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THE DONOR-ACCEPTOR AND CHARGE ALTERNATION PRINCIPLE AND THE ELECTROCHEMICAL OXIDATION AND REDUCTION OF DISUBSTITUTED BENZENES

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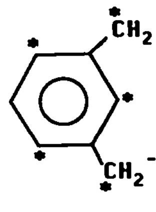
The charge alternation principle correlates nicely with the redox potential of disubstituted benzenes, and predicts that the least thermodynamically stable isomer in a given series of *ortho-*, *para-*, and *meta-* disubstituted benzenes, is also the easiest to oxidize or reduce, electrochemically.

Introduction

We have recently[1,2] discussed a very simple concept, the charge or donor-acceptor alternation, that permits to predict the relative stabilities of polysubstituted compounds. This concept was applied to polymetalation of xylenes[3,4], acetophenones[5], trimethylenemethane dianion[6] and propargylic systems, and found to be quite useful. It explained nicely the regioselectivity of polymetalation of allylic, benzylic and propargylic systems. Recently the charge alternation concept was also extended to charged polycyclic molecules (for both dianions and dications)[7]. Rules, which are based on calculated charge densities and ^{13}C-NMR, were formulated to help to predict how the charges will be placed in a given compound.

The essence of the charge alternation rule is that when a molecule contains more than one charged atom of the same kind (positive or negative), these charged centers will prefer to be located on the same set of atoms, starred or unstarred, of an alternating system. An isomer containing such an arrangement of charges, as e.g., in *meta-* xylylene dianion **1**, will be more stable[1,2] than its positional isomer with a different distribution of charges, as in *para-* xylylene dianion **2**. This means that the additional introduction of charges on the same set of atoms, where the first charge was located, is preferred to their distribution on all atoms of the system. A similar stabilization[6] of the trimethylene dianion **3** relative to the butadiene dianion **4**



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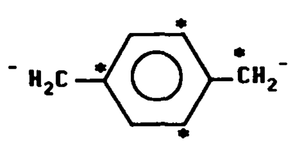

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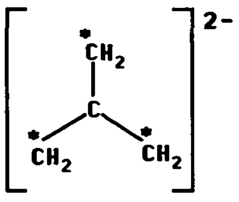

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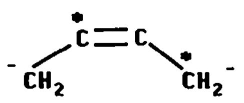

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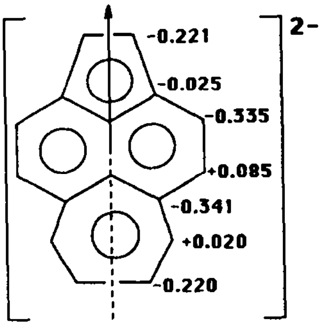
was also observed. Moreover, the set of atoms which are not carrying the main charge of the system is polarized in such a way, that these atoms assume a small charge of the opposite sign. This polarization was also observed by ^{13}C-NMR[7,8a] and calculations on monoanions[8b] and monocations.[8c]

In addition, uncharged molecules containing more than one donor or more than one acceptor, will also be more stable relative to their isomers with a different location of these substituents, if all the donors or acceptors are on the same set of atoms of an alternating system. The calculated energies of *meta*-difluorobenzene, *meta*- dihydroxybenzene, *meta*- fluorophenol and *meta*- aminophenol, are lower than those of their corresponding *para*- isomers. However, the energies of *para*- fluorobenzonitrile, *para*-nitrophenol and *para*- hydroxybenzonitrile, are lower than those of their corresponding *meta*- isomers.[9] These molecules undergo a polarization similar to that of the ions, where donors are the negative centers and acceptors the positive ones.

Compounds containing both donors and acceptors will be stabilized when all the donors are on one set, and all the acceptors on the other set of atoms (starred or unstarred).

