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Theoretical Model of Solvated Lithium Dienediolate of 2-Butenoic Acid

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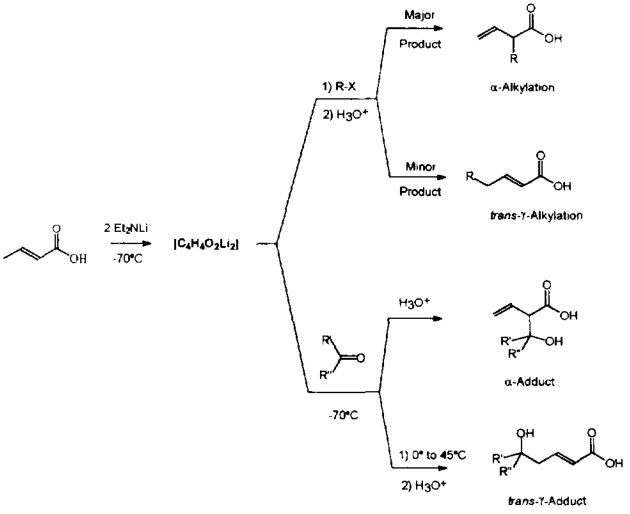
Abstract: A *s-trans* dienediolate structure has been theoretically found as a model for the solvated lithium dianion of 2-butenoic acid which is in good agreement with both its chemical reactivity and ^{13}C NMR spectral data. Semiempirical and *ab initio* calculations reveal the importance of including a discrete number of the ether solvanting molecules in the calculations of this charged species in solution, and that these ether molecules cannot be substituted by water in the calculations when a conformational equilibrium is possible.

Introduction

Unsaturated carboxylic acids are synthetically useful building blocks. On deprotonation by two equivalents of a lithium dialkylamide they afford dianions that react as ambident nucleophiles through their α or γ carbon, and lead to single, or clearly predominant compounds when allowed to react with electrophiles under adequate conditions.[1-3] Regioselectivity trends depend on the electrophile as well as on reaction conditions. Thus, α attack predominates in the irreversible reactions with alkyl halides or hydronium ion,[4,5] and in the



Scheme 1

addition to aldehydes and ketones under kinetic conditions, whereas γ-adducts are obtained when the latter reversible additions are carried out under equilibration conditions (Scheme **1**).[6-10] In agreement with the kinetic α-regioselectivity trend, the ^{13}C NMR chemical shifts of the dianions of the different unsaturated carboxilic acids reveal higher π electron density charges at the C2 than at the C4 atoms[11] (Table **1**).

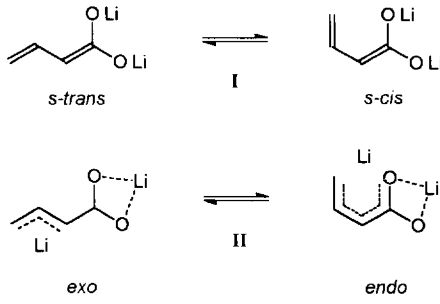
Table 1 Averaged ^{13}C NMR shifts of crotonic acid dianion and electron densities* based on ^{13}C NMR shifts of butadiene [11]

C-1		C-2		C-3		C-4	
δ	q_c	δ	q_c	δ	q_c	δ	q_c
173.9	0.36	73.4	-0.40	139.0	0.01	86.8	-0.19

(∗) Charges obtained by equation $(\delta_n - \delta)/160 = q_c$ [12]

The stereoselectivity for γ-attack is usually very high, and most frequently one single *cis-γ* or *trans-γ* compound is obtained, for C3 substituted and C3 unsubstituted butenoic acids, respectively. Thus, the unsubstituted 2-butenoic acid affords *trans-γ* compounds.

