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Quantification of the Aromaticity of 2-Alkylidenethiazolines Subjected to Push−Pull Activity

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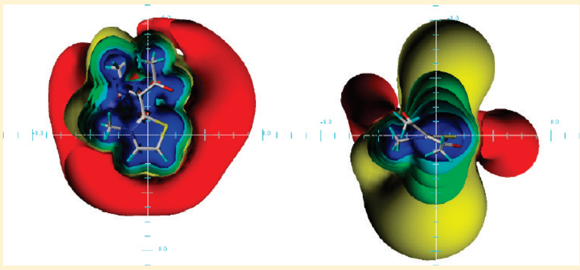
Supporting Information

ABSTRACT: Through-space NMR shieldings (TSNMRSs) of a series of 2-alkylidenethiazolines subjected to push−pull activity have been calculated by the GIAO method employing the nucleus-independent chemical shift (NICS) concept and visualized as iso-chemical-shielding surfaces (ICSSs). The ICSSs were applied to quantify and visualize the degree of aromaticity of the studied compounds, which has been shown to be in excellent correlation with the push−pull behavior, quantified by the quotient (π^*/π) method. Dissection of the absolute magnetic shielding values into individual contributions of bonds and lone pairs by the natural chemical shielding−natural bond orbital (NCS−NBO) analysis has revealed unexpected details.

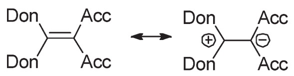


INTRODUCTION

Since its introduction in 1996,[1] nucleus-independent chemical shift (NICS) has been widely used to characterize aromaticity and antiaromaticity of organic compounds.[2] NICS is the negative of the magnetic shielding computed at ring centers, NICS (0), or 1 Å above the ring center, NICS (1).[1−3] The out-of-plane component of the NICS tensor, NICS$(1)_{zz}$, and the π contribution to the out-of-plane component, NICS$(0)_{\pi zz}$, have also been recommended as a good measure of aromaticity.[3c] Significantly negative (i.e., magnetically shielded) NICS values indicate the presence of induced diatropic ring currents or aromaticity, whereas positive values (i.e., deshielded) denote paratropic ring currents and antiaromaticity. The grid distribution of NICS values around molecules has been employed to provide better insight about diatropic and paratropic regions of the molecules.[3b]

On the basis of the NICS concept, Klod and Kleinpeter[4] calculated absolute magnetic shieldings around some functional groups and aromatic ring systems and visualized the through-space NMR shieldings (TSNMRSs) as iso-chemical-shielding surfaces (ICSSs). In this process, the studied functional group is placed in the center of a lattice of "ghost atoms" ranging from −10.0 to +10.0 Å in all three dimensions with a step width of 0.5 Å resulting in a cube of 68921 ghost atoms. The magnetic shieldings are computed using the GIAO[5] method, and the resulting data set is transformed into a contour file of ICSSs using SYBYL modeling software.[6] In this way, one can visualize the TSNMRSs by ICSSs and obtain quantitative information about the spatial extension, sign, and scope of the corresponding anisotropic/ring current effects in the studied molecules. A number of applications of this method have been published, for example, to determine the stereochemistry of nuclei proximal to the functional group,[4,7] to separate the anisotropic effect of the C═C double bond from the influence of steric hindrance on the same protons[8] or to visualize and quantify planar[9] and spherical (anti)aromaticity.[10] The application of this method has also been used to argue against the influence of an anisotropic effect. For example, it has been shown that the deshielding of H-4 by 1.57 ppm in 11-ethynylphenantrene does not arise from the anisotropic effect of the C≡C triple bond, as has long been thought, but from steric compression.[11] The conventional explanation of the ^{1}H NMR chemical shift difference of the axial and equatorial protons in cyclohexane in terms of the anisotropic effect of the C−C single bond has been shown to be incorrect. Rather, it is the magnetic contributions from the C(2)−C(3) and C(6)−C(5) bonds which essentially determine the chemical shift difference between these two protons at C(1).[12] The TSNMRS is also a recommendable alternative for the identification of benzenoid/quinonoid structures in case ^{1}H NMR spectra are too complex or X-ray structures are not available.[13]

Scheme 1. Push−Pull Alkenes



Push−pull alkenes, containing electron-donor substituent(s) at one end and electron-accepting substituent(s) at the other end

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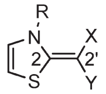
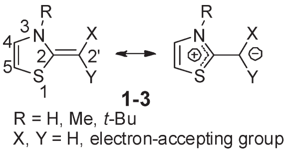
Table 1. Twist Angles about the C(2)═C(2′) Double Bonds, Bond Lengths, Occupation Numbers of π-Bonding and π*-Antibonding Orbitals, Their Quotient (π*/π), and Occupation Numbers of Sulfur Lone-Pair Orbitals (LP S) in the Thiazoline Derivatives 1−3



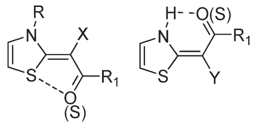
R = Me	X	Y	twist angle	$d_{C(2)=C(2')}$ (Å)	π	π*	π*/π	LP S
1a	H	H	0.01	1.3569	1.9265	0.3564	0.1850	1.7377
1b-*Z*	H	pyridine *N*-oxide	0.00	1.3731	1.8301	0.4333	0.2368	1.7042
1c-*Z*	H	CN	0.00	1.3750	1.8438	0.4618	0.2504	1.6766
1d-*Z*	H	CO_2Et	0.00	1.3779	1.8065	0.4689	0.2596	1.6445
1d-*Z* *s-trans*	H	CO_2Et	0.00	1.3770	1.8191	0.4529	0.2490	1.6640
1d-*E*	CO_2Et	H	21.97	1.3809	1.8084	0.4690	0.2593	1.6651
1e-*Z*	H	COMe	0.00	1.3833	1.7785	0.4870	0.2738	1.6229
1f-*Z*	H	CHO	0.00	1.3858	1.7672	0.4980	0.2818	1.6145
1f-*Z* *s-trans*	H	CHO	0.00	1.3775	1.7994	0.4414	0.2453	1.6858
1g-*Z*	H	COPh	1.58	1.3864	1.7575	0.4988	0.2838	1.6083
1g-*E*	COPh	H	24.64	1.3891	1.7661	0.5009	0.2836	1.6438
1h	Cp ring		18.65	1.3960	1.6485	0.5009	0.3039	1.6341
1i-*Z*	H	CSMe	0.01	1.3957	1.6903	0.5209	0.3082	1.5722
1j	CN	CN	0.05	1.3958	1.7807	0.5538	0.3110	1.6266
1k	CO_2Et	CO_2Et	17.76	1.4013	1.7441	0.5568	0.3192	1.5910
1l-*Z*	CN	CO_2Et	0.05	1.4010	1.7501	0.5616	0.3209	1.5948
1 m-*E*	CO_2Et	COPh	12.00	1.4032	1.7067	0.5588	0.3274	1.5769
1 m-*Z*	COPh	CO_2Et	17.98	1.4051	1.7218	0.5700	0.3310	1.5832
1n-*Z*	CN	COMe	0.00	1.4051	1.7210	0.5776	0.3356	1.5737
1o	COPh	COPh	14.66	1.4105	1.6817	0.5759	0.3424	1.5629
1p-*Z*	CN	COPh	13.33	1.4091	1.7081	0.5933	0.3473	1.5601
1q-*Z*	CN	CSMe	0.01	1.4169	1.6674	0.5954	0.3571	1.5448
1r	COMe	COMe	33.07	1.4241	1.6442	0.6405	0.3895	1.5209
R = *t*-Bu	X	Y						
2	COMe	COMe	39.80	1.4272	1.6095	0.6665	0.4141	1.5165
R = H	X	Y						
3a-*Z*	H	CO_2Et	0.00	1.3733	1.8086	0.4477	0.2475	1.6494
3a-*Z* *s-trans*	H	CO_2Et	0.00	1.3724	1.8211	0.4317	0.2371	1.6687
3a-*E*	CO_2Et	H	0.00	1.3790	1.7942	0.4655	0.2594	1.6687
3b-*Z*	H	CHO	0.01	1.3813	1.7690	0.4773	0.2698	1.6188
3b-*Z* *s-trans*	H	CHO	0.00	1.3730	1.8013	0.4200	0.2332	1.6902
3b-*E*	CHO	H	0.00	1.3914	1.7339	0.5133	0.2960	1.6379
3c-*Z*	H	COPh	1.30	1.3820	1.7599	0.4778	0.2715	1.6129
3c-*E*	COPh	H	1.47	1.3923	1.7239	0.5128	0.2974	1.6359
3d	COMe	COMe	0.01	1.4293	1.6244	0.6327	0.3895	1.5390

