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Conformational Effects on ^{13}C NMR Parameters in Alkyl Formates

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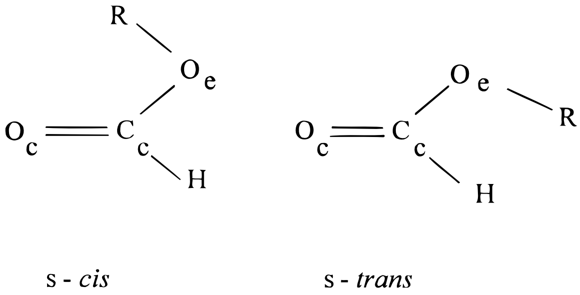
ABSTRACT: The ^{13}C NMR spectra of a series of alkyl formates which show the coexistence of *s-cis* and *s-trans* rotamers at room temperature were measured at 125 MHz. ^{13}C chemical shifts and $^{1}J(CH)$ couplings are compared for both types of rotamers. Their differences are rationalized in terms of different intramolecular interactions. The ^{17}O NMR spectra of these compounds could be observed only for the most abundant rotamer, which in all cases was identified as the *s-cis* rotamer. In the three members of this series with the shortest alkyl chains, a $2J(^{17}O,^{1}H)$ coupling constant of *ca.* 40 Hz was observed. In ethyl formate, ^{13}C magnetic shielding constants were calculated using the LORG approach with *ab initio* optimized geometries in both types of rotamers for the carbon atom β to the dicoordinated oxygen atom. A comparison between the calculated and experimental values yields support for the rationalizations quoted above. © 1998 John Wiley & Sons, Ltd.

KEYWORDS: NMR; ^{13}C NMR; ^{17}O NMR; alkyl formates; conformational effects; *ab initio* LORG study

INTRODUCTION

Several years ago, Bond and Schleyer[1] reported a theoretical study on interactions that define the *s-cis* as more preferential than the *s-trans* conformation in methyl vinyl ether, methyl formate and related compounds. They found, on the one hand, that the energy due to the conjugation between the π-type lone pair of the two-coordinated oxygen atom and the π electronic system of the unsaturated moiety is almost the same for both types of rotamers and, on the other hand, that the difference in energy known for those rotamers in this type of compound originates mainly in an electrostatic interaction. Similar interactions are now known to be important in defining the methoxy group conformation in aryl methyl ethers[2] and some insight into how such interactions operate was obtained recently.[3,4] In this last type of compound a detailed knowledge of this interaction could be very important since side-chain methoxy group conformations are known to define the biological activity of many drugs.[5,6]

With these ideas in mind, in this work alkyl formates were taken as model compounds to study how much NMR parameters depend on the *s-cis* and *s-trans* conformations. Such a comparison is desirable since variations in these parameters could shed some light on how different interactions are operating in both types of rotamers. To this end, ^{13}C and ^{17}O NMR spectra were measured for compounds **1**–**7** (Scheme 1). ^{13}C NMR spectra of alkyl formates **1**–**6** and of benzyl formate (**7**) show, at room temperature, the coexistence of the *s-cis* and *s-trans* rotamers which are differently populated (Scheme 1). ^{13}C chemical shifts and as $^{1}J(CH)$ coupling constants are compared for both types of rotamers and differences are interpreted in terms of intramolecular



Comp.	R	% s- *trans*
1	Me	8
2	Et	8
3	n-Pr	6
4	t-Bu	9
5	Bu	18
6	i-Bu	15
7	CH_2Ph	27

Scheme 1

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interactions. For all compounds, the ^{17}O spectra could be obtained only for the most populated rotamer, which, on the basis of the ^{13}C spectra, was in all cases identified as the *s-cis* rotamer, in agreement with known preferential conformations in two members of this series.[1,7–9] Apparently, in all cases the difference in ^{17}O chemical shifts for the two rotamers is not large enough to be able to observe the ^{17}O signals of the less abundant rotamer. NMR measurements were complemented with *ab initio* MO calculations for different rotamers of compound **2**. Their relative energies and the ^{13}C magnetic shielding constants within the LORG approach[10] for the carbon atom β to the dicoordinated oxygen atom were calculated.

