OH	0.1369	0.05	−0.3042	−0.2042	^{13}C	51.7	54.0	50.2
$CH_3OH_2^+$	0.3104	2.01	−0.2954	−0.2803	^{13}C	78.4	80.2	
$CH_4OH_2^{2+}$	0.0425	0.67	−0.4701	−0.4395	^{13}C	49.9	51.4	
CH_3OCH_3	0.0582	0.01	−0.3084	−0.1913	^{13}C	58.5	62.4	59.4
$CH_3(OH)CH_3^+$	0.2721	1.54	−0.3006	−0.2518				
$(CH_3)_3O+$	0.3246	1.56	−0.3122	−0.2604	^{13}C	76.6	81.9	79.3
$(CH_3)_3(OH)^{2+}$	0.3022	4.93	−0.2388	−0.2813	^{13}C	128.1	133.1	
				Carboxonium Mono- and Dications				
H_2CO	0.6508	0.95	0.2259	0.0809	$^{13}C_{carbonyl}$	203.1	185.3	
H_2COH^+	0.7725	9.81	0.4081	0.1367	$^{13}C_{carbonyl}$	240.0	228.8	223.8
$H_2C(OH_2)^{2+}$	0.8715	25.96	0.5626	0.2488	$^{13}C_{carbonyl}$	266.4	265.3	
CH_3COH	0.6031	0.67	0.4111	0.2617		208.5[d]	190.8[d]	
$CH_3CH(OH)^+$	0.7084	7.41	0.5472	0.2964		224.8[d]	211.6[d]	
$CH_3CH(OH_2)^{2+}$	0.7217	19.75	0.5890	0.3703		254.7[d]	249.6[d]	
CH_3COCH_3	0.5353	0.51	0.5863	0.4514	$^{13}C_{carbonyl}$		198.6	205.1
$CH_3C(OH)CH_3^+$	0.6540	6.04	0.7163	0.4874	$^{13}C_{carbonyl}$	268.4	256.3	248.7
$CH_3C(OH_2)CH_3^{2+}$	0.6728	16.64	0.7564	0.5464	$^{13}C_{carbonyl}$	291.7	278.8	

	f_C^+	ω_C	Q_C[b]	Q_C[c]	NMR	IGLO(II) (δ)[a]	GIAO-MP2 (tzp/dz) (δ)[a]	expt (δ)[a]
				Mono- and Diprotonated Carboxylic Acids				
HCOOH	0.6222	0.62	0.6435	0.3651	$^{13}C_{carbonyl}$	173.0	160.2	167.6
$HC(OH)_2^+$	0.6767	6.25	0.7595	0.4653	$^{13}C_{carbonyl}$	192.6	183.3	177.6
$HC(OH)(OH_2)^{2+}$	0.7022	16.03	0.8264	0.5675	$^{13}C_{carbonyl}$	189.7	180.5	
CH_3COOH	0.5360	0.45	0.8223	0.5614	$^{13}C_{carbonyl}$	184.3	171.9	176.9
$CH_3C(OH)_2^+$	0.6226	5.01	0.9393	0.6493	$^{13}C_{carbonyl}$	211.3	202.0	193.0
$CH_3C(OH)(OH_2)^{2+}$	0.6393	13.75	0.9864	0.7360	$^{13}C_{carbonyl}$	213.7	203.4	

[a] From ref 30 and references therein. [b] Net charges from NBO population analysis at the same level of theory. [c] Net charges from Mulliken population analysis at the same level of theory. [d] Predicted values from correlation equation of Figure 1a and b.

site.[52] This means that electrophilic activation/deactivation may be better represented as local changes in the ω index. Local electrophilicity may be obtained from the global counterpart and the electrophilic Fukui function, as described in eq 2.

For the series of alkyloxonium ions, the enhanced local electrophilicity predicted for the hydrogen atoms in H_4O^{2+} ($\omega_H = 4.42$ eV, see Table 2) may be indicative of the cluster formation in superacid media: under this condition the H_4O^{2+} protons might be shared by more than one H_3O^+ by hydrogen bonding. [11] This interpretation also is in agreement with previous results suggesting that this associative mechanism minimizes the charge−charge repulsion.[30,53] For the methanol subseries, the second H^+ added to form the dication is bound to the CH_3 group. This substitution pattern causes the local electrophilicity of carbon to dramatically decrease from 2.01 eV in the monocation to 0.67 eV in the dication. Note that this prediction is in agreement with the theoretical NMR chemical shifts as described by the IGLO and GIAO-MP2 indexes. Unfortunately, the experimental NMR chemical shift for these compounds is only available for methanol. However, for the first series of alkyloxonium ions our predicted electrophilicity enhancement is in agreement with the experimental chemical shift for water and hydronium ion. It is also interesting to mention that while the carbon atom is electrophilically deactivated, one of the hydrogen atoms bound to the carbon atom of the CH_3 group notably increases its electrophilicity to $\omega_H = 5.39$ eV (not shown in Table 2). Here again, the high value in local electrophilicity predicted for the hydrogen atom is consistent with the explanation offered by Olah,[9,11] to account for the extra stabilization of the dication due to the possibility to form clusters in superacidic media.

For the dimethyl ether subseries, a qualitative good correlation between local electrophilicity and the theoretical ^{13}C NMR chemical shifts described by the IGLO and GIAO-MP2 indexes was obtained. Note further that for the species for which the experimental NMR chemical shift is available (dimethyl ether and the trimethyl oxonium cation), the enhancement in electrophilicity is again correlated with the enhancement in the experimental chemical shift at the carbon atom.