of the C═C double bond are characterized by strong bond polarization (Scheme 1). The push−pull effect can easily be quantified by the restricted rotation about the partial C═C double bond,[14] bond length, experimentally available by X-ray analysis,[15] or the ^{13}C NMR chemical shift difference ($\Delta\delta_{C=C}$) of the two carbons of the double bond.[14b,16] The occupation quotient π*/π of this bond can be alternatively employed.[14d,16h,17] Since electron-donating substituents release π-electron density into the antibonding π*-orbital of the C═C double bond and electron-accepting substituents withdraw π-electron density from the bonding π-orbital, both effects tend to elongate the C═C double bond by reducing its π-bond order. Whereas the determination of rotational barriers by NMR is limited by the NMR time scale to a window of ca. 5−23 kcal/mol, the application of the bond length is restricted to solid-state measurements, and employment of $\Delta\delta_{C=C}$ is confined to alkenes with a very similar substitution pattern, the occupation quotient π*/π has proven to be the most general criterion for quantifying the push−pull effect in this kind of compounds.[17,18] The quotient approach[14d] has been successfully used for the characterization of normal and vinylogous thio(seleno)amides,[19] push−pull alkynes,[20] azines,[21] azo dyes,[22] and triazenes.[23]

Scheme 2. Thiazolines Studied



Scheme 3. Intramolecular Interactions



The aim of the present paper is to (i) quantify the push−pull effect of push−pull alkenes **1**−**3** (Scheme 2) containing the proaromatic thiazoline moiety at the donor side, (ii) investigate if the push−pull effect of the partial C(2)═C(2′) double bond can develop aromaticity in the thiazoline ring, and (iii) examine if the quasi-ring systems, formed by intramolecular S···O(S) interactions or hydrogen bonds (Scheme 3), are partially aromatic.

■ COMPUTATIONAL DETAILS

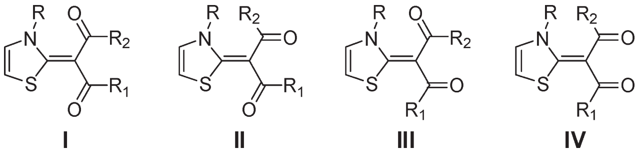
Ab initio MO calculations and the natural bond orbital (NBO) population analysis[24] were performed using the Gaussian 03 program package.[25] Geometry optimization was performed at the MP2/6-311G(d,p) level of theory.[26] The chemical shieldings of the "ghost atoms" surrounding the molecules were calculated on the basis of the NICS concept,[2] whereby the molecule was placed in the center of a grid of ghost atoms ranging from −10.0 to +10.0 Å in all three dimensions with a step width of 0.5 Å resulting in a cube of 68921 ghost atoms. The chemical shielding calculations were performed using the GIAO[5] method at the B3LYP/6-311G(d,p) level of theory.[27] From the GIAO calculations, the coordinates and isotropic shielding values of the ghost atoms were extracted. After transformation of the tabulated chemical shieldings into the SYBYL[6] contour file, the TSNMRSs were visualized, providing a 3-D view of spatial extension, sign, and scope of the anisotropic/ring current effects in space. The natural chemical shielding−natural bond orbital (NCS−NBO) analysis[28] was done using the NBO 5.0 program linked to the Gaussian 98 program.[29]

The occupation of the π-bonding and π^*-antibonding orbitals of the C(2)═C(2′) partial double bond were computed using the NBO population analysis at the MP2/6-311G(d,p) level of theory. The keyword density = current was included in the Gaussian route card to ensure that the NBO software programe analyzes the MP2 densities. The HOMA values are based on geometries optimized at the MP2/6-311G(d,p) level.

■ RESULTS AND DISCUSSION

Structure of Thiazolines 1−**3.** The studied thiazoline derivatives **1**−**3** are listed in Table 1. In all structures having an exocyclic α,β-unsaturated fragment, C═C−C═O(S), the *s-cis* conformation is energetically the preferred one, owing to the stabilization either by hydrogen bonds or nonbonded 1,5-type S···O interactions.[18,30] The stabilization mechanism of the S···O interactions involves both electrostatic interactions[30g] and weak $n_O \rightarrow \sigma^*_{S(1)-C(5)}$ orbital interactions, as shown by the second-order perturbation theory analysis of Fock matrix at the B3LYP/6-311G(d,p) level. The reason for the greater stability of the *s-cis* conformation even in the *N*-Me *E* isomers (**1d**-***E*** and **1g**-***E***) is the destabilization of the *s-trans* conformer by steric hindrance with the *N*-Me group. In the case of compounds **1k**, **1m**, **1o**, **1r**, **2**, and **3d**, which could exist in four conformers **I**−**IV** shown in Scheme 4, the double *s-cis* conformation **I** is the most stable. When R = Me, next comes the *s-cis/s-trans* conformation **II** for **1k** (R_1 = R_2 = OEt), **1r** (R_1 = R_2 = Me), and **1m**-***E*** (R_1 = Ph, R_2 = OEt), obviously destabilized by steric repulsion of the R_2 and *N*-Me group. The *s-trans/s-cis* conformer **III**, having no stabilizing S···O interaction is energetically the next one and *s-trans/s-trans* conformer **IV** is the least stable.[31] In the case of compounds **1m**-***Z*** (R = Me, R_1 = OEt, R_2 = Ph) and **1o** (R = Me, R_1 = R_2 = Ph) there is only one higher energy conformer **III**, the *s-trans* conformation of benzoyl group *syn* to the *N*-Me would be of very high energy. When R = H, R_1 = R_2 = Me (compound **3d**), hydrogen-bonded structure **III** has lower energy than the structure **II**, thus reflecting the higher stabilization energy of hydrogen bonds with respect to the S···O interactions.[18] The nonstabilized conformation **IV** would not be a viable conformation, and its geometry optimization resulted in the hydrogen-bonded structure **III**. Absolute energies (kcal/mol) of all conformers of **1k**, **1m**, **1o**, **1r**, and **3d** are presented in Table S1 (Supporting Information). The following discussion refers to the most stable conformers.