EXPERIMENTAL

NMR measurements

All compounds used in this work were available commercially and when necessary they were purified by distillation. Their identities and purities were checked from their ^{1}H and ^{13}C NMR spectra.

The ^{13}C NMR spectra were recorded with a Bruker AM 500 spectrometer operating at 125.760 MHz. Samples were prepared as neat liquids with 10% (w/w) of CD_3CN and hexamethyldisiloxane (HMDS). The former provided the internal lock signal and the latter was taken as an internal standard to reference ^{13}C chemical shifts. Sample tubes of 5 mm were used. The digital resolution for ^{13}C proton-decoupled spectra was typically 0.7 Hz per point. For ^{13}C proton-coupled spectra this resolution was improved to 0.037 Hz per point.

^{17}O NMR spectra were obtained with the same spectrometer, operating at 67.801 MHz. Sample temperatures were established at 303 K using the instrument's temperature control. The samples were the same as those used when studying the ^{13}C NMR spectra. Hexamethyldisiloxane was used as an internal standard. ^{17}O chemical shifts were subsequently referenced to external water considering that $\delta(^{17}\text{O})$ in HMDS is 42.6 ppm with respect to external water. Linewidths ranging from 30 to 130 Hz were found for the formates studied in this work. These values are much lower than those found in other oxygen-containing compounds. Therefore, it was not necessary to resort to using a special acoustic ringing reducing program. Spectra were taken with the following parameters: memory size, 32K; spectral width, 35 700 Hz; acquisition time; 0.46 s; digital resolution, 2.18 Hz per point; and pulse width, 20 μs. In compounds **1**, **2** and **3** a splitting of the 'high-field' ^{17}O signal was evident and in others it was suggested by a lower signal height. Therefore, while general view spectra were drawn using an exponential noise-reducing constant of barely 5, all samples were later studied using the Gaussian resolution enhancement technique with constants $LB = -50$ and $GB = 0.1$. With this technique a definite J coupling constant of about 40 Hz was made clearly visible for the first three compounds of the series. To apply this resolution enhancement technique, a good signal-to-noise ratio was essential. Therefore, a large number of 'sweeps' was used, ranging from 90 000 to 480 000 depending on the sample. Proton decoupling experiments confirmed that such splittings correspond to $J(^{17}\text{O},^1\text{H})$ coupling constants.

MO calculations

The molecular structures of four rotamers of compound **2** were fully optimized by the gradient method at the HF/6–31G* level using the GAMESS program.[11] The LORG calculations were performed using the GAMESS molecular package to generate the electronic wavefunctions and the RPAC molecular properties package[12] to calculate the shielding tensors. The magnetic shielding calculations were carried out on these optimized geometries using the 6–31G* basis set. All calculations were performed on an IBM RISC System/6000 workstation.

RESULTS AND DISCUSSION

In Table 1, ^1J(CH) couplings for both types of rotamers, *s-cis* and *s-trans*, are compared for compounds **1**–**7**. Alkyl carbon atoms are labeled α, β, γ and δ according to their positions relative to the dicoordinated oxygen atom, O_e. Assignments of spectra belonging to the *s-cis* and *s-trans* rotamers were made according to the value of the formyl ^1J(CH) couplings. In all these compounds a systematic difference ranging from 5.3 to 9.8 Hz was observed for both rotamers. Such a difference is thought to originate in the well known[13–15] lone pair effect that takes place between the formyl C—H bond and the in-plane lone pair of the dicoordinated oxygen atom which is only present in the *s-cis* rotamers. This lone pair effect is now called the Perlin effect.[16] Accordingly, spectra showing the smaller formyl ^1J(CH) couplings are assigned to the *s-trans* rotamers. With this assignment in all cases the *s-cis* rotamer is notably more populated than the *s-trans* rotamer.

