Effect of intramolecular interaction between polar and polarizable bonds on ^{13}C shielding constants in different conformations of 2-methoxy- and 2-vinyloxynaphthalene molecules: an *ab initio* study

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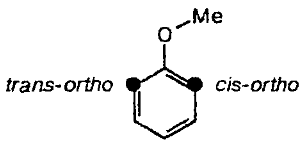
Shielding constants of ^{13}C nuclei calculated for different conformations of 2-methoxynaphthalene and 2-vinyloxynaphthalene molecules by the GIAO *ab initio* method in the D95** basis set indicate a strong shielding effect of the intramolecular interaction between the polar O—C bond of the substituent and the polarizable π-bond of the naphthyl moiety on the C atom in *cis*-position. The results obtained are in agreement with the experimentally found trends of changes in the chemical shifts of ^{13}C nuclei and are in reasonable quantitative agreement with experimental data.

Key words: effect of conformation on the ^{13}C shielding constants, *ab initio* calculations, GIAO method, 2-methoxy- and 2-vinyloxynaphthalenes.

It has been established that biological activity of compounds containing the phenyl moiety and several methoxy groups strongly depends on the predominant conformation of their molecules.[1] Salient features of the interactions determining the position of the methoxy group in the molecules of unsaturated methyl ethers have been revealed. In anisole derivatives, the methoxy group lies in the phenyl ring plane[2—7] unless it is between two bulky substituents.[8,9] In the molecules of several aryl and heteroaryl compounds, *viz.*, 3-NO_2-4-NH_2-anisole,[10] 2-methoxypyridine,[11,12] 2-methoxyphenazine,[13] and 2-fluoroanisole,[14] the methoxy group mostly occupies one of two possible positions. It has been shown that the methoxy group is preferably in the *cis*-position with respect to the unsaturated bond with the higher π-order value.[15,17]

In most studies dedicated to conformational analysis of methoxy derivatives of unsaturated compounds, ^1H and ^{13}C NMR spectroscopy data are used. It has been found that changes in the chemical shifts (CS) of the nuclei of carbon atoms in *cis-ortho-* and *trans-ortho*-positions with respect to the methoxy group (see A) in anisole derivatives are markedly inequivalent.



A

The shift of the CS of the nuclei of *cis-ortho*-carbon atoms are 7 ppm larger than that of the nuclei of *trans-ortho*-carbon atoms.[18]

This effect can be explained as follows.[19] The polar O—C(Me) bond, which is close to the highly polarizable π-bond, induces a dipole on the latter. The higher the π-order of a corresponding bond, the higher the degree of polarization. The induced dipole provides additional shielding of the *cis-ortho*-carbon atom; at the same time, the *cis*-position of the O—C(Me) bond relative to the unsaturated bond with a high π-order is more favorable energetically.[19,20]

The same effect was found using analysis of the CS of ^{13}C nuclei in the case of arylvinyl and hetarylvinyl ethers containing the vinyloxy group.[21] Hence, consideration of the increments of CS of ^{13}C nuclei can serve as a powerful tool for the conformational analysis of a wide range of unsaturated oxygen-containing compounds. Therefore, it was of interest to study stereochemical dependences of shielding constants of the ^{13}C nuclei in model unsaturated ethers and to use the results obtained for establishing the role of the intramolecular interaction between the polar O—C bond and polarizable π-bonds of the unsaturated fragment in the change in the CS of ^{13}C nuclei with the aid of *ab initio* quantum-chemical calculations. 2-Methoxynaphthalene (**1**) and 2-vinyloxynaphthalene (**2**) were chosen as model compounds.

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Calculation procedure

The geometries of the conformers of compounds **1** and **2** were optimized using the GAMESS program[22] in the 6-31G* basis set and were then used in calculations of shielding constants by the GIAO method[23] in the D95** basis set using the GAUSSIAN-94 program.[24] The values of shielding constants were transformed to match a scale of CS measured relative to tetramethylsilane, taking into account that the value of the ^{13}C shielding constant in methane calculated by the GIAO method in the D95** basis set is 198.7 ppm and the difference between the CS of methane and tetramethylsilane is 7.0 ppm.[29]

Results and Discussion

The experimental values of the CS of ^{13}C nuclei in the molecules of compounds **1** and **2** are listed in Table 1. The calculated values of the CS of ^{13}C nuclei for different conformations of these molecules are listed in Table 2. We calculated the CS of ^{13}C nuclei for two planar conformations of molecule **1** with *cis*-C(1)- and *cis*-C(3)-position of the methoxy group (conformers **1a** and **1b**, respectively).