Scheme 4. Thiazoline Conformers



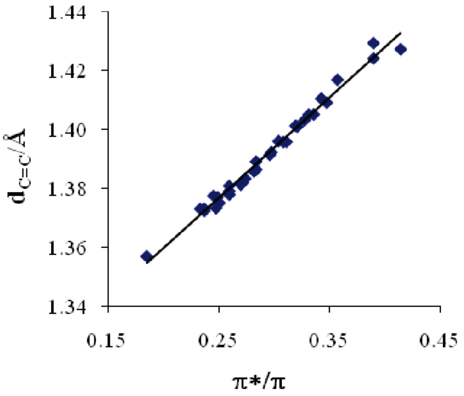
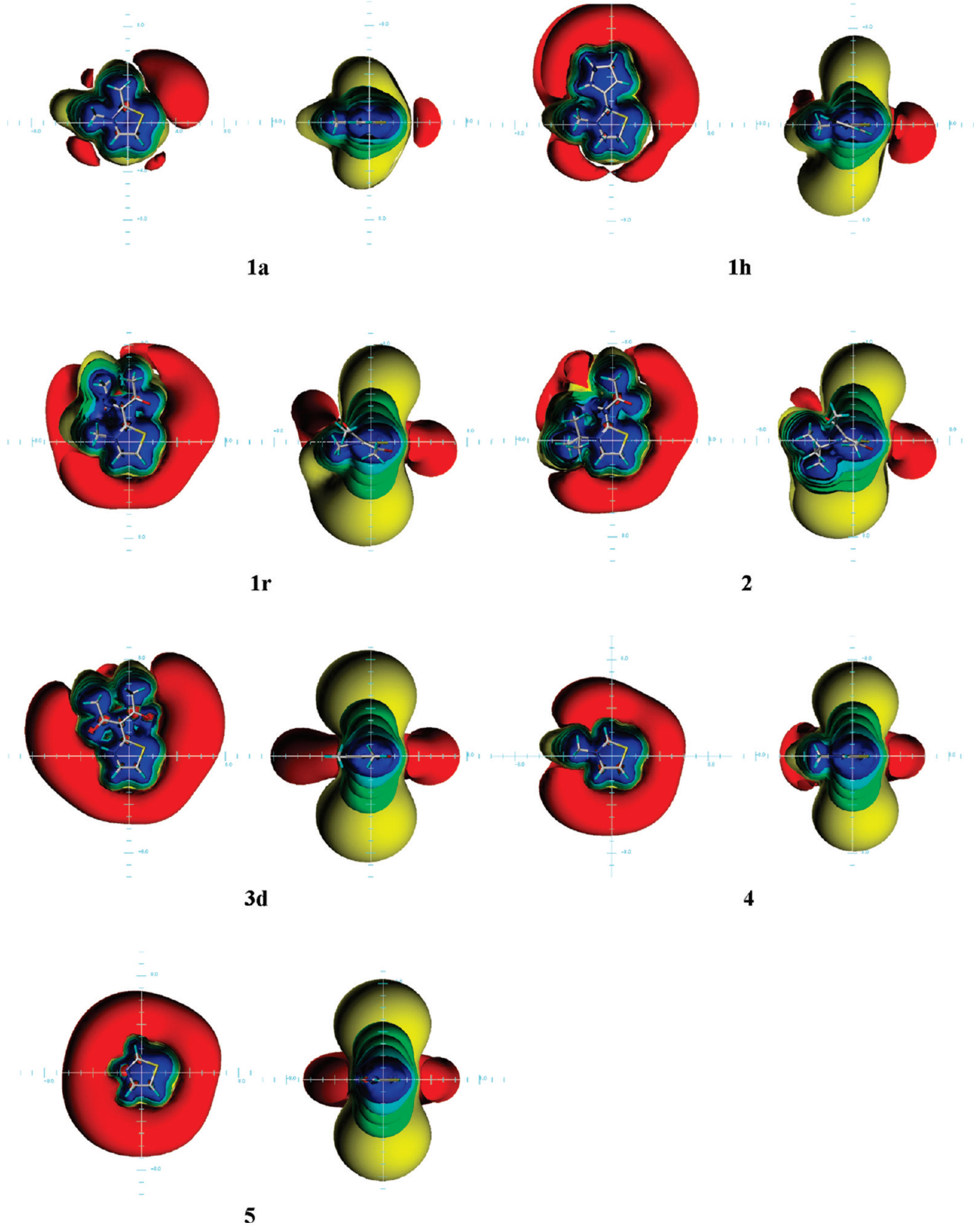


Figure 1. Correlation of the bond length and the occupation quotient π^*/π of the partial C(2)═C(2′) double bond in compounds **1**−**3** (R^2 = 0.9866).

The structures free of steric hindrance are planar; others are twisted from the partial C(2)═C(2′) double bond. The twist angle[32] for all compounds **1**−**3** is shown in Table 1. The twisting around the partial C(2)═C(2′) double bond is the result of (i) steric repulsion and (ii) the push−pull effect which reduces its π-bond order, making it easier to twist out-of-plane. The extent of twisting is a compromise between the relaxation of steric strain, leading to energy drop, and the deviation from the ideal coplanar geometry, leading to energy rise.

Quantification of the Push−**Pull Effect in Thiazolines 1**−**3.** In order to obtain the occupation numbers of π-bonding and π^*-antibonding orbitals of the partial C(2)═C(2′) double bond and their quotient (π^*/π), the compounds were studied by NBO



1a **1h**

1r **2**

3d **4**

5

Figure 2. Visualization of the TSNMRSs (ICSSs: blue represents 5 ppm shielding, cyan 2 ppm shielding, green-blue 1 ppm shielding, green 0.5 ppm shielding, yellow 0.1 ppm shielding, and red −0.1 ppm deshielding) of the selected thiazolines **1**−**3**, *N*-methylthiazolium cation **4**, and thiazole **5**.

population analysis.[24] As already mentioned, in push−pull alkenes electron-donating substituents donate π-electron density into the π^*-antibonding orbital and electron-accepting substituents attract π-electron density from the π-bonding orbital, both increasing the length of the double bond. The occupation numbers of π and π^* orbitals, their quotient, and the length of the C(2)=C(2′) double bond are presented in Table 1. It was interesting to see if these two push−pull parameters still correlate in alkenes containing a proaromatic donor substituent. Thus, the occupation quotient π^*/π and bond length are correlated, as shown in Figure 1.

Table 2. Distances *d*/Å of the ICSS = 0.5, 1, and 2 ppm Perpendicular to the Ring Center[a]

			d/Å		
R = Me	X	Y	ICSS = 0.5 ppm	ICSS = 1 ppm	ICSS = 2 ppm
1a	H	H	3.00	2.30	1.70
1b-Z	H	pyridine *N*-oxide	3.70	2.70	2.00
1c-Z	H	CN	3.50	2.70	2.00
1d-Z	H	CO_2Et	3.90	3.00	2.20
1d-Z *s-trans*	H	CO_2Et	3.75	2.85	2.10
1d-*E*	CO_2Et	H	3.50	2.75	2.00
1e-Z	H	COMe	4.15	3.15	2.35
1f-Z	H	CHO	4.15	3.15	2.30
1f-Z *s-trans*	H	CHO	3.50	2.70	2.00
1g-Z	H	COPh	4.10	3.10	2.30
1g-*E*	COPh	H	3.65	2.80	2.15
1h	Cp ring		3.65	2.80	2.00
1i-Z	H	CSMe	4.50	3.40	2.55
1j	CN	CN	3.70	2.90	2.25
1k	CO_2Et	CO_2Et	4.05	3.10	2.30
1l-Z	CN	CO_2Et	4.00	3.10	2.35
1 m-*E*	CO_2Et	COPh	4.05	3.15	2.35
1 m-Z	COPh	CO_2Et	3.95	3.10	2.40
1n-Z	CN	COMe	4.20	3.20	2.40
1o	COPh	COPh	3.95	3.15	2.40
1p-Z	CN	COPh	4.20	3.25	2.45
1q-Z	CN	CSMe	4.40	3.40	2.55
1r	COMe	COMe	4.65	3.55	2.65

			d/Å		
R =*t*-Bu	X	Y	ICSS = 0.5 ppm	ICSS = 1 ppm	ICSS = 2 ppm
2	COMe	COMe	4.75[b]	3.70[b]	2.70[b]

			d/Å		
R = H	X	Y	ICSS = 0.5 ppm	ICSS = 1 ppm	ICSS = 2 ppm
3a-Z	H	CO_2Et	3.75	2.85	2.10
3a-Z *s-trans*	H	CO_2Et	3.50	2.70	2.00
3a-*E*	CO_2Et	H	3.65	2.80	2.05
3b-Z	H	CHO	4.00	3.00	2.30
3b-Z *s-trans*	H	CHO	3.30	2.55	1.95
3b-*E*	CHO	H	3.90	3.00	2.25
3c-Z	H	COPh	3.95	3.00	2.25
3c-*E*	COPh	H	3.85	2.95	2.25
3d	COMe	COMe	4.75	3.55	2.70
4			4.60	3.65	2.80
5			4.90	3.80	3.00

[a] Mean of the sum of the distances above and below the ring. [b] Opposite of the *t*-Bu group.