The following features of other data displayed in Table 1 are worth noting. In **1**, **2**, **3**, **5** and **6** there is a conspicuous difference of about 7 Hz in $^1J(C_\alpha,H)$ between the *s-cis* and *s-trans* rotamers. This difference is smaller for **7**, 6 Hz. The trend followed by the $^1J(C_\alpha,H)$ coupling constants can be rationalized as follows. The preferential conformation of one of the C_α—H bonds in the *s-cis* rotamers is *cis* to the in-plane lone pair of the two-coordinated oxygen atom and therefore an important Perlin effect[16] takes place in the corresponding $^1J(C_\alpha,H)$ coupling constant. For the *s-trans* rotamers of **1**, **2**, **3**, **5**, **6** and **7** the preferential conformation of the corresponding C_α—H bond would be such that this Perlin effect is no longer present. In $^1J(C_\beta,H)$ couplings the differences for the *s-cis* and *s-trans* rotamers are too small to attempt any rationalization.

Table 1. Comparison of ^1J(CH) coupling constants (Hz) for *s-cis* and *s-trans* rotamers in compounds **1–7**.[a]

	1	**2**	**3**	**4**	**5**	**6**	**7**
C=O (*cis*)	225.6	225.3	225.3	221.9	225.0	225.6	227.4
C=O (*trans*)	217.4	218.0	217.7	216.6	217.9	216.7	217.6
Δ	+8.2	+7.3	+7.6	+5.3	+7.1	+8.9	+9.8
C_α (*cis*)	147.2	147.7	146.9	—	146.8	146.4	147.8
C_α (*trans*)	140.2	140.0	139.9	—	139.6	139.8	141.8
Δ	+7.0	+7.7	+7.0	—	+7.2	+6.6	+6.0
C_β (*cis*)	—	126.9	125.4	126.8	127.2	127.8	—
C_β (*trans*)	—	125.1	127.6	124.9	120.5	128.6	—
Δ	—	+1.8	−2.2	+1.9	+6.7	−0.8	—
C_γ (*cis*)	—	—	125.9	—	126.4	125.6	—
C_γ (*trans*)	—	—	125.9	—	126.4	125.6	—
Δ	—	—	0.0	—	0.0	0.0	—
C_δ (*cis*)	—	—	—	—	124.9	—	—
C_δ (*trans*)	—	—	—	—	124.6	—	—
Δ	—	—	—	—	+0.3	—	—

[a] α, β, γ and δ refer to the position of the coupled carbon atom with respect to the two-coordinated oxygen atom.

In Table 2, the three-bond couplings between the carbonyl ^{13}C nucleus and the protons attached to the C_α atom, $J(C{=}O,H_\alpha)$, for **1**–**7** are displayed. In all *s-cis* rotamers, with the exception of **4** where there is no C_α—H bond, a coupling of *ca.* 3 Hz is observed, being slightly larger for **1**. These values are in fair agreement with those reported by Dorman *et al.*,[17] who only observed the *s-cis* conformer. It is interesting that in the *s-trans* rotamers of all these compounds this type of coupling could not be observed.

In Table 3, ^{13}C chemical shifts are compared for the *s-cis* and *s-trans* rotamers. For the *s-cis* rotamers of a few members of this series such chemical shifts were reported by Couperus *et al.*[18] The present results are in fair agreement with those values once the different referencing is taken into account. In all cases the carbonyl ^{13}C signal appears at a low frequency, which can be taken as an indication that in this type of compound there is a strong conjugative interaction between the carbonyl π electronic system and the π-type lone pair of the dicoordinated oxygen atom.[19] Although differences between the carbonyl ^{13}C chemical shifts of the *s-cis* and *s-trans* rotamers are small, in all cases it is slightly more deshielded for the *s-trans* rotamer. This suggests that the conjugative interaction quoted above is only very slightly reduced on going from the *s-cis* to the *s-trans* conformation. This observation is in agreement with a similar conclusion, based on theoretical grounds, reported several years ago by Bond and Schleyer[1] for **1**.