The structures of the dianions of unsaturated carboxylic acids can be simply formulated here as lithium dienolates **I** or as lithiumoxycarbonyl substituted allyl anions **II** (Scheme **2**). In any case these formulations provide an oversimplified view of the structures, as these dianions are expected to form ion pairs and aggregates in weakly polar solvents as diethyl ether or THF.[13] A good number of studies have been published on the structures of lithium and other metal enolates, but as far as we know, the structure of the dienediolates of unsaturated carboxylic acids has been studied only for 3-methyl-2-butenoic acid by Bongini,[14] who found that the ^{13}C NMR spectrum of the dianion of this acid was consistent with a delocalized π system. At the STO-3G basis set level that author assumed an *endo* structure with a lithium atom placed above the molecular plane and coordinated to one of the oxygen atoms and to both C2 and C4 carbon atoms. The same calculations showed that coordination of each lithium atom with two water molecules, as a model of ethereal solvent, do not modify substantially the *endo* structure. However, Bongini's model is not in agreement with the almost exclusive protonation or alkylation of the dianion at the C2 centre, as the STO-3G calculations give higher negative charge at the C4 than at the C2 centre. Kaneti and Schleyer[15] had previously studied the lithium dianion of acetic acid through 3-21G calculations and found an "ate" structure with a lithium atom placed



Scheme 2

above the molecular plane and coordinated to one of the oxygen atoms and to the C2 centre. Again lithium solvation with water did not lead to any important structural change. All these structures show a higher negative charge at the C centre coordinated to the lithium atom.

In the present paper we report a theoretical model for the solvated lithium dienediolate of 2-butenoic acid which explains the experimentally observed regioselectivity, and the electron density charges obtained from the ^{13}C NMR study.

Computing Methods

The study of several geometries for the dianions of 2-butenoic acid was carried out using the MNDO[16] and PM3[17] semiempirical Hamiltonian, included in the MOPAC93 program,[18] where lithium is parametrized.[19,20] The different conformations were optimized by means of the EF[21] procedure until the stationary points were obtained.

The *ab initio* calculations of the *s-trans* and *s-cis* structures **2** and **3** were performed using the GAUSSIAN92 package[22] at STO-3G [23] and 3-21G [24] basis set levels, and optimized geometries were found with Berny's procedure.[25]

All calculations were performed on a IBM RS/6000 workstation of the Departament de Química Orgànica of the Universitat de Valencia.

Results and Discussion

Our goal was to obtain a *s-trans* structure for the dilithium dianion of 2-butenoic acid (Scheme **2**), which could be in agreement with the *trans*-stereoselectivity of γ-addition, the kinetic α-regioselectivity, and the electron density localization obtained from the ^{13}C NMR spectrum of this dianion.

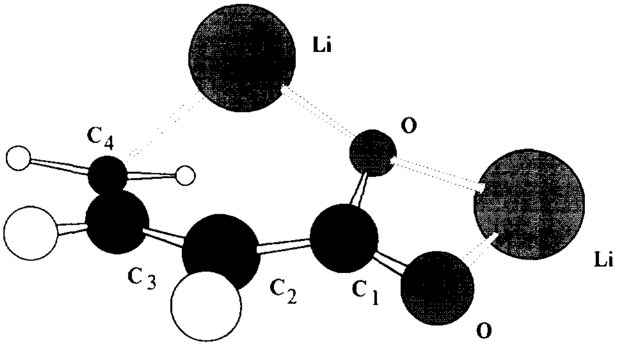


Figure 1. Calculated (3-21G basis set) structure of monomeric non solvated dilithium dianion of 2-butenoic acid **1**.

The dilithium dianion of 3-methyl-2-butenoic acid in its non solvated monomeric form was studied first, by semiempirical calculations and gave the same *endo* conformation which Bongini found at RHF/STO-3G.[13] Semiempirical calculations performed for the non solvated monomeric form of lithium dianion of 2-butenoic acid led to an *endo* structure **1** (Figure 1) which did not differ substantially from the structure obtained by

Bongini. Similar results were obtained at STO-3G and 3-21G calculations. Complexation of the lithium atoms with a discrete number of water molecules afforded very similar results to those obtained for the unsolvated species.

It is known that lithium enolates are usually present in solution as oligomeric aggregates, a feature confirmed by the complexity of the ^{13}C NMR signals for each carbon of the dianion[11]. In view of the *endo* structure obtained for the monomeric form of the dianion of the 2-butenoic acid, dimeric structures without and with inclusion of a discrete number of water and dimethyl ether molecules were then considered. We found that the increase in the coordination of lithium atoms with solvent molecules led to a change from *endo* to *exo* structures, the latter showing a net atomic charge distribution in better agreement with those estimated from ^{13}C NMR data [11]. This feature is particularly true for solvation by two ether molecules with each lithium atom, as an *exo* dimeric structure is then attained.