The correlation is excellent, thus proving the quotient method[14d,17] to be general and a sensitive measure of donor−acceptor character in polarized alkenes. A similarly good correlation has also been obtained in the case of Don-π-Acc chromophores containing 4*H*-pyran as a proaromatic donor group.[33] The strongest push−pull effect is observed for X,Y = COMe as acceptor substituents (compounds **1r**, **2**, and **3d**). Among them, the *N*-*t*-Bu group in **2** acts as a stronger pushing function than *N*-Me in **1r** ($\pi^*/\pi = 0.4141$ in **2** and 0.3895 in **1r** and *N*-unsubstituted **3d**). Obviously, the high volume effect of this group is more than compensated by its larger $+I$ effect. When the push−pull effect of the $C(2){=}C(2')$ partial double bond is increased, the bond length is increasingly elongated, resulting in tetrasubstituted alkenes values of 1.40−1.43 Å, which is substantially longer than the normal C═C double bond in ethene (1.34 Å).[34]

Aromaticity of Thiazolines 1−3. Now, with the quantified push−pull character, the next step was to evaluate the degree of

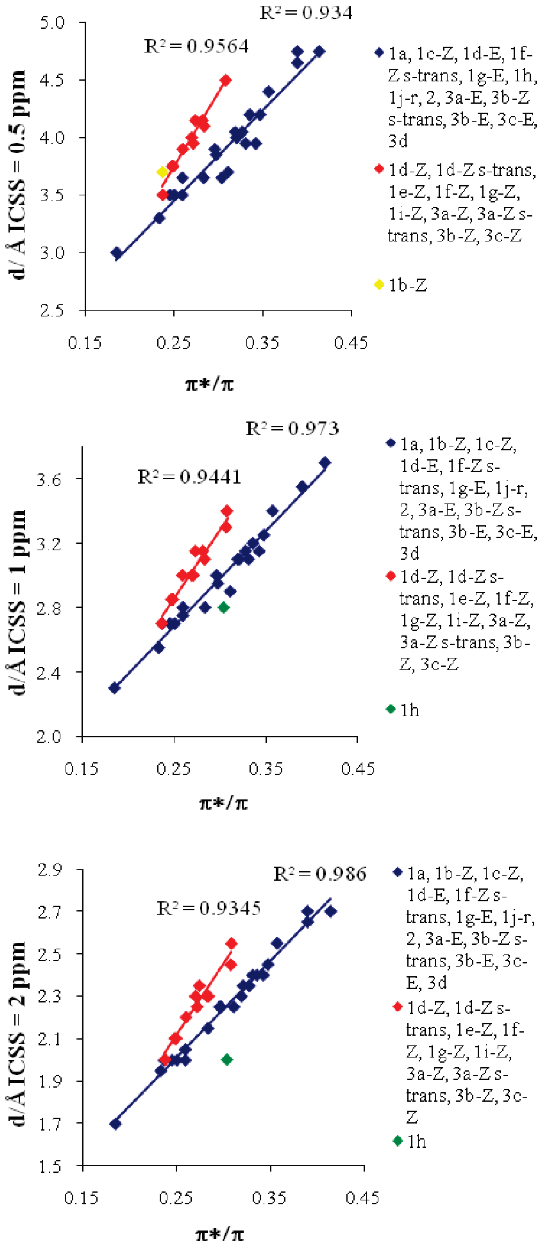
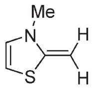
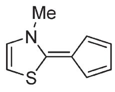


Figure 3. Correlation of distances d/Å of ICSS = 0.5, 1, and 2 ppm with the occupation quotient π^*/π of compounds **1**−**3**. Red line includes all **1**−**3** with one acceptor group, having close S···O(S) contact. Blue line comprises other compounds **1**−**3**.

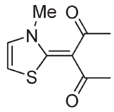
aromaticity in the thiazoline ring. Thus, the ICSSs have been created for all studied derivatives **1**−**3**, and they are portrayed in Figure 2 for the selected compounds **1a**, **1h**, **1r**, **2**, and **3d** and in Figure S1 (Supporting Information) for all other compounds **1**−**3**.



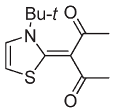
1a



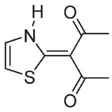
1h



1r



2



3d

In these views, the center of the thiazoline ring is placed in the center of the coordinate system. All TSNMRS visualizations are given from two perpendicular directions: the in-plane ICSSs at the left and the ICSSs perpendicular to the ring viewed from the side of the C(2)═C(2′) partial double bond at the right. The ICSSs for *N*-methylthiazolium cation **4** and thiazole **5** are also included in Figure 2 for comparison. Though the deshielding belt (ICSS = −0.1 ppm, red color) around the thiazoline ring reflects the degree of aromaticity in an expected manner (developing aromaticity generates wider and more closed deshielding surfaces), it is also affected by the functional groups present in the molecules. For example, the deshielding belt is not closed as in the aromatic thiazole **5** even in the compounds with high degree of aromaticity (see below), and this is due to the functional groups attached to the thiazoline ring. For this reason, the shielding surfaces above and below the ring are taken as a measure of aromaticity. However, since the ICSS = 0.1 ppm is highly influenced by the substituent anisotropic effects (see Figure S2, Supporting Information, where the view from the side of the selected molecules is presented) only distances d in Å of ICSS = 0.5, 1, and 2 ppm perpendicular to the ring center are collected in Table 2 and correlated with the occupation quotient π^*/π in Figure 3. The correlations are very good and point in the right direction: with increasing the push−pull effect the distances of ICSSs are longer; i.e., partial aromaticity gets higher. In particular, the *tert*-butyl derivative **2** is almost aromatic as *N*-methylthiazolium cation **4**. The distances of ICSS = 0.5 and 1 ppm are even larger than in **4**, but this is due to the anisotropic effects of substituents which, in this highly twisted molecule, still affect these ICSSs. The other two compounds containing X,Y = COMe as acceptor substituents also develop a high degree of aromaticity, the ICSS values being near to those of *N*-methylthiazolium cation **4** (Table 2).[35] Decreasing the push−pull effect, the aromaticity gradually drops until the unsubstituted **1a**, which is not aromatic at all, and its ICSSs are the result of anisotropic effects of double and single bonds and heteroatoms present in the ring.

An interesting feature of all three diagrams shown in Figure 3 is the appearance of two lines with different slopes. The red line includes all compounds **1**−**3** of *Z* configuration with one acceptor group, having close S···O(S) contact. Another blue line, of lower aromaticity and slope, comprises all other compounds. In the beginning of this study, only the *N*-methyl derivatives **1d-Z**, **1e-Z**, **1f-Z**, **1g-Z**, and **1i-Z** with the *s-cis* arrangement around the C═C−C═O(S) fragment lay on the "red line". Then, in order to explore the reason why some compounds have higher aromaticity than expected from their push−pull character, another series of compounds were included in the examination: all *N*-unsubstituted derivatives **3** and all the structures with the *s-trans* conformation around the α,β-unsaturated part. It should be noted here that the structures **3** are studied in the less stable enamino tautomer in order to compare with the *N*-substituted compounds. The absence of the *N*-Me group in **3** excluded any steric or anisotropic effect of this group on the ICSSs. Also, the fact that of all structures with the *s-trans* conformation of the exocyclic moiety only esters, still having the S···O contact, lie on the "red line" confirms that these nonbonded interactions should be responsible for the higher aromaticity of certain compounds. However, one question arises: why are only some of the compounds having S···O(S) interactions of higher aromaticity, when the same interactions are also present in molecules with two acceptor substituents, but lying on the "blue line"?

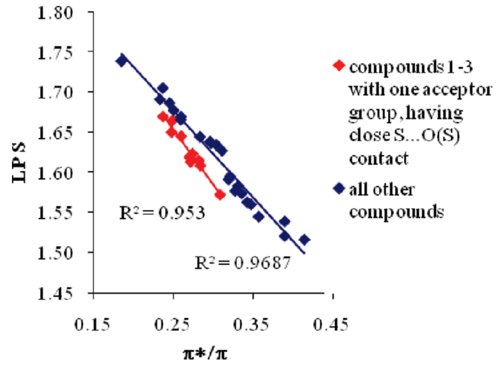


Figure 4. Correlation of the occupancy of the ring sulfur lone-pair orbitals (LP S) with the occupation quotient π^*/π.

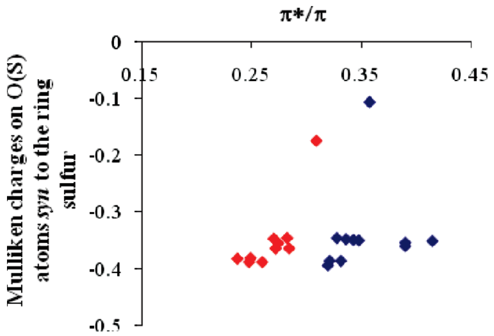


Figure 5. Changes of Mulliken charges, developed on the exocyclic O(S) involved in the interaction with the ring S, with the occupation quotient π^*/π (red dots represent compounds with one acceptor group and close S···O(S) contact; blue dots denote compounds with two acceptor groups having the same S···O(S) interactions.

