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The Elongated (One Electron) Carbon-Carbon Bond in σ and n Organic Cation Radicals

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Abstract: Results of MNDO calculations for the ethane cation radical are favorably compared to optimized minimum (STO-3G) and extended (4-31G; 6-31G**) basis set ab initio SCF MO calculations and to available SCF MO/CI calculations, especially in characterizing the elongated (one electron) bond in this species. This unusual structural feature is shown to be rather general for alkane cation radicals in an MNDO and ab initio study of the cation radicals of propane, neo-, iso-, and cyclobutane, and neopentane. The results are also compared with appropriate mass spectrometric observations. The cation radicals of a variety of functionalized organic molecules were further included in the study. Ground-state long-bond structures were found for fluoro- and chloroalkanes and alcohols and (implicitly) ethers. Long-bond relative minima were found for esters, but not ketones, aldehydes, amines, or thiols.

The impressive current flux of new cation radical chemistry (solution, gas phase, and solid state) presents a challenge to and opportunity for the theoretician to understand better a class of reactions that has been somewhat neglected in reference to theory. A key prerequisite for a such a theoretical/mechanistic study was considered to be the acquisition of basic structural information on the various types of cation radical intermediates involved. An ab initio and semiempirical SCF MO study of the structures of organic π cation radicals was described in a recent paper, where it was shown that the novel twisting characteristic of the ethene cation radical is treated extremely accurately by MNDO, in terms of both the equilibrium twist angle (25°) and the barrier height (0.67 kcal mol^{-1}).[1] The accuracy of MNDO was found superior to that of the minimum basis set (STO-3G) and even the moderately extended (4-31G; 6-31G**) basis set ab initio SCF MO calculations, all of which predict a planar ground-state structure. The efficiency and economy of MNDO permitted extension of the twisting study to more complex alkene cation radicals as well as to conjugated π-cation radicals. Subsequently, attention has focused on the novel structures of σ- and n-cation radicals.

The electronic configuration of ground-state, neutral ethane is known to be $(1a_{1g})^2(1a_{2u})^2(2a_{1g})^2(2a_{2u})^2(1e_u)^4(3a_{1g})^2(1e_g)$,[4] from which the HOMO's are seen to be a doubly degenerate pair of MO's of $1e_g$ symmetry (D_{3d} point group).[2] One of these HOMO's, for example, is delocalized over a four-atom HCCH orbital system that involves two anti hydrogens, bonded in the CH region, antibonded in the CC region, and heavily concentrated on the hydrogens. From Koopmans' theorem, ionization of an electron from one of the $1e_g$ orbitals should presumably give the ground-state ethane cation radical. This reasoning receives apparent support from the photoelectron spectrum (PES) of ethane[3] and from a very recent matrix isolation/electron spin resonance study of this cation radical.[4] Nevertheless, the $3a_{1g}$ level of ethane is very proximate, energetically, to the $1e_g$ level. Ionization from the former level could give rise to a rival ($^2A_{1g}$) state. In contrast to the $1e_g$ level, the $3a_{1g}$ MO is bonding in both the CC and CH regions, but heavily concentrated on the carbon atoms. Geometry-optimized semiempirical[5] and ab initio[6] SCF MO calculations find the $^2A_{1g}$ state actually to lie well below the ^2E_g (Koopmans') state as a result of elongation of the CC bond, which inverts the ordering of the two levels in question. The excellent SCF MO/CI calculations of Buenker and Peyerimhoff confirm this prediction and establish an energy difference between the two states on the order of 10-15 kcal mol^{-1}.[7] The latter authors point out that the observation of a ^2E_g ground state by PES is in accord with theory, since photoionization is a vertical (Franck-Condon) process, and the ^2E_g state does indeed lie slightly below the $^2A_{1g}$ state at the CC distance of neutral ethane. That the ^2E_g state is also the ground state in at least some matrices presumably is a result of the (steric) difficulty of stretching the CC bond in a matrix cavity and possibly also of the greater (electrostatic) matrix stabilization of the ^2E_g state, which has its positive charge primarily on the periphery of the ion in contrast to the $^2A_{1g}$ state, in which the charge is predominantly on the central (carbon) atoms. Nevertheless, the theoretical studies leave little doubt that, in the gas phase, the ground state of the ion is $^2A_{1g}$. In this state the ethane cation radical (**1**) has, as a good approximation, a one-electron CC bond similar to the prototype one-electron bond of $H_2^{+}\cdot$. The dissociation energy of this bond in various MO approximations is listed in Table I, along with other pertinent geometric parameters, the most noteworthy of which is the CC bond length. The two methyl fragments retain the staggered conformation of neutral ethane, but the carbons adjust toward (but do not quite achieve) an sp^2 hybridization state (see the HCC angle). The state is essentially of D_{3d} symmetry, but the CI calculation indicates a tendency to distort toward a diborane-like C_{2h} structure.[7]