Table 2. Mulliken population analysis* of the *s-trans* and *s-cis* solvated lithium dienediolates **2** and **3**.

	2				**3**			
	MNDO	PM3	STO-3G	3-21G	MNDO	PM3	STO-3G	3-21G
C-1	0.524	0.510	0.288	0.898	0.546	0.521	0.292	0.907
C-2	-0.552	-0.743	-0.242	-0.562	-0.525	-0.730	-0.245	-0.543
C-3	0.083	0.028	-0.045	-0.179	0.089	0.048	-0.043	-0.162
C-4	-0.379	-0.625	-0.220	-0.518	-0.365	-0.641	-0.225	-0.568

* Mulliken charges are best correlated with σ^{para}, which controls ^{13}C chemical shifts[26] allowing direct comparison of calculated charges with those derivated from ^{13}C chemical shifts for crotonic acid dianion[11].

Conversion of the non solvated *endo* dimeric structures, which do not differ significantly from the monomeric dianion **1**, into flat solvated *exo* dimeric structures is probably the result of the higher basicity of the ether oxygen atoms, and hence of their stronger coordination to the lithium atoms, as well as of the repulsive interactions between the carbon chain and the methyl groups of the ether molecule, which do not occur on solvation with water.

This result suggested that similar solvation effects could be found for the monomeric form. Coordination of each lithium atom with three water molecules had led to an oxycarbonyl allylanion structure, similar to the structure **1** previously obtained, but we were pleased to find that substitution of these water molecules by dimethyl ether led to a planar *s-trans* dienediolate structure **2**, where each lithium atom is coordinated to four oxygen atoms. The charge distribution obtained by our semiempirical calculations was in agreement with that obtained from ^{13}C NMR data for this lithium dienediolate.[11] The same calculations allowed to obtain as well a *s-cis* structure **3** as a local minimum. Similar results were obtained by calculations for the lithium dianion solvated with THF molecules.

PM3 calculations for the dimethyl ether solvated structures **2** and **3** gave bond lengths in better agreement with 3-21G calculations (Table 3). These calculations revealed an exothermic solvation process, -17.57 kcal mol^{-1} for complexation of three ether molecules with each lithium atom in the *s-trans* structure **2**, which is a minimum, 3.15 kal mol^{-1} more stable that the *s-cis* structure **3**.

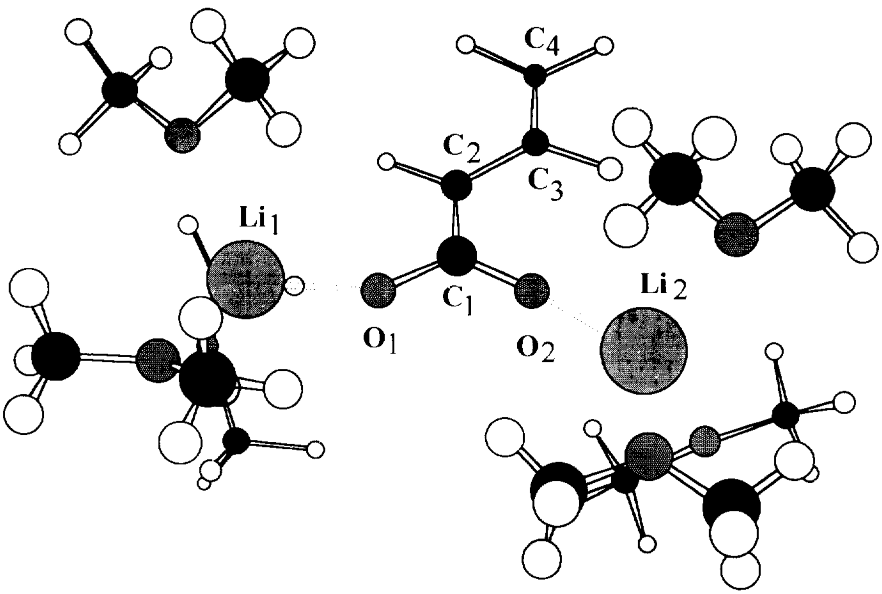


Figure 2. Calculated (3-21G basis set) structure of dimethyl ether solvated monomeric dilithium dianion of 2-butenoic acid **2**.