To answer this question, the occupancy of the sulfur lone pair orbital (LP S, given in Table 1) was examined and correlated with the occupation quotient π^*/π, as shown in Figure 4. Of notice is the lower occupancy in compounds **1**−**3** with one acceptor group, having close S···O(S) contact (compounds lying on the "red line"). In addition, in the same compounds, Mulliken charges on the exocyclic oxygen/sulfur, *syn* to the ring sulfur, have similar values as in molecules with two acceptor groups, even though their push−pull character is lower (Figure 5 and Table S2, Supporting Information). This is understandable since in the case of two acceptor groups the π-electron density attracted from the partial C(2)=C(2′) double bond is spread over both substituents, but it is located on only one acceptor group in three-substituted alkenes **1**−**3**. Finally, the Wiberg bond order (BO)[36] was computed for the S(1)−C(2) and S(1)−C(5) bonds, as presented in Table S3 (Supporting Information), and correlated with the occupation quotient π^*/π in Figure 6. The correlation for the S(1)−C(5) bond is poor, but the trend is present: increasing BO, i.e., increasing aromaticity with rising push−pull effect. Though there is no difference in this dependence between the two series of compounds the difference is noticeable in the case of the S(1)−C(2) bond: the BO is higher for the molecules **1**−**3** with one acceptor subjected to S···O(S) interactions (compounds lying on the "red line"). Thus, the conclusion to be drawn from these findings is this: the higher electron density on the exocyclic oxygen/sulfur *syn* to the ring sulfur in compounds lying on the "red line" pushes more sulfur electrons into the C(2)=C(2′) double bond, thereby increasing their aromaticity. In addition, the reason for the steeper slope of this line (Figure 3) is that the degree of aromaticity of these compounds depends on both the push−pull character present and stronger polar nonbonded interactions. The distance of ICSS = 0.5 ppm of **1b**-**Z** coincides with the "red line" (Figure 3) due to the contribution of pyridine ring current effects, clearly visible in Figure S2 in the Supporting Information.

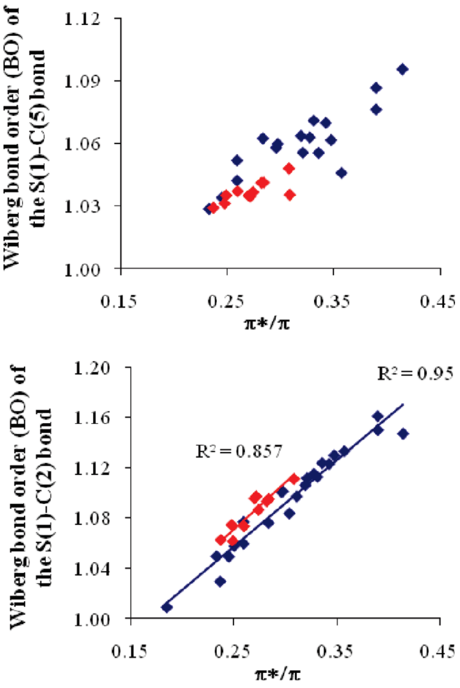


Figure 6. Correlation of the Wiberg bond order (BO) of the S(1)−C(5) and S(1)−C(2) bonds with the occupation quotient π^*/π (red dots represent compounds with one acceptor group and close S···O(S) contact; blue dots denote all other compounds).

The aromaticity of **1h**, the only compound having two proaromatic rings, is lower than expected from its push−pull character. This is the most striking on the diagram showing the ICSS = 2 ppm (Figure 3, green dot).[35] The low occupation of the bonding π-orbital of the partial C(2)=C(2′) double bond (almost equal as in **1r** with two acetyl groups as acceptor substituents (Table 1) reflects the strong tendency of the cyclopentadienyl (Cp) ring to attain partial 6π-electron aromaticity. Indeed, the ICSS values perpendicular to the Cp ring (4.2 (0.5 ppm), 3.3 (1 ppm) and 2.5 (2 ppm)) are close to the values of the single cyclopentadienyl anion (4.7 (0.5 ppm), 3.7 (1 ppm), and 2.8 (2 ppm)). However, the propensity of the thiazoline ring to repulse the π-electrons in order to gain partial aromaticity is lower, and it seems as if the partial aromaticity of the acceptor group weakens the partial aromaticity of the donor group.

It should be noted that a good correlation was found between the distances of ICSSs, used for the assessment of aromaticity, and the HOMA index of aromaticity[37] (R^2 = 0.6953 for ICSS = 0.5 ppm, R^2 = 0.7641 for ICSS = 1 ppm and R^2 = 0.8061 for ICSS = 2 ppm; see the Supporting Information). This is in accordance with the previous studies which showed that a good correlation between different aromaticity indices (ASE, Λ, NICS,

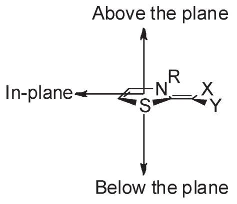


Figure 7. Coordinate system.

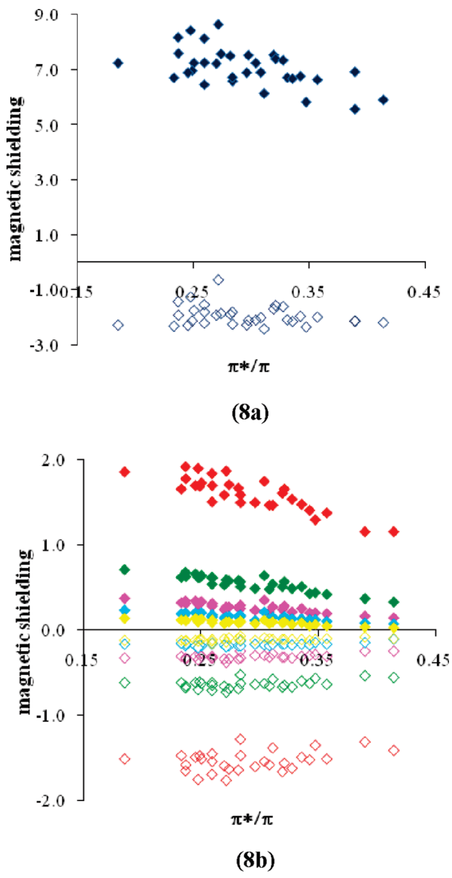


Figure 8. Correlation of the in-plane total ring π and σ shielding values, along the axis going from the ring center through the C(4)=C(5) bond, with the occupation quotient π^*/π in the compounds **1**−**3** at the specified distances: (a) 2 Å; (b) 3−7 Å, red: 3 Å, green: 4 Å, pink: 5 Å, blue: 6 Å, yellow: 7 Å. Full dots represent total ring π shielding, and empty dots show total ring σ shielding. Correlation coefficients for the ring π shielding values: 3 Å, R^2 = 0.7222; 4 Å, R^2 = 0.8360; 5 Å, R^2 = 0.7704; 6 Å, R^2 = 0.7707; 7 Å, R^2 = 0.7587.

NICS(1), HOMA) exists when comparing aromatic, nonaromatic, and antiaromatic systems ($R^2 > 0.8$). However, within one of these three groups or in a particular group of aromatic compounds the correlations deteriorate or even vanish.[38]

Dissection of Absolute Magnetic Shielding Values. Dissection of absolute magnetic shielding values into contributions from bonds and lone pairs using natural chemical shielding−natural bond orbital (NCS−NBO) analysis,[28] along the three axes with a step width of 0.5 Å (Figure 7), has led to some unusual and unexpected results.

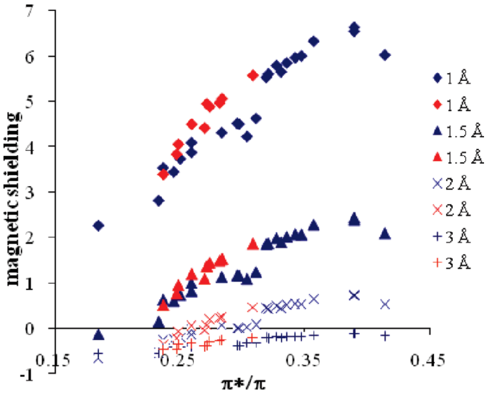
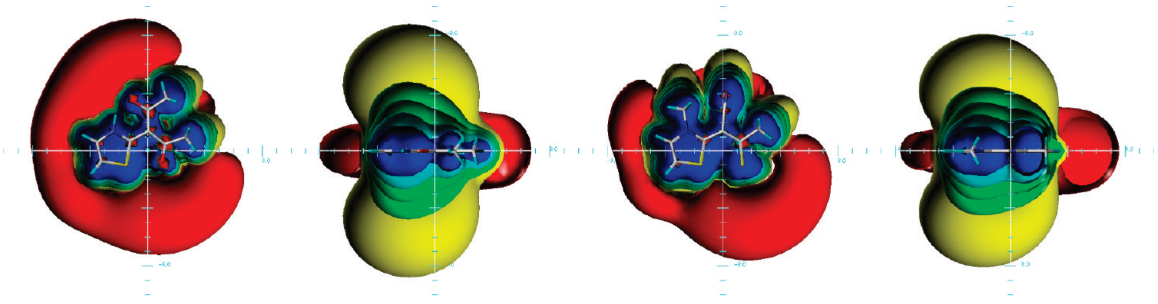


Figure 9. Correlation of the total ring π magnetic shielding with the occupation quotient π^*/π in the compounds **1**−**3** at 1 − 3 Å perpendicular to the ring center. Red points denote compounds having one acceptor group and close S···O(S) contact and blue points represent all other compounds. Correlation coefficients: blue points: 1 Å = 0.9053; 1.5 Å = 0.8964; 2 Å = 0.8806; 3 Å = 0.8520. red points: 1 Å = 0.9256; 1.5 Å = 0.9257; 2 Å = 0.9026; 3 Å = 0.7628.