Diprotonated carbonyl compounds such as aldehydes and ketones are highly stabilized by resonance as compared to alkyl cations.[16,53] They have been extensively examined in the past using a wide variety of techniques.[2,5,16,53] These compounds can behave like oxonium (positive charge on the oxygen atom of the carbonyl group) or carbenium (positive charge on the carbon atom) ions. Despite the numerous theoretical works concerned

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(52) (a) Neuvonen, H.; Neuvonen, K. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1497. (b) Neuvonen, H.; Neuvonen, K.; Koch, A.; Kleinpeter, E.; Pasanen, P. *J. Org. Chem.* **2002**, *67*, 6995.

(53) Perst, H. In *Carboxonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York 1976; Vol. 5.

with the prediction of their existence, diprotonated species have not been experimentally observed by NMR techniques, due to the low concentration of these extremely reactive electrophiles, even in superacid media. From Table 2, it may be seen that the diprotonated formaldehyde exhibits the highest local electrophilicity ($\omega_C = 25.96$ eV) in agreement with the strong theoretical ^{13}C NMR chemical shifts deshielding predicted from the IGLO and GIAO-MP2 indexes (compare third, seventh, and eighth columns in Table 2). For the acetone subseries both the IGLO and GIAO-MP2 indexes predict an increasing deshielding of about of 23 ppm at the carbonyl carbon atom in $CH_3C(OH_2)CH_3^{2+}$ as compared to the protonated acetone, $CH_3C(OH)CH_3^{+}$.[23] Note that this pattern is again in qualitative agreement with the local electrophilicity variations at the carbonyl carbon atom ($\omega_C = 6.04$ and 16.64 eV, respectively). Finally, for the carboxylic acid series, the comparison of the local electrophilicity index with the theoretical ^{13}C NMR chemical shifts obtained by IGLO and GIAO-MP2 methods and the available experimental data is again in good qualitative agreement. The carbonyl carbon atom of dications is predicted to be shifted to downfield, and this result is consistent with an electrophilicity enhancement described by the local electrophilicity index. A general look at Table 2 reveals that the comparison between charges obtained from Mulliken and NBO population analysis and IGLO and GIAO-MP2 indexes shows a poorer comparison than the one obtained using the local electrophilicity index.

A definitive test of the reliability and usefulness of the present model based on global and local electrophilicity indexes must be proved on a more quantitative basis. Following a suggestion by a reviewer we performed a correlation analysis between the local electrophilicity index and the IGLO and GIAO quantities for the formaldehyde series to predict the unavailable IGLO and GIAO chemical shifts for the acetaldehyde series. Figure 1a shows the comparison between IGLO and ω_C quantities for the formaldehyde series. The resulting regression equation shown in Figure 1a was used to predict the IGLO chemical shifts for the acetaldehyde series included in Table 2, seventh column. A similar comparison was performed between GIAO and ω_C indexes for the series of formaldehyde. The results are displayed in Figure 1b. From the resulting regression equation shown in Figure 1b, the GIAO values for the acetaldehyde series were predicted. They are displayed in Table 2, eighth column. Note that the predicted IGLO and GIAO values of the acetaldehyde series are bound by those of formaldehyde (lower bound) and acetone (upper bound) series. However, a definite testing of these predictions is subject to experimental confirmation.

Conclusions

A relationship between the enhanced electrophilicity pattern of isolated alkyloxonium and carboxonium ions and diprotonated carboxylic acids and the global electrophilicity indexes has been presented. The local responses at the electrophilic sites are easily assessed by using the electrophilic Fukui function to project the global electrophilic potential into the different atoms in the dications. The theoretical local electrophilicity index roughly reproduces the experimental superelectrophilicity hierarchy established on the basis of the theoretical and experimental data of ^{17}O and ^{13}C NMR chemical shifts. The reliability and usefulness of the present model was illustrated by predicting the theoretical chemical shifts for the acetaldehyde series from regression equations between the IGLO and GIAO numbers and the local electrophilicity values for the formaldehyde series.

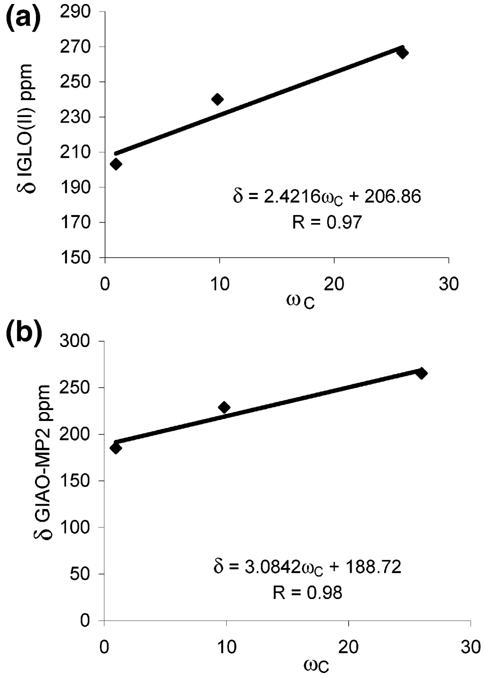

FIGURE 1. (a) Comparison between ^{13}C NMR/IGLO(II) chemical shifts and the local electrophilicity index, ω_C, for the monocation, dication, and the neutral formaldehyde species. *R* is the regression coefficient. (b) Comparison between ^{13}C NMR/GIAO-MP2 chemical shifts and the local electrophilicity index, ω_C, for the monocation, dication, and the neutral formaldehyde species. *R* is the regression coefficient.

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Supporting Information Available: Cartesian coordinates and total energies for the optimized geometries of the whole series of species considered in the present study. This material is available free of charge via the Internet at http://pubs.acs.org.

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