Table 2. ^3J(C=O,H) coupling constants for the *s-cis* and *s*-trans rotamers of compounds **1–7**

Compound	Rotamer	^2J(C=O,H) (Hz)
1	*s-cis*	3.9
	s-trans	—
2	*s-cis*	3.2
	s-trans	—
3	*s-cis*	3.0
	s-trans	—
4	*s-cis*	—
	s-trans	—
5	*s-cis*	3.1
	s-trans	—
6	*s-cis*	3.0
	s-trans	—
7	*s-cis*	3.4
	s-trans	—

Other ^{13}C chemical shifts differences between the *s-cis* and *s-trans* rotamers can be thought to originate mainly in proximity effects between the alkyl side-chain and the carbonyl moiety which operate only in the *s-cis* rotamers. For nuclei other than protons, such effects operate mainly through the paramagnetic part of the magnetic shielding constant and they can yield both deshielding and shielding effects[20] depending on the nature of that interaction. In the former case, proximity effects can be taken as an indication that this interaction is replusive, whereas in the latter case it can be taken as an indication that there is an attractive interaction between the two proximate moieties.[21,22] Based on these ideas, the following trends are observed and rationalized.

In all cases the C_α carbon atom is more shielding for the *s-trans* than for the *s-cis* rotamer, with the exception of **4** where C_α is the central atom of the *t*-Bu group. Such differences can be taken as an indication that for the *s-cis* conformation there is a repulsion between the C_α atom and the carbonyl moiety. As indicated above, the trends observed for $^1J(C_\alpha,H)$ couplings suggest that

Table 3. Comparison of ^{13}C chemical shifts (ppm) for *s-cis* and *s-trans* rotamers in compounds **1–7**[a]

	1	2	3	4	5	6	7
C=O (*cis*)	159.09	160.14	159.97	158.61	159.64	159.68	159.47
C=O (*trans*)	159.61	160.76	160.53	160.04	160.21	160.79	161.05
Δ	−0.52	−0.62	−0.56	−1.43	−0.57	−1.11	−1.58
C_α (*cis*)	48.50	58.43	63.82	78.91	61.94	68.12	63.59
C_α (*trans*)	47.68	56.17	62.44	79.05	60.38	67.43	62.60
Δ	+0.82	+2.26	+1.38	−0.14	+1.56	+0.69	+1.99
C_β (*cis*)	—	12.47	20.66	26.37	29.38	26.28	133.97
C_β (*trans*)	—	16.57	24.53	29.25	33.59	29.23	139.81
Δ	—	−4.10	−3.87	−2.88	−4.21	−2.95	−5.84
C_γ (*cis*)	—	—	8.54	—	11.87	17.16	—
C_γ (*trans*)	—	—	8.54	—	12.15	17.21	—
Δ	—	—	0.00	—	−0.28	−0.05	—
C_δ (cis)	—	—	—	—	17.71	—	—
C_δ (*trans*)	—	—	—	—	17.64	—	—
Δ	—	—	—	—	+0.07	—	—

[a] α, β, γ and δ refer to the position of the carbon atom with respect to the two-coordinated oxygen atom.

the preferential conformation of one of the C_α—H bonds is *cis* to the in-plane dicoordinated oxygen lone pair (with the exception of **4**) and therefore the other C_α—X (X=H, C) bonds should be *gauche* to the carbonyl oxygen atom. It is interesting that this $^{13}C_\alpha$ deshielding effect for the *s-cis* rotamer contrasts notably with the important shielding effect observed in amides[17,23,24] for a methyl C_α atom proximate to the carbonyl moiety.