Table I. Calculated Structures of Ethane Cation Radical

calculation	R_{CC}, Å	HCC angle, deg	D, kcal	ΔE, kcal	ρ_C[b]
STO-3G[6]	1.8585	100	52	12	0.466
4-31G[a]	2.0334	98	37	12	0.496
6-31G**[a]	1.9833	98	38	12	0.457
MO/CI[7]	1.8515	100		(12-15)	
MNDO[a]	1.9076	99.2	16.5	2.7	0.466

[a] This work. [b] Spin density on carbon.

The careful theoretical scrutiny that has been centered on **1** provides an ideal opportunity for the continuation of the examination and validation of MNDO as an efficient and reliable means for estimating structures, and eventually reaction paths, of cation radicals that are too complex to be readily amenable to study via extended basis set ab initio SCF MO and MO/CI methods. The MNDO results for **1** are included in Table I. The geometric parameters, in fact, closely approximate those for the ab initio

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(1) Bellville, D. J.; Bauld, N. L. *J. Am. Chem. Soc.* **1982** *104*, 294.

(2) Rabelais, J. W.; Katrib, A. *Mol. Phys.* **1974**, *27*, 923.

(3) Baker, A. D.; Betteridge, D.; Kemp, N. R.; Kirby, R. E. *J. Mol. Struct.* **1971**, *8*, 75.

(4) Iwasaki, M.; Toriyama, K.; Numone, K. *J. Am. Chem. Soc.* **1981**, *103*, 3591.

(5) Dewar, M. J. S. D.; Worley, S. D. *J. Chem. Phys.* **1969**, *50*, 654.

(6) Pople, J. A.; Lathan, W. A.; Curtiss, L. A. *J. Am. Chem. Soc.* **1971**, *93*, 808.

(7) Richartz, A.; Buenker, R. J.; Bruna, P. J.; Peyerimhoff, S. D. *Mol. Phys.* **1977**, *33*, 1345.

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Table II. Calculated Structures of Alkane Cation Radicals

alkane	calcn	$R_{C\cdots C}(R_{CC})^a$	ΔH_f, kcal	ΔE, kcal
ethane	MNDO	1.9076	251.95	2.7
propane	MNDO	1.8824 (1.4883)	237.50	3.3
propane	STO-3G	1.8588 (1.5169)		
n-butane[b]	MNDO	1.9144 (1.4930)	224.82	10.1
n-butane[c]	MNDO	1.8947 (1.4937, 1.5552)	231.49	6.7
isobutane	MNDO	1.9018 (1.5064)	228.58	4.8
cyclobutane	MNDO	1.9210 (1.5030, 1.5651)		
cyclobutane	STO-3G	1.8506 (1.5290, 1.5763)		

[a] $R_{C\cdots C}$ is the optimized long-bond distance in angstroms. The R_{CC}, where applicable, are other optimized CC distances. The CC bonds adjacent to the long bond are shortened by hyperconjugation. [b] The more stable isomer, with $C_2\cdots C_3$ long bond. [c] The isomer with $C_1\cdots C_2$ long bond.