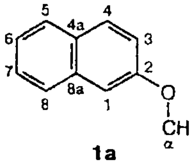
Table 1. Experimental CS of ^{13}C nuclei (δ) in 2-methoxynaphthalene (**1**), 2-vinyloxynaphthalene (**2**), and naphthalene (**3**)

Carbon atom	δ ^{13}C **1**[a]	 **2**[b]	 **3**[b]
1	105.7 (−22.0)[c]	111.45 (−16.3)	127.7
2	157.5 (+31.9)	154.61 (+29.0)	125.6
3	118.7 (−6.9)	118.82 (−6.8)	125.6
4	129.3 (+1.6)	129.76 (+2.1)	127.7
4a	129.0 (−4.4)	130.06 (−3.3)	133.4
5	127.6 (−0.1)	127.72 (0)	127.7
6	123.4 (−2.2)	124.56 (−1.0)	125.6
7	126.3 (+0.7)	126.57 (+1.0)	125.6
8	126.7 (−1.0)	127.07 (−0.6)	127.7
8a	134.6 (+1.2)	134.23 (+0.8)	133.4
α	55.0	147.98	—
β	—	95.63	—

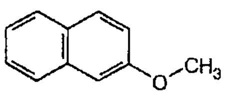
[a] Data were taken from Ref. 33.

[b] Data were taken from Ref. 21; the signals of the C(4), C(5), C(7), and C(8) atoms were refined using the HMQC[35] and HMBC[36] procedures of 2D heteronuclear NMR spectroscopy.

[c] The values of corresponding increments of the CS of ^{13}C nuclei are given in parentheses.

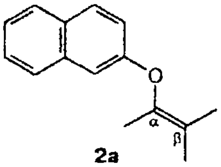


1a

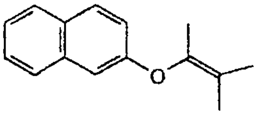


1b

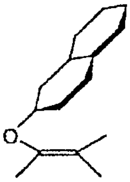
For molecule **2**, the number of conformers is larger than for molecule **1** because of the presence of two unsaturated fragments. In addition to two planar conformations (**2a** and **2b**) in which the vinyl group is in *trans*-position with respect to the naphthyl fragment, the molecule of compound **2** can have a conformation in which these fragments are in *cis*-position relative to each other (**2c**)[26–28] and lie in mutually orthogonal planes; the fraction of this conformation can be substantial.[23–40]



2a



2b



2c

For this reason, we calculated the CS of ^{13}C nuclei for the three above conformations of the molecule of compound **2** (see Table 2).

It should be noted that planar conformers **2a** and **2b** do not correspond to global energy minima on the potential energy surface of internal rotation of molecule **2**. In fact, the vinyl group and the aromatic fragment should deviate out of the plane passing through the C(2), O, and C(α) atoms by an angle of about 30°.[30] However, consideration of the CS of ^{13}C nuclei in these conformers would make difficult a comparison of the effects of rotation of the methoxy and vinyloxy groups on the shielding of endocyclic C atoms in molecules **1** and **2**.

The *cis*-C(1)-conformations of the molecules of compounds **1** and **2** dominate appreciably at room temperature.[21] According to calculations in the D95** basis set, the **1a** conformation is ~2.1 kcal mol^{-1} more energetically favorable than **1b**, while the **2a** conformation is 1.5 kcal mol^{-1} more stable than **2b**. Therefore, the CS of ^{13}C nuclei calculated for these conformers must be best to compare with experimental ones. A comparison shows a regular underestimation of the absolute values of the calculated CS of ^{13}C nuclei in conformations **1a** and **2a** relative to the experimental values for **1** and **2** (see Tables 1 and 2). For both molecules **1** and **2**, the largest differences are observed for the calculated CS of the nuclei of the C(1) and C(α) atoms (11.7 and 11.7 ppm, and 17.7 and 12.2 ppm, respectively). The CS of the nucleus of the C(4) atom is the best to calculate for both molecules (the difference between the calculated and experimental CS values is 2.6 ppm, see Table 2).