Pople's ring current model (RCM)[39] provides the conventional explanation for the unusual downfield chemical shift of arene hydrogens. According to it, the ring currents induced in the mobile π electrons by an external magnetic field perpendicular to the ring deshield the region around an aromatic molecule but shield its interior. In the case of the studied compounds **1**−**3**, the total ring σ-bond contributions (obtained as a sum of the contributions of all ring σ bonds) and the total ring π-bond contributions (obtained as a sum of contribution of C(4)=C(5) π bond and sulfur and nitrogen π lone pairs) to the in-plane magnetic shielding is given in Table S4 (Supporting Information) (together with the values for *N*-methylthiazolium cation **4** and thiazole **5**) and correlated with the occupation quotient π^*/π at distances of 2 Å in Figure 8a and 3−7 Å in Figure 8b. The most surprising finding is that over the whole range outside the ring (2 − 7 Å) *deshielding* originates only from the ring σ electrons, whereas the ring π electrons have the *shielding* effect, irrespective of the degree of aromaticity of the studied compounds. Similarly, Wannere et al.[40] in their study of the origin of the downfield ^{1}H NMR chemical shifts of benzene and other aromatic compounds, using the individual gauge for localized orbitals (IGLO) method, reported that benzene protons are *shielded* by the ring C=C π bonds and *deshielded* by the C−C σ bonds, thus disputing the RCM. Soon after it, Viglione et al.[41] showed that the RCM is still valid if only the out-of-plane component of the magnetic shielding tensor is considered, but this was argued by Wannere et al.[42] by the statement that *isotropic* chemical shift is the quantity which is physically observable. Having in mind the results of our study, one may want to ask the following question: Do the in-plane ICSSs correctly describe the aromaticity of the studied compounds? The answer is given by the correlations presented in Figure 8a,b. Whereas the total ring σ deshielding effects do not correlate with the push−pull effect, the total ring π shielding does correlate with the push−pull character, i.e., aromaticity of the compounds. As the push−pull effect *rises* the π shielding *decreases*, thus revealing the deshielding surface. The correlation at the distance of 2 Å is poor, but the tendency is clearly visible.

Table S5 in the Supporting Information shows total ring σ and π shielding contributions perpendicular to the ring center (mean of the sum of the values above and below the plane is presented). The ring σ contributions are diatropic over the whole range from 1 to 9 Å. Starting from 1.5 Å, they overcome the ring π shielding contributions



3d **1q-*Z***

Figure 10. Visualization of the TSNMRSs (ICSSs: blue represents 5 ppm shielding, cyan 2 ppm shielding, green-blue 1 ppm shielding, green 0.5 ppm shielding, yellow 0.1 ppm shielding, and red −0.1 ppm deshielding) of quasi-ring systems formed by S···O(S) interactions in compounds **3d** and **1q**-*Z*.

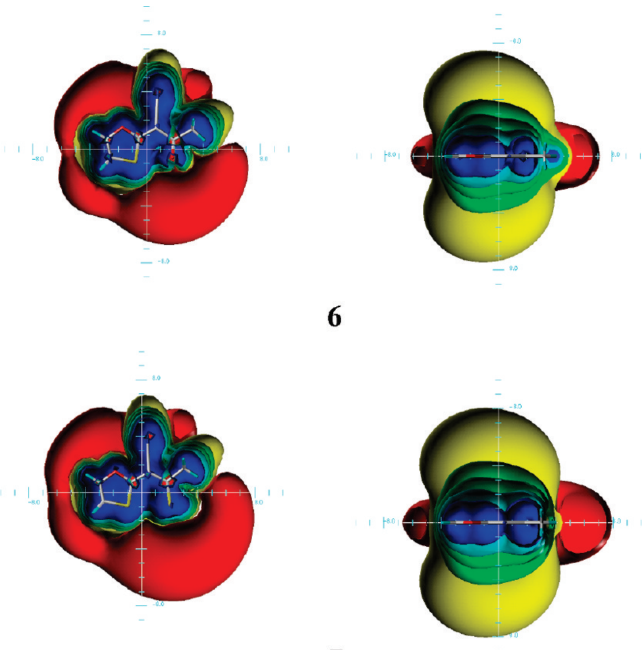


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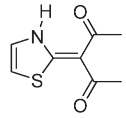
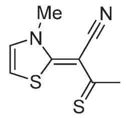
Figure 11. Visualization of the TSNMRSs (ICSSs: blue represents 5 ppm shielding, cyan 2 ppm shielding, green-blue 1 ppm shielding, green 0.5 ppm shielding, yellow 0.1 ppm shielding, and red −0.1 ppm deshielding) of compounds **6** and **7**.

which are diatropic near to the ring plane, but become paratropic farther away. In fact, as the degree of aromaticity increases, the distance of π shielding effect increases, too (for example, π electron contributions are diatropic until 1 Å in **1a**, until 2.5 Å in **1r** and **3d**, until 3 Å in *N*-methylthiazolium cation **4** and thiazole **5**). Again, there is no correlation between the σ shielding values with the push−pull character, but the π magnetic shieldings do correlate with the push−pull effect (Figure 9), thus creating the ICSSs which perfectly describe the aromaticity of the studied compounds.[43] Noticeable here is the higher shielding effect of π electrons in **1**−**3** having one acceptor group and close S···O(S) contact (red points in Figure 9), as already discussed in the previous section. The shielding values at distances >3 Å are still negative and their absolute values get smaller with increasing distance.

Aromaticity of the Quasi-Ring Systems Formed by S···O(S) Interactions and Hydrogen Bonds. There are examples in the literature that the existence of nonbonded S···S interactions can result in the formation of an aromatic system.[30b] Since the quasi-ring systems formed by the S···O(S) interactions in the studied compounds contain 6 π electrons (see Scheme 3), we were intrigued to see if these rings are partially aromatic or not. Thus, the ICSSs of these quasi-rings were examined. For the two compounds, **3d** and **1q**-*Z* having S···O and S···S interactions, respectively, and the highest push−pull effect among the compounds with planar quasi-rings, these ICSSs are shown in Figure 10. In both cases, shielding ICSSs above and below the quasi-rings drop indicating the absence of partial aromaticity. The same findings apply to all other studied molecules stabilized by these nonbonded interactions.

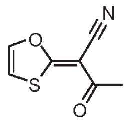


3d



1q-*Z*

It is known that a strong electron-donor combined with a weaker donor substituent decreases the donor activity of the latter and increases its own activity (the same is true for electron-accepting groups).[14d] Thus, the compounds **6** and **7** with higher donor−acceptor character at the side of the S···O(S) stabilized quasi-ring were also examined with respect to the partial aromaticity of both rings. The ICSSs obtained for these two compounds are portrayed in Figure 11. While there exist partial aromaticity of the oxathiol ring in both compounds (ICSS (2 ppm) = 2.3 Å and ICSS (1 ppm) = 3.0 Å for **6**, ICSS (2 ppm) = 2.35 Å and ICSS (1 ppm) = 3.15 Å for **7**), the ICSSs perpendicular to the center of the quasi-rings drop, again indicating no ring current effects of the latter.