For all compounds there are conspicuous C_β *s-cis*/*s-trans* deshielding effects on going from the *s-cis* to the *s-trans* rotamers. This suggests that such a trend originates in a $^{13}C_\beta$ shielding effect for the *s-cis* conformations. It is known[25] that in ethyl formate (**2**) one of the main contributions to the rotational equilibrium of the *s-cis* rotamer is a *gauche* conformer with a peculiar value of the C_c—O_e—C_α—C_β dihedral angle, i.e. 85°. Therefore, it can be expected that such C_β shielding effect present in the *s-cis* rotamer of **2** corresponds to an attractive interaction between the C_α—C_β moiety and the proximate carbonyl π electronic system. As such a shielding effect is present in the *s-cis* rotamer of all compounds **2** to **7**, it can be expected that similar *gauche* conformers are present in all of them. The differences in the C_γ and C_δ chemical shifts for the *s-cis* and *s-trans* rotamers in all cases are, as expected, very small and no rationalization of them is attempted.

As indicated above, the ^{17}O resonances corresponding to the *s-trans* rotamer could not be observed for any of these compounds. This suggests that in all cases the difference in chemical shifts for the *s-cis* and *s-trans* rotamers is small and the ^{17}O signals for the *s-trans* rotamers are masked by the broad tails of the signals corresponding to the more populated rotamer. As ^{17}O chemical shifts for both types of oxygen atoms are very sensitive to conjugation, such a result further supports Bond and Schleyer's conclusion[1] that the conjugative interaction between the carbonyl π electronic system and the π-type lone pair of the two-coordinated oxygen atom is only slightly different for the two types of rotamers. Such rationalization is in agreement with the carbonyl carbon chemical shift trend quoted above. Nonetheless, for the sake of completeness, in Table 4 the ^{17}O chemical shifts for the *c-cis* rotamers of **1–7** are displayed. While the carbonyl ^{17}O resonance appears at a low frequency, that of the two-coordinated oxygen atom appears at a high frequency. Such trends are typical of a strong conjugative interaction between the carbonyl π electronic system and the π-type lone pair of the two-coordinated oxygen atom.[26–28] The ^{17}O chemical shifts of the carbonyl oxygen atom, O_c, are within a small interval, with the exception of **4**, i.e. $\delta(^{17}O_c) = 364.7 \pm 0.7$ ppm. Similarly, the chemical shifts of the dicoordinated oxygen atom, O_e, with the exception of **1** and **4**, are in the interval $\delta(^{17}O_e) = 171.4 \pm 3.2$ ppm. In **1** the dicoordinated oxygen atom is notably more shielded. This effect is similar to that reported by Kalabin *et al.*,[29] who found a deshielding effect of 29

Table 4. ^{17}O chemical shifts for compounds **1–7**[a]

Compound	C=O	—O—
1	365.3	143.3
2	364.4	174.6
3	364.7	169.9
4	375.4	211.0
5	365.4	169.9
6	364.5	168.2
7	364.7	174.3

[a] Chemical shifts are in ppm downfield from external D_2O. In all compounds only one rotamer could be observed.