Most interesting is to consider changes in the CS of ^{13}C nuclei due to the introduced substituent (the methoxy group or the vinyloxy group). The calculated values of the CS of ^{13}C nuclei for unsubstituted naphthalene (**3**) are also listed in Table 2; they are explicitly overestimated as compared to the observed effects. For instance, the experimental increments of the CS of the nuclei of the C(4a), C(6), and C(7) atoms in molecule **1** are halved as compared to the calculated values and that of the CS of the nucleus of the C(8) atom is 5 times smaller than the calculated value. The same is also observed for compound **2** (see Tables 1 and 2). However, GIAO calculations adequately reproduce the tendency and order of changes in the experimental CS of the nuclei of the endocyclic carbon atoms in the naphthyl fragment under the action of the methoxy or vinyloxy group. For this reason, the reported data are well suited for qualitative analysis of stereochemical dependences of shielding constants of ^{13}C nuclei in the compounds considered.

Introduction of a substituent, the methoxy or the vinyloxy group, affects to the greatest extent the CS of the nuclei of the carbon atoms in *ipso*-C(2), *ortho*-C(1), *ortho*-C(3), and *para*-C(4a) positions (the C(2), C(1), C(3), and C(4a) atoms, respectively, see Table 2). In the first case, an appreciable low-field shift of the CS of ^{13}C nuclei occurs due to direct effect of the electronegative O atom.[31] Considerable high-field shifts of the CS of the nuclei of the C(1), C(3), and C(4a) atoms are mainly due to p-π-conjugation.[2,30] Noteworthy is the large difference in the increments of the CS of ^{13}C nuclei of the C(1) and C(3) atoms adjacent to the methoxy and vinyloxy groups in conformations **1a** and **2a**. The increment of the CS for the C(1) atom is about 5 times larger than for the C(3) atom (see Table 2). Calculations performed by the AM1 method showed that the π-order of the C(1)—C(2) bond in the naphthalene molecule is higher by a factor of 1.5 than that of the C(2)—C(3) bond.[21] It is known that the higher the π-order of a corresponding unsaturated bond, the stronger the p-π-conjugation.[32] Therefore, the fact that the p-π-conjugation of the oxygen atom with the double C(1)—C(2) bond is stronger than its conjugation with the C(2)—C(3) bond could be explained by a larger value of the increment of the CS for the nucleus of the C(1) atom as compared to that of the nucleus of the C(3) atom in compounds **1** and **2**.

Table 2. Calculated values of chemical shifts of ^{13}C nuclei (δ) in conformers of 2-methoxynaphthalene (**1**), 2-vinyloxynaphthalene (**2**), and in naphthalene (**3**)

C atom	δ ^{13}C					
	1a	**1b**	**2a**	**2b**	**2c**	**3***
1	94.4 (−31.3)	104.42 (−20.9)	93.74 (−31.6)	105.81 (−19.5)	112.82 (−12.5)	125.35
2	150.45 (+29.8)	149.12 (+28.5)	147.10 (+26.5)	146.32 (+25.7)	144.07 (+23.5)	120.62
3	113.92 (−6.7)	103.94 (−16.7)	114.00 (−6.6)	102.21 (−18.4)	117.06 (−3.6)	120.62
4	126.67 (+1.3)	126.82 (+1.5)	127.14 (+1.8)	126.90 (+1.6)	124.85 (−0.5)	125.35
4a	121.28 (−9.0)	120.67 (−9.6)	122.01 (−8.2)	121.54 (−8.7)	124.99 (−5.2)	130.23
5	123.53 (−1.8)	123.23 (−2.1)	123.22 (−2.1)	123.00 (−2.4)	123.01 (−2.4)	125.35
6	116.26 (−4.4)	115.93 (−4.7)	117.11 (−3.5)	116.90 (−3.7)	118.96 (−1.7)	120.62
7	122.21 (+1.6)	122.11 (+1.5)	122.49 (+1.9)	122.52 (+1.9)	121.16 (+0.5)	120.62
8	120.24 (−5.1)	120.31 (−5.0)	120.36 (−5.0)	120.37 (−5.0)	121.52 (−3.8)	125.35
8a	130.75 (+0.5)	131.65 (+1.4)	130.07 (−0.2)	131.57 (+1.3)	129.24 (−1.0)	130.23
α	43.32	43.42	135.77	136.01	145.65	—
β	—	—	86.15	85.26	79.42	—

Note. The values of corresponding increments of the CS of ^{13}C nuclei are given in parentheses.