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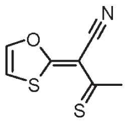

7

Another interesting question is if resonance assisted hydrogen-bonded chelates, such as in **3**, containing 6 π-electrons can be partially aromatic. The answer comes from the examination of the in-plane ICSSs of **3a**-*E*, **3b**-*E*, **3c**-*E* and **3d**, shown in Figure 2 and in Figure S1 in the Supporting Information. There are no consistent shielding surfaces inside these chelates, which is synonym for aromaticity, but only isolated anisotropic effects of the functional groups are generated. Thus, intramolecularly hydrogen-bonded six-membered quasi-rings in thiazoline derivatives **3** are not aromatic. Similar results, i.e., the lack of aromaticity in intramolecularly hydrogen-bonded enol forms of 1,3-dihydroxynaphthyl-2-aldehyde, were already published.[33]

CONCLUSIONS

The study of 2-alkylidenethiazolines **1**−**3** subjected to push−pull activity at the ab initio level of theory resulted in the following conclusions:

(1) The excellent correlation of the two push−pull parameters, the occupation quotient π^*/π, and partial C=C double bond length of the studied push−pull alkenes having the proaromatic donor substituent has proven the quotient method π^*/π to be a general and reliable parameter for quantifying the push−pull behavior of substituted alkenes.

(2) The degree of aromaticity of compounds **1**−**3**, estimated from the distances of ICSSs perpendicular to the ring center, is in excellent correlation with the occupation quotient (π^*/π), i.e., push−pull character. With increasing the push−pull effect the partial aromaticity rises, reaching in compounds with X,Y = COMe acceptors the aromaticity of the single *N*-methylthiazolium cation. Intramolecular nonbonded S$\cdots$O(S) interactions can affect aromaticity as well. This has been found in compounds **1**−**3** with one acceptor group, the aromaticity of which was higher than expected from their push−pull character.The approach we used is related to NICS. Whereas the NICS index uses the shielding at one point in the vicinity of a molecule, we used the distance of fixed shielding value to assess the aromaticity.

(3) Dissection of absolute magnetic shielding values into contributions from bonds and lone pairs has revealed the following: The in-plane region outside the ring is *deshielded* by the ring σ electrons and not by the ring π electrons, which actually *shield* the area. Distances perpendicular to the ring center are shielded by the σ electrons over the whole range studied, and by the π electrons very near to the ring. Farther away, the π electrons have deshielding effect which decreases with the distance. As the degree of aromaticity increases, the distance of π shielding effect increases, too. The total ring σ deshielding (in plane)/shielding effects (above/below plane) do not correlate with the push−pull effect but total π shielding effects (both in plane and above/below plane) do so and, thus, with the aromaticity of the thiazoline ring moiety of **1**−**3**.

(4) No aromaticity has been found for the quasi-rings formed by the intramolecular S$\cdots$O(S) interactions and hydrogen bonds in all **1**−**3**, and in addition, **6** and **7** with higher push−pull activity at the side of the S$\cdots$O(S) stabilized the quasi-ring.

ASSOCIATED CONTENT

Supporting Information. Coordinates and absolute energies (a.u.) at the MP2/6-311G(d,p) level of theory of all studied compounds; absolute energies in kcal/mol for all conformers of compounds **1k**, **1 m**-*E*, **1 m**-*Z*, **1o**, **1r**, and **3d**; Mulliken charges on the exocyclic O(S) involved in the nonbonded interaction with the ring sulfur in compounds **1**−**3**; Wiberg bond order (BO) of the S(1)−C(5) and S(1)−C(2) bonds in compounds **1**−**3**; total ring σ and π contributions to the in-plane and perpendicular to plane magnetic shielding values along the axes shown in Figure 7; visualization of the TSNMRSs of thiazolines **1**−**3**; HOMA values of compounds **1**−**5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jiao, H.; Hommes, N. J. R. v. E. *J. Am. Chem. Soc.* **1996**, *118*, 6317.

(2) Chen, Z.; Wannere, C. S.; Corminboeuf, C.; Puchta, R.; Schleyer, P. v. R. *Chem. Rev.* **2005**, *105*, 3842.

(3) (a) Schleyer, P. v. R.; Jiao, H.; Hommes, N. J. R. v. E.; Malkin, V. G.; Malkina, O. L. *J. Am. Chem. Soc.* **1997**, *119*, 12669. (b) Schleyer, P. v. R.; Manoharan, M.; Wang, Z.-X.; Kiran, B.; Jiao, H.; Puchta, R.; Hommes, N. J. R. v. E. *Org. Lett.* **2001**, *3*, 2465. (c) Fallah-Bagher-Shaidaei, H.; Wannere, C. S.; Corminboeuf, C.; Puchta, R.; Schleyer, P. v. R. *Org. Lett.* **2006**, *8*, 863.

(4) Klod, S.; Kleinpeter, E. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1893.

(5) (a) Ditchfield, R. *Mol. Phys.* **1974**, *27*, 789. (b) Cheeseman, J. R.; Trucks, G. W.; Keith, T. A.; Frisch, M. J. *J. Chem. Phys.* **1996**, *104*, 5497.

(6) SYBYL 7.1, Tripos Inc., St. Louis, MO, 2005.

(7) (a) Tóth, G.; Kovács, J.; Lévai, A.; Koch, A.; Kleinpeter, E. *Magn. Reson. Chem.* **2001**, *39*, 251. (b) Kleinpeter, E.; Holzberger, A. *Tetrahedron* **2001**, *57*, 6941. (c) Germer, A.; Klod, S.; Peter, M. G.; Kleinpeter, E. *J. Mol. Model* **2002**, *8*, 231. (d) Kovács, J.; Tóth, G.; Simon, A.; Lévai, A.; Koch, A.; Kleinpeter, E. *Magn. Reson. Chem.* **2003**, *41*, 193. (e) Szatmári, I.; Martinek, T. A.; Lázár, L.; Koch, A.; Kleinpeter, E.; Neuvonen, K.; Fülöp, F. *J. Org. Chem.* **2004**, *69*, 3645. (f) Ryppa, C.; Senge, M. O.; Hatscher, S. S.; Kleinpeter, E.; Wacker, Ph.; Schilde, U.; Wiehe, A. *Chem.—Eur. J* **2005**, *11*, 3427. (g) Kleinpeter, E.; Schulenburg, A.; Zug, I.; Hartmann, H. *J. Org. Chem.* **2005**, *70*, 6592. (h) Kleinpeter, E.; Schulenburg, A. *J. Org. Chem.* **2006**, *71*, 3869. (i) Heydenreich, M.; Koch, A.; Klod, S.; Szatmári, I.; Fülöp, F.; Kleinpeter, E. *Tetrahedron* **2006**, *62*, 11081. (j) Kleinpeter, E.; Koch, A.; Sahoo, H. S.; Chand, D. K. *Tetrahedron* **2008**, *64*, 5044.

(8) (a) Kleinpeter, E.; Koch, A.; Seidl, P. R. *J. Phys. Chem. A* **2008**, *112*, 4989. (b) Kleinpeter, E.; Szatmári, I.; Lázár, L.; Koch, A.; Heydenreich, M.; Fülöp, F. *Tetrahedron* **2009**, *65*, 8021.

(9) (a) Kleinpeter, E.; Klod, S.; Koch, A. *THEOCHEM* **2007**, *811*, 45. and references therein(b) Kleinpeter, E.; Klod, S.; Koch, A. *THEOCHEM* **2008**, *857*, 89. (c) Kleinpeter, E.; Koch, A.; Shainyan, B. A. *THEOCHEM* **2008**, *863*, 127. (d) Kleinpeter, E.; Klod, S.; Koch, A. *J. Org. Chem.* **2008**, *73*, 1498. (e) Kleinpeter, E.; Koch, A. *THEOCHEM* **2010**, *939*, 1.

(10) Kleinpeter, E.; Koch, A. *THEOCHEM* **2008**, *851*, 313.

(11) Kleinpeter, E.; Klod, S. *J. Am. Chem. Soc.* **2004**, *126*, 2231.

(12) Klod, S.; Koch, A.; Kleinpeter, E. *J. Chem. Soc., Perkin Trans. 2* **2002**, 1506.

(13) Kleinpeter, E.; Koch, A. *J. Phys. Chem. A* **2010**, *114*, 5928.

(14) (a) Sandström, J. *Top. Stereochem.* **1983**, *14*, 83. (b) Fischer, G.; Rudorf, W.-D.; Kleinpeter, E. *Magn. Reson. Chem.* **1991**, *29*, 212. (c) Benassi, R.; Bertarini, C.; Kleinpeter, E.; Taddei, F. *THEOCHEM* **2000**, *498*, 217. (d) Kleinpeter, E.; Klod, S.; Rudorf, W.-D. *J. Org. Chem.* **2004**, *69*, 4317. (e) Rattananakin, P.; Pittman, C. R., Jr.; Collier, W. E.; Saebø, S. *Struct. Chem.* **2007**, *18*, 399.