In non-alternating systems (e.g., 5) or in alternating systems (e.g., 6), containing an even number of charges and an axis or plane of symmetry crossing one or more bonds, it is impossible to distribute the charges on alternating atoms, for symmetry reasons. In such a case, the system can be divided by the element of symmetry into two subsystems. In each of the subsystems, the charge alternation is preserved.[7] A similar distribution of charges was also observed in dications of polycyclic hydrocarbons, and in dianions of heterocyclic compounds, e.g. 7. The numbers indicated near the atoms are calculated charges, that are in good agreement with the values of charge densities derived from ^{13}C-NMR shifts.[7]



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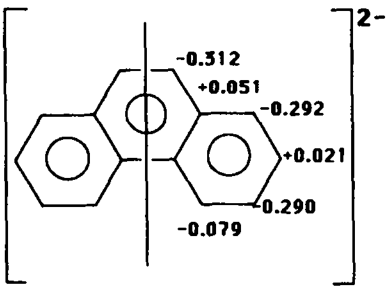

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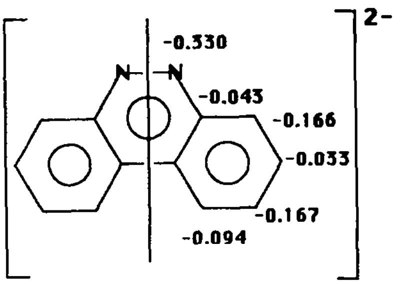

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The present paper deals with the donor-acceptor alternation principle in relation to the redox potentials of disubstituted benzenes. The influence of substituents on the oxidation and reduction potentials of aromatic compounds has been studied extensively. Under electrochemically reversible conditions the redox potentials should depend on the differences in stabilities between the unsubstituted neutral species and its corresponding ion, relative to the substituted neutral one and its corresponding ion. Eventually other factors play also a role, such as the solvation of the various species, which may sometimes lead to unexpected results.

Results and Discussion

Recently we have discussed the concept of stabilization by charge alternation in uncharged systems containing more than one donor or acceptor[1,2]. This simple concept permits to predict the relative thermodynamic stabilities of polysubstituted compounds. For instance, in aromatic compounds, it predicts the larger stabilities of the *ortho*- and *para*- relative to the *meta*- isomers, containing one donor and one acceptor substituents. Moreover, when two donors or two acceptors are located on the aromatic ring, it predicts the larger stability of the *meta*- isomers relative to the *ortho*- and *para*- ones. In all these compounds, partial charge alternation takes place in the whole molecule. This charge alternation is disturbed in the ions of all isomers when an additional charge, positive or negative, is introduced in the molecule. Consequently, such a perturbation may lead to the anticipation that the relative stabilities of the neutral molecules caused by charge alternation before the electrochemical reduction or oxidation, will determine the extent of the reduction and oxidation potentials, respectively. Therefore, in order to test this hypothesis, we examined a number of electrochemical results appeared in the literature.

The electrochemical data presented in Table 1 include the reduction potentials of a wide range of disubstituted benzenes containing one donor and one acceptor (entries 1-22), and five examples (entries 23-27) containing two acceptors attached to the benzene ring. The results, which were obtained by different researchers and under different experimental conditions, show that in general, the electrochemical reduction of the *ortho-* and *para-* isomers in the latter examples is easier than that of the corresponding *meta-* isomers. However, when the two substituents involve one donor and one acceptor, the reduction of the 1,3- isomer now becomes more facile than for the corresponding 1,2- and 1,4- isomers. As is expected, in both these cases the ease of the reduction is indirectly proportional to the relative stability predicted by the charge alternation principle. It is noteworthy that whenever a deviation from this correlation was found, it was always related to the *ortho-* isomer (values in parentheses). This phenomenon is not surprising since it is not unusual for *ortho-* isomers to be exceptional, due to steric and other effects. It is remarkable that also the electrochemical oxidation (Table 2) of disubstituted benzenes with one donor and one acceptor (entries 1-5), and with two donors (entries 6-15), follow the same rules that we have outlined above for the electrochemical reduction.

In conclusion, we found out that the types of compounds which undergo an easier reduction also undergo an easier oxidation. Furthermore, on the basis of the correlations which are described in this work, one may reach the conclusion that the energy of the charged species is similar for all isomers in a given series.