* Data were taken from Ref. 34.

Rotation of the methoxy or vinyloxy group from the *cis*-C(1)-position to occupy the *cis*-C(3)-position (conformations **1a** and **1b** and **2a** and **2b**, respectively) is not accompanied by pronounced changes in the CS of the nuclei of all cyclic C atoms, except for those of the C(1) and C(3) atoms (see Table 2). The chemical shifts of the nuclei of the C(α) and C(β) atoms of the vinyl group in conformers **2a** and **2b** also remain virtually unchanged. This indicates that the p-π-conjugation with the unsaturated fragments persists as the spatial orientation of the substituent in position 2 of the naphthyl fragment changes.

At the same time, the CS of the nucleus of the C(1) atom in conformations **1b** and **2b** is 10—12 ppm larger than in conformations **1a** and **2a**, whereas that of the nucleus of the C(3) atom is smaller by the same value. Such antiparallel changes in the CS of the C(1) and C(3) atoms are due to the intramolecular interaction between the polar O—C(α) bond and the polarizable C(1)—C(2) and C(2)—C(3) π-bonds.[19—21] Polarization of the C(1)—C(2) π-bond in *cis*-C(1)-conformers **1a** and **2a** causes an additional high-field shift of the CS of the nucleus of the C(1) atom. In *cis*-C(3)-conformations **1b** and **2b**, the C(2)—C(3) π-bond is polarized and an additional high-field shift of the CS of the nucleus of the C(3) atom occurs.[19—21] Thus, the marked inequivalence of changes in the CS of the nuclei of the C(1) and C(3) atoms in compounds **1** and **2** is due not only to differences in the p-π-conjugation with the C(1)—C(2) and C(2)—C(3) bonds, but also to polarization of the C(1)—C(2) π-bond induced by the O—C(α) polar bond in the energetically more favorable *cis*-C(1)-conformer.

From experimental data it follows that the increment of the methoxy group is responsible for the larger increase in the CS of the nucleus of the C(1) atom than that of the vinyloxy group (see Table 1). In this case the increments of these substituents for the CS of the nucleus of the C(3) atom are virtually equal (see Table 1). This was explained assuming that the more polar O—C(sp^3) bond in molecule **1** polarizes the C(1)—C(2) π-bond to a greater extent compared to the effect of the O—C(sp^2) bond in derivative **2**.[21] However, data of quantum-chemical calculations do not confirm this assumption. The increment of the methoxy group for the CS of the nucleus of the C(1) atom in conformation **1a** is equal to the analogous increment of the vinyloxy group for conformation **2a**. Hence the polarizing effect of the O—C(α) bond on the C(1)—C(2) π-bond in compound **2** is not less than in derivative **1**.

When explaining the above differences, one should take into account that substituted naphthalenes **1** and **2** have different sets of conformations. The derivative **2** also exists in the orthogonal conformation **2c**, in which the unsaturated fragments are in *cis*-position relative to each other, and the fraction of this conformation is ~20%.[26—28] Violation of p-π-conjugation with the naphthyl fragment in conformer **2c** manifests itself in decreasing the increments of the CS of the nuclei of the C(1), C(3), and C(4) atoms in *ortho*- and *para*-positions relative to the vinyloxy group. This is accompanied by an increase in p-π-conjugation in the vinyloxy group, which manifests itself as a high-field shift of the CS of the nucleus of the C(β) atom and as a low-field shift of the CS of the nucleus of the C(α) atom (see Table 2).[30]

The increment of the CS of the nucleus of the C(1) atom decreases to the greatest extent on going from conformer **2a** to **2c** (from -31.6 to -12.5 ppm, respectively), since the C(1)—C(2) π-bond is nonpolarized in the orthogonal conformation **2c**. The CS value of the ^{13}C nucleus recorded experimentally is averaged over all states because of low barriers to internal rotation. For this reason, the experimental increment of the CS of the nucleus of the C(1) atom in 2-vinyloxynaphthalene is substantially smaller than in 2-methoxynaphthalene.

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