Table III. MNDO Structures for Various Organic Cation Radicals

cation radical	$R_{C\cdots C}$,[a] Å	state type	$\Delta E'$,[b] kcal	ρ_{Het}[c]
$CH_3CH_2CH_2NH_2$		n	*d*	0.98
$CH_3CH_2CH_2SH$		n	*d*	1.01
$CH_3CH_2C(O)H$		n	*d*	0.85
$CH_3C(O)CH_3$		n	*d*	0.88
$CH_3CH_2CH_2F$		n/π	14.9	0.18
$CH_3\cdots CH_2CH_2F$	1.909	σ	18.7	0.01
$CH_3CH_2\cdots CH_2F$	2.0478	σ/n	0.0	0.20
$CH_3CH_2CH_2Cl$		n	3.7	0.83
$CH_3\cdots CH_2CH_2Cl$	1.8913	σ	5.1	0.10
$CH_3CH_2\cdots CH_2Cl$	1.8996	σ/n	0.0	1.00
$CH_3C(O)OCH_2CH_2CH_3$		n (C=O)	0.0	1.00
$CH_3C(O)OCH_2\cdots CH_2CH_3$	1.9003	σ/n	17.9	

[a] R_{CC} is listed only if a long bond is present. [b] Energy relative to the ground state as 0.0 kcal. [c] Spin density on the heteroatom. [d] Only state.

Table IV. Calculated Structures for Alcohol Cation Radicals

cation radical	calcn	$R_{C\cdots C}$, Å	state type	$\Delta E'$, kcal
CH_3CH_2OH	MNDO		n	2.4
	MNDO	1.6699	σ/n	0.0
	STO-3G		n	*b*
	4-31G		n	0.0
	4-31G	1.9688	σ/n	11.2
	6-31G*		n	0.0
	6-31G*	1.9975	σ/n	2.0
$CH_3CH_2CH_2OH$	MNDO	1.8115	σ/n	*b*
	STO-3G		n	*b*
	4-31G		n	0.0
	4-31G	2.0147	σ/n	2.5
	6-31G*	*a*	n	4.8
	6-31G*	(2.0147)[a]	σ/n	0.0

[a] Point calculations at 4-31G optimized geometry. [b] Only state.

methods, although the energy difference (ΔE) between the $^2A_{1g}$ ground state and the next higher state is appreciably smaller in MNDO. This may be partially accounted for by the fact that the upper state in MNDO is not the ^2E_g state, but an unsymmetric state having elongated geminal CH bonds (i.e., primarily having a delocalized HCH orbital system) that has not been explicitly considered in any of the previous ab initio studies. MNDO does not locate a true minimum for the ^2E_g state, but neither do any of the fully optimized ab initio calculations indicate the existence of such a minimum.

With use of MNDO, the structure investigation was extended to the cation radicals of propane, neo-, iso-, and cyclobutane, and neopentane. In the case of the propane and cyclobutane cation radicals, optimized STO-3G calculations were also carried out as a check. Results are listed in Table II. In every case except that for the neopentane cation radical, where no minimum at all is encountered prior to dissication to the *tert*-butyl cation and the methyl radical, the ground state has a long-bond structure analogous to that of the ethane cation radical. Significantly, the preference (ΔE) for the long-bond structure increases as thee alkyl fragments are converted from methyl to ethyl to isopropyl, following the familiar order of both carbocation and radical stability. In the *n*-butane cation radical there are two positionally isomeric long-bond states, the structure with the $C_2\cdots C_3$ long bond being favored, in accord with the foregoing generalization. These results also strongly support the recent proposal that *n*-alkane cation radicals rearrange in the mass spectrometer to branched alkane cation radicals, competitively with their decomposition.[8] The rearrangements were proposed to involve long-bond cation radicals in equilibrium with delocalized (perhaps ^2E_g-like) cation radicals, the former undergoing hydrogen and alkyl shifts and other chemistry analogous to that familiar for carbocations. The present results additionally suggest that the long-bond cation radicals actually represent the ground state and that their rearrangement from linear to branched structures is therefore thermodynamically favored. Whether a true mimimum even exists at a ^2E_g-like geometry is less certain. The observation that the neopentane cation radical, in sharp contrast to those mentioned previously, affords no significant amount of its parent ion in the mass spectrometer is in excellent accord with the inability of MNDO to locate an energy mimimum corresponding to either a long- or short-bond structure.[9] Interestingly, the matrix-isolated propane and *n*-butane cation radicals still appear to exist in the delocalized (^2E_g-like) state.[4,10] However, the isobutane and neopentane cation radicals adopt long-bond structures even in the matrix, in accord with the trends calculated by MNDO.[4] The results for cyclobutane are particularly significant in the context of the mechanism for the [2 + 1] cycloaddition of alkene cation radicals to neutral alkenes to give cyclobutane cation radicals, suggesting a possible long-bond intermediate that might be capable of a least partially maintaining stereochemistry.[11] An analogous structure has been proposed for the 1,2-diphenylcyclopropane cation radical based on CIDNP data.[12]