Table 1. Reduction potentials of disubstituted benzenes

	C_6H_4XY		$-E_{1/2}$ vs. SCE[a]				
Entry	X	Y	*ortho*	*meta*	*para*	media	Ref.
1.	NO_2	OMe	0.285	$\underline{0.225}$	0.320	55% EtOH-0.22N H_2SO_4	10a
2.	NO_2	F	0.235	$\underline{0.215}$	0.275	"	10b
3.	NO_2	Cl	0.200	$\underline{0.175}$	0.205	"	10b
4.	NO_2	Br	0.180	$\underline{0.160}$	0.170	"	10b
5.	NO_2	I	0.160	$\underline{0.120}$	0.130	"	10b
6.	NO_2	OH	(0.200)	$\underline{0.250}$	0.355	"	10a
7.	NO_2	NH_2	0.355	$\underline{0.270}$	0.360	"	10b
8.	NO_2	Me	0.300	$\underline{0.245}$	0.270	"	10b
9.	NO_2	Me	1.005	$\underline{0.936}$	1.035	66% EtOH-0.01M Et_4NBr	11
10.	CHO	OH	1.504	$\underline{1.500}$	1.720	"	11
11.	CHO	Cl	(1.331)	$\underline{1.384}$	1.422	"	11
12.	CHO	Br		$\underline{1.358}$	1.410	"	11
13.	CHO	Br	(0.733)	$\underline{0.768}$	0.812	aq. buffer-50% dioxane	12
14.	CHO	I	(1.248)	$\underline{1.390}$	1.400	66% EtOH-0.01Et_4NBr	11
15.	CHO	NH_2		$\underline{1.52}$	1.700	"	11
16.	CHO	NH_2	1.030	$\underline{0.95}$	1.064	pH=1.73	11
17.	CHO	OMe	0.918	$\underline{0.845}$	1.190	aq. buffer-50% dioxane	12
18.	COMe	OH	1.065	$\underline{1.00}$	1.101	"	12
19.	COMe	Cl	0.964	$\underline{0.925}$	0.926	"	12
20.	COMe	Br	0.982	$\underline{0.899}$	0.928	"	12
21.	COMe	Br	1.904	$\underline{1.778}$	1.831	0.1M KCl	13
22.	COMe	Me	(1.863)	$\underline{1.891}$	1.985	0.1M KCl	13
23.	NO_2	CHO	$\underline{0.690}$	0.822	$\underline{0.632}$	66% EtOH-0.01M Et_4NBr	13
24.	NO_2	COOEt	$\underline{0.826}$	0.850	$\underline{0.770}$	"	13
25.	NO_2	CN	$\underline{0.115}$	0.155	$\underline{0.100}$	55% EtOH-0.22N H_2SO_4	10b
26.	NO_2	COOEt	(0.230)	0.160	$\underline{0.115}$	"	10b
27.	NO_2	COOH	(0.230)	0.190	$\underline{0.100}$	"	10b,10c

[a] Polarographic half-wave potentials (in volts) on mercury working electrodes. The underlined values correspond to the least stable isomer, as predicted by the charge alternation concept.

Table 2. Half-wave oxidation potentials of disubstituted benzenes (C_6H_4XY)[a]

Entry	X	Y	*ortho*	*meta*	*para*	Ref.
1.	NO_2	NH_2	0.989	0.854	0.935	14
2.	NH_2	COMe	0.847	0.758	0.820	14
3.	OH	COMe	0.801	0.754	0.791	14
4.	NH_2	COOH	0.676	0.668	0.84	14
5.	NO_2	OH	(0.846)	0.855	0.924	14
6.	OH	OEt	0.451	0.620	0.413	14
7.	OH	OMe	0.456	0.619	0.406	14
8.	OH	Me	0.556	0.607	0.543	14
9.	OH	Et	0.551	0.616	0.567	14
10.	Cl	NH_2	0.742	0.774	0.675	14
11.	Cl	OH	0.625	0.734	0.653	14
12.	NH_2	OMe	0.573	0.606	0.537	14
13.[b]	NH_2	NH_2	0.309	0.678	0.10	15
14.[c]	NH_2	NH_2	0.495	0.811	0.495	16
15.[d]	OH	*t*- Bu	0.38	0.47	0.41	17

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[a] Potential values are in volts vs. SCE reference electrode, on graphite working electrode, at pH=5.6

[b] At pH=4.5

[c] At pH=1.0

[d] At pH=9.0

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