(15) Ye, G.; Chatterjee, S.; Li, M.; Zhou, A.; Song, Y.; Barker, B. L.; Chen, C.; Beard, D. J.; Henry, W. P.; Pittman, C. U. *Tetrahedron* **2010**, *66*, 2919 and references therein.

(16) (a) Kleinpeter, E; Thomas, St.; Uhlig, G.; Rudorf, W.-D. *Magn. Reson. Chem.* **1993**, *31*, 714. (b) Kleinpeter, E; Heydenreich, M.; Chatterjee, S. K.; Rudorf, W.-D. *Magn. Reson. Chem.* **1994**, *32*, 473. (c) Kleinpeter, E; Koch, A.; Heydenreich, M.; Chatterjee, S. K.; Rudorf, W.-D. *J. Mol. Struct.* **1995**, *356*, 25. (d) Mueller, J. L.; Gibson, M. S.; Hartman, J. S. *Can. J. Chem.* **1996**, *74*, 1329. (e) Chiara, J. L.; Gómez-Sánchez, A.; Bellanato, J. *J. Chem. Soc., Perkin Trans. 2* **1998**, 1797. (f) Kleinpeter, E.; Heydenreich, M.; Woller, J.; Wolf, G; Koch, A.; Kempter, G. *J. Chem. Soc., Perkin Trans. 2* **1998**, 1877. (g) Meier, H.; Mühling, B.; Gerold, J.; Jacob, D.; Oehlhof, A. *Eur. J. Org. Chem.* **2007**, 625. (h) Kleinpeter, E. *J. Serb. Chem. Soc.* **2006**, *71*, 1.

(17) Kleinpeter, E.; Schulenburg, A. *Tetrahedron Lett.* **2005**, *46*, 5995.

(18) Baranac-Stojanović, M.; Klaumünzer, U.; Marković, R.; Kleinpeter, E. *Tetrahedron* **2010**, *66*, 8958.

(19) Kleinpeter, E.; Schulenburg, A.; Zug, I.; Hartmann, H. *J. Org. Chem.* **2005**, *70*, 6592.

(20) (a) Kleinpeter, E.; Frank, A. *J. Phys. Chem. A* **2009**, *113*, 6774. (b) Kleinpeter, E.; Frank, A. *Tetrahedron* **2009**, *65*, 4418. (c) Kleinpeter, E.; Schulenburg, A. *J. Org. Chem.* **2006**, *71*, 3869.

(21) Kleinpeter, E.; Stamboliyska, B. A. *Tetrahedron* **2009**, *65*, 9211.

(22) Kleinpeter, E.; Bölke, U.; Kreicberga, J. *Tetrahedron* **2010**, *66*, 4503.

(23) Kleinpeter, E.; Stamboliyska, B. A. *J. Org. Chem.* **2008**, *73*, 8250.

(24) Bohmann, J. A.; Weinhold, F.; Farrar, T. C. *J. Chem. Phys.* **1997**, *107*, 1173.

(25) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennuci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Babuol, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzales, C.; Pople, J. A. *Gaussian 03(Revision C.02)*; Gaussian, Inc., Wallingford, CT, 2004.

(26) Møller, C.; Plesset, M. S. *Phys. Rev.* **1934**, *46*, 618.

(27) (a) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648. (b) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev.* **1988**, *37*, 785. This was the highest possible level for computation of ICSS. The lattice points ("ghost atoms") should be sensor points only without energy contribution in the present calculations. Only if HF calculations were applied did this prove to be true; in the case of electron correlation calculations, the "ghost atoms" get their own electron density and are of some influence on the energy of the studied molecule hereby. In these cases, the TSNMRS surfaces proved to become heavily distorted.

(28) Bohmann, J. A.; Weinhold, F.; Farrar, T. C. *J. Chem. Phys.* **1997**, *107*, 1173.

(29) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheesman, 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.; Rega, N.; Salvador, P.; Dannenberg, J. J.; 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.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzales, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.11.3; Gaussian Inc.; Pittsburgh, PA, 2002.

(30) (a) González, F. V.; Jain, A.; Rodríguez, S.; Sáez, J. A.; Vicent, C.; Teris, G. *J. Org. Chem.* **2010**, *75*, 5888. (b) Rašović, A.; Steel, P. J.; Kleinpeter, E.; Marković, R. *Tetrahedron* **2006**, *63*, 1937 and references cited therein. (c) Andreu, R.; Cerdán, M. A.; Garín, H.; Orduna, J. *Arkivoc* **2004**, *iv*, 32. (d) Fragoso-Serrano, M.; Guillén-Jaramillo, G.; Pereda-Miranda, R.; Cerda-García-Rojas, C. M. *J. Org. Chem.* **2003**, *68*, 7167. (e) Iwaoka, M.; Takemoto, S.; Tomoda, S. *J. Am. Chem. Soc.* **2002**, *124*, 10613. (f) Dal Colle, M.; Bertolasi, V.; de Palo, M.; Distefano, G.; Jones, D.; Modelli, A.; Olivato, P. R. *J. Phys. Chem.* **1995**, *99*, 15011. (g) Burling, F. T.; Goldstein, B. M. *J. Am. Chem. Soc.* **1992**, *114*, 2313. (h) Fabius, B.; Cohen-Addad, C.; Larsen, F. K.; Lehmann, M. S.; Becker, P. *J. Am. Chem. Soc.* **1989**, *111*, 5728. (i) Hordvik, A.; Jynge, K. *Tetrahedron* **1979**, *35*, 1199. (j) Rosenfield, R. E., Jr.; Parthasarathy, R.; Dunitz, J. D. *J. Am. Chem. Soc.* **1977**, *99*, 4860. (k) Mellor, I. P.; Nyburg, S. C. *Acta Crystallogr.* **1971**, *B27*, 1959.

(31) Geometry optimization of the *s-trans/s-trans* conformation of **1r** actually gave the *s-cis/s-trans* conformation **II**.

(32) Twist angle is defined as the angle between the bisectors of the 1,1- and 2,2-substituent angles on a Newman diagram projecting down the $C{=}C$ bond of an olefin. See: (a) Baum, K; Bigelow, S. S.; Nguyen, N. V.; Archibald, T. G. *J. Org. Chem.* **1992**, *57*, 235. (b) Winkler, F. K.; Dunitz, J. D. *J. Mol. Biol.* **1971**, *59*, 169.

(33) Kleinpeter, E.; Bölke, U.; Koch, A. *J. Phys. Chem. A* **2010**, *114*, 7616.

(34) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4907.

(35) In some compounds, there is still a small contribution of substituents anisotropic effects to the ICSS = 0.5 ppm, so that the values are somewhat higher.

(36) Wiberg, K. B. *Tetrahedron* **1968**, *24*, 1083.

(37) (a) Krygowski, T. M.; Cyrański, M. K. *Chem. Rev.* **2001**, *101*, 1385. (b) Krygowski, T. M.; Cyrański, M. K. *Tetrahedron* **1996**, *52*, 10255. (c) Krygowski, T. M.; Cyrański, M. K. *Tetrahedron* **1996**, *52*, 1713. (d) Kruszewski, J.; Krygowski, T. M. *Tetrahedron Lett.* **1972**, 3839.

(38) Cyrański, M. K.; Krygowski, T. M.; Katritzky, A. R.; Schleyer, P. v. R. *J. Org. Chem.* **2002**, *67*, 1333.

(39) Pople, J. A. *J. Chem. Phys.* **1956**, *24*, 1111.

(40) Wannere, C. S.; Schleyer, P. v. R. *Org. Lett.* **2003**, *5*, 605.

(41) Viglione, R. G.; Zanasi, R.; Lazzeretti, P. *Org. Lett.* **2004**, *6*, 2265.

(42) Wannere, C. S.; Corminboeuf, C.; Allen, W. D.; Schaefer, H. F.; Schleyer, P.; von, R. *Org. Lett.* **2005**, *7*, 1457.

(43) The total contributions of the ring C−H bonds, N−H(Me, *t*-Bu), and $C(2){=}C(2')$ bond are much smaller, especially to the out-of-plane magnetic shielding.