The possibility that long-bond structures might be viable even in heteroatom-containing organic molecules which have nonbonded (n) electrons apparently has not been explicitly considered. This possibility has been investigated, using MNDO to survey the structures of cation radicals of a number of classes of functionalized organic molecules and validating some key conclusions by means of optimized ab initio calculations. For relatively easily ionized functional groups, such as amine, thiol, aldehyde, and ketone groups, MNDO calculations do not detect long-bond minima for the cation radicals. The structures of these species correspond to ionization of a nonbonded electron from the heteroatom, giving an n-type cation radical. The calculations were carried out specifically for ethyl- and propylamine, ethane- and propanethiol, acetaldehyde, propionaldehyde, and acetone.[13] At the other extreme of heteroatom electronegativity and functional group ionizability, long-bond absolute minima are found for fluoroethane and 1-fluoropropane. In the latter case, two long-bond minima are found, but the ground state corresponds to stretching the $C_1\cdots C_2$ bond (Table III). This species has both σ and n character (σ/n), and the odd electron is delocalized mainly over C_1, C_2, and the heteroatom. Similar σ/n long-bond minima are calculated for chloroethane and 1-chloropropane. These are also accompanied by minima of the n type, the n type being slightly

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(8) Wendelboe, J. F.; Bowen, R. D.; Williams, D. H. *J. Am. Chem. Soc.* **1981**, *103*, 2333.

(9) American Petroleum Institute Research Project 44, Mass sepctra Data, Serial No. 8.

(10) Wang, J. T.; Williams, F. *Chem. Phys. Lett.* **1981**, *82*, 177.

(11) Tentative experimental support for this hypothesis is apparently in hand and will be discussed elsewhere: Pabon, R.; Bauld, N., unpublished work.

(12) Roth, H. D.; Mannion, M. L. *J. Am. Chem. Soc.* **1981**, *103*, 7210.

(13) The longer-chain member of each class was included in the study in light of the observation that long-bond chain radicals are more favorable for ethyl than methyl fragments in the alkane cation radicals.

favored in chloroethane but the σ/n type being favored in 1-chloropropane. These results reflect the decreased electronegativity of chlorine relative to fluorine (yielding a more competitive n state) and the alkyl stabilization order discussed previously.

The alcohols are perhaps the most interesting class of those studied. The MNDO calculations find both n and σ/n (long bond) minima for ethanol, the latter being slightly favored (Table IV), but only a σ/n minimum for 1-propanol. Fully optimized ab initio calculations on the ethanol cation radical employing an STO-3G basis set locate only an n-type minimum, but with a 4-31G basis set both minima are found, the n type still being favored. The same results are obtained with a 6-31G** basis set, but the energy difference is reduced to only 2 kcal. The ab initio results for the cation radical of 1-propanol are entirely analogous (Table IV) but the σ/n (long bond) cation radical emerges as the ground state in the 6-31G* calculation, as expected from the alkyl stabilization effect. With use of the CC bond as the reaction coordinate, ab initio calculations were also used to probe for the existence of a σ/n minimum in acetaldehyde, but again none was found. The excellent correspondence between the MNDO and extended basis set ab initio calculations for alcohols and carbonyl compounds justifies considerable confidence in these results and further enhances the credibility of MNDO, especially in its cation radical applications. Apparently, long-bond minima do indeed exist generally in alcohol cation radicals and, in most cases, probably represent the ground-state structure, at least in the gas phase. Although they have not yet been explicitly investigated, the cation radicals of ethers should presumably be subject to the same generalization. Esters appear (Table IV) to have n-type minima corresponding to carbonyl ionization accompanied by considerably less stable σ/n-type minima corresponding to stretching the appropriate CC bond in the ether fragment of the ester.