Finally, calculations for the structures **2** and **3** have been performed at STO-3G and 3-21G basis set levels. The atomic charges given in table **2** show that *s-trans* structure **2** is in agreement with experimental regioselectivity and ^{13}C NMR chemical shifts,[11] as they render a higher negative charge at C2 than at C4. The structural data given in Tables **3** and **4** show that the carbon skeletons of the structures **2** and **3** are basically 1,3-butadiene systems. These *ab initio* calculations gave the *s-trans* structure **2** less energetic than the *s-cis* structure **3** (3-4 kcal), in agreement with the experimental γ-E-stereoselectivity observed for irreversible alkylation of the lithium dianion of 2-butenoic acid. It is worthwhile to mention here that the bond length C1-C2 is larger than C3-C4. This is the result of the C1 atom being bonded to three atoms with π symmetry, which gives a lower bond order between the C1 and C2 centres.

The tables show that there is a good agreement between the structural data for the dimethyl ether solvated monomeric dilithium dianion of 2-butenoic acid obtained by the different computing methods used, as well as that the results for the PM3 calculations do not differ significantly from those obtained by the HF/3-21G calculations. The PM3 calculations afford reliable results for large systems in which the solvent molecules play a important role in the conformational analysis, as a consequence of their strong coordination to lithium atoms.

To validate the importance of lithium coordination with ether molecules as a model of solvation in ethereal solvents, we have studied as well the lithium dianion of acetic acid at PM3 level and obtained a flat enediolate structure, with each lithium atom coordinated to a carboxylic oxygen and three ether oxygens. The solvation process, as for structure **2**, is exothermic process by -21.7 Kcal mol^{-1}. This structure is likely to be a more accurate model of solvated acetic dianion that the "ate" complex found by Kaneti and Schleyer when water was used to coordinate lithium.

Table 3. Bonds lengths in Å for the solvated lithium dienediolates of 2-butenoic acid **2** and **3**

	2				**3**			
	MNDO	PM3	STO-3G	3-21G	MNDO	PM3	STO-3G	3-21G
C1-C2	1.448	1.406	1.383	1.393	1.438	1.407	1.387	1.400
C2-C3	1.421	1.417	1.444	1.427	1.419	1.413	1.446	1.427
C3-C4	1.361	1.344	1.326	1.339	1.358	1.345	1.327	1.345
O1-C1	1.294	1.298	1.328	1.302	1.292	1.293	1.320	1.291
O2-C1	1.301	1.302	1.324	1.320	1.304	1.306	1.332	1.321
Li1-O1	1.855	1.706	1.547	1.743	1.853	1.708	1.553	1.743
Li2-O2	1.971	1.757	1.548	1.794	1.893	1.748	1.546	1.783

Table 4. Bonds and Dihedral Angles in degrees for the solvated lithium dienediolates of 2-butenoic acid **2** and **3**

	2				**3**			
	MNDO	PM3	STO-3G	3-21G	MNDO	PM3	STO-3G	3-21G
C1-C2-C3	127.0	123.9	123.9	123.0	130.8	128.6	129.1	126.7
C2-C3-C4	127.5	124.2	128.1	128.9	133.1	129.2	132.1	132.3
O1-C1-C2	124.4	126.9	123.2	122.3	124.8	128.6	125.3	122.6
O2-C1-C2	120.9	123.9	120.8	119.8	120.8	122.6	119.5	119.4
Li1-O1-C1	178.0	168.6	178.2	154.4	175.5	175.1	176.3	156.7
LI2-O2-C1	114.9	144.0	174.4	135.5	141.0	147.5	174.1	134.9
C1-C2-C3-C4	-179.8	177.6	178.9	-178.3	-5.4	5.2	-3.8	0.5
Li1-O1-C1-C2	-21.7	-25.0	-93.1	-99.8	-90.0	-52.0	125.3	-99.0
Li2-02-C1-C2	-0.8	-10.2	6.1	7.0	4.6	0.0	3.2	-3.8

Acknowledgments

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