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Registry No. Ethane radical cation, 34488-65-8; propane radical cation, 34479-70-4; butane radical cation, 34479-72-6; isobutane radical cation, 34479-71-5; cyclobutane radical cation, 34474-99-2.

Synthesis of Oligodeoxyribonucleotides Using *N*-Benzyloxycarbonyl-Blocked Nucleosides

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Abstract: The exo amino groups of 2′-deoxyadenosine and 2′-deoxycytidine have been blocked as the benzyl carbamates, and 2′-deoxyguanosine has been blocked as its 2-*N*-(benzyloxycarbonyl)carbamate and 6-*O*-benzyl ether. These blocked nucleosides have been incorporated into an efficient oligodeoxyribonucleotide synthetic scheme, and the resulting oligomer has been successfully deblocked by using transfer hydrogenation. The deblocking conditions result in no reduction of the pyrimidine bases.

The synthesis of oligodeoxyribonucleotides primarily involves blocking-group chemistry. Nucleosides and nucleotides have multiple reactive centers, and selective reagents must be found for the various functional groups or else the other reactive centers must be blocked. Since such high selectivity has not been attained, blocking strategies are required. The blocking groups should be introduced in high yield, be stable to the subsequent reaction conditions, and be selectively removed when necessary. In the most common oligonucleotide synthetic route, the triester method, the choice is to block each reactive center because of the poor specificity of the reagents used, the need for high yield and purity, and the difficult separations often encountered. As new reagents and methods are being developed, the choice of whether or not to block is constantly being reevaluated.

There has been a great variety in the nature and scope of the blocking groups used in oligonucleotide synthesis with one exception: the exocyclic amine blockers, which are invariably amides.[1] Benzoyl has been most frequently selected for 2′-deoxyadenosine, anisoyl for 2′-deoxycytidine, and isobutyryl for 2′-deoxyguanosine, although other acyl groups have been examined.[1,2] These groups have been selected for this purpose, and have survived, because they represent a compromise between stability and ease of removal. Recently, the subject of nucleoside amine blockers has been reexamined[2] with emphasis upon developing groups that are hydrolytically more stable than those currently in vogue. It has not been clearly established at what point hydrolytic stability will require overly harsh conditions for removal such that the resulting oligonucleotide would be seriously degraded. What is needed is a blocking group that possesses a high degree of hydrolytic stability and yet can be easily removed under mild conditions.

An obvious choice is the benzyloxycarbonyl (carbobenzoxy, Cbz) group that has been used so effectively in polypeptide syntheses. This blocking group is stable to a variety of hydrolytic conditions, imparts a good deal of lipophilicity to otherwise polar molecules, and most notably is removable under neutral hydrogenolysis conditions.[3] Its stability also can be modified as needed by adding substituents to the phenyl ring and benzylic carbon. Previous reports concerning the use of benzyl groups to block ribose hydroxyls during olignonucleotide synthesis indicate that substantial reduction of the pyrimidine 4,5 double bond occurs upon their reductive removal.[4] However, recent advances in hydrogenation technology hold out the promise that this side reaction could be avoided when removing Cbz groups from oligonucleotides.

There is another aspect of base blocking that has not been satisfactorily addressed. Generally, the synthesis of oligomers containing guanosine gives consistently low yields.[1] It had been suspected, and recently confirmed, that another reactive center on guanosine, in addition to the exo amine, is the 6-oxygen. This oxygen has been blocked in only one[5] previous oligonucleotide

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(1) (a) Reese, C. B. *Tetrahedron* **1978**, *34*, 3143. (b) Amarnath, V.; Broom, A. D. *Chem. Rev.* **1977**, *77*, 183. (c) Zhdanov, R. I.; Zhenodarova, S. M. *Synthesis* **1975**, 222.

(2) Koster, H.; Kulikowski, K.; Liese, T.; Heikens, W.; Kohli, V. *Tetrahedron* **1981**, *37*, 363.

(3) Boissonnas, R. A. *Adv. Org. Chem.* **1963**, *3*, 159.

(4) Reitz, G.; Pfleiderer, W. *Chem. Ber.* **1975**, *108*, 2878.

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