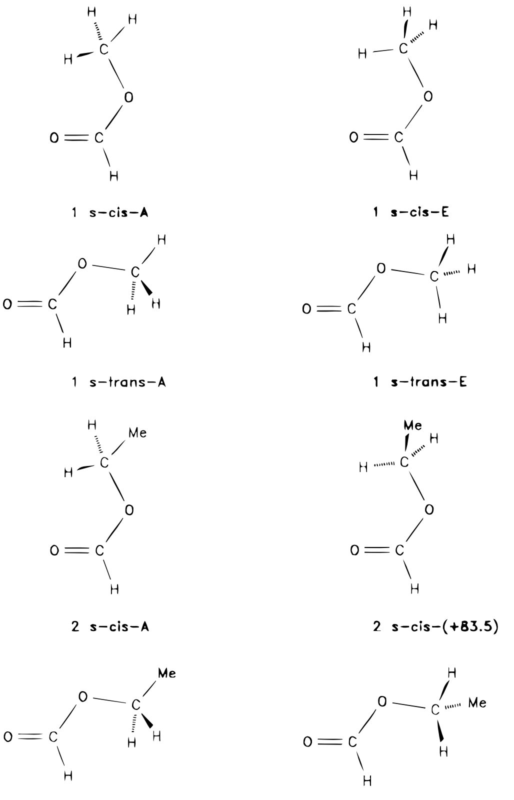
ppm on comparing the ^{17}O chemical shift in phenetole and that in anisole. Comparing the data in Table 4 for **1** and **2**, it is observed that the β-Me substitution, i.e. the replacement of the Me group (**1**) by the Et group (**2**), renders a deshielding effect of 31.3 ppm. These values are close to the β-Me substituent effect reported by Delseth and Kintzinger[30] in the aliphatic ethers $CH_3OCH_3 \rightarrow CH_3CH_2OCH_3$ (30 ppm) and $CH_3OCH_2CH_3 \rightarrow CH_3CH_2OCH_2CH_3$ (29 ppm). These results indicate that this β-Me substituent effect is insensitive to the conjugation of one of the lone pairs of the dicoordinated oxygen atom. The rationalization of this effect in aliphatic ethers and the similar one in aliphatic alcohols was reviewed by Chandrasekaran.[31] Apparently, in conjugated systems similar rationalizations hold.

In tert-butyl formate (**4**) the carbonyl ^{17}O nucleus is deshielded by *ca.* 10 ppm with respect to the average value shown above. Probably the three proximate methyl groups cause this deshielding effect[21,22,32–35] owing to a replusive interaction with the oxygen lone pairs. It can be expected that an interaction of this type will also yield an increase in the $C_\alpha—O_e—C_c$ angle, rendering a deshielding effect on O_e.

In **1**–**3** a distinct $J(^{17}O,^{1}H)$ coupling of *ca.* 40 Hz was observed, which was assigned to the geminal $^2J(O_e,C_c,H)$ couplings.[36] They constitute another interesting case of surprisingly large geminal couplings across a carbonyl moiety, $^2J(XY)$.[37]

MO calculations

In order to obtain an insight into the large C_β deshielding effect observed in Table 1 for all the *s-trans* conformers, the geometries of four conformers of compound **2** were optimized at the HF/6–31G* level. Two of them correspond to the *s-cis* and the other two to the *s-trans* conformation. The ethyl *s-cis*-A and *s-trans*-A conformations are with the $C_\alpha—C_\beta$ bond antiperiplanar to the $C_c—O_e$ bond and, in the *s-cis*-(+83.5) and *s-trans*-(+ 92.8) conformations the angles between the $C_\alpha—C_\beta$ and the $C_C—O_e$ bonds are 83.5 and 92.8°, respectively (Scheme 2). Energies were calculated at the MP2/6–31G*//HF/6–31G* level. Their relative values are given in Table 5. Values in parentheses for the two conformations correspond to the $C_\beta—C_\alpha—O_e—C_c$ dihedral angle (in degrees) measured from the A conformation. To the authors' knowledge, only the energy difference between the two *s-cis* rotamers has been measured.[25] In one of them a $C_\beta—C_\alpha—O_e—C_c$ dihedral angle of +85° was estimated, in agreement with the value of +83.5° obtained with the HF/6–31G* optimized geometry. The energy difference between the two rotamers was measured, using microwave spectroscopy, as 0.19 ± 0.6 kcal mol^{-1} and the barrier between them as 1.10 ± 0.25 kcal mol^{-1} (1 kcal = 4.184 kJ). It is interesting that the analogous dihedral angle in ethoxy benzene (phenetole) was recently calculated as +82.58° with a full optimization at the D95** level.[38] The values in Table 5 seem to indicate that for the *s-cis*-(+83.5)



Scheme 2

Table 5. Relative energies of four rotamers of 2 obtained at the MP2/6–31G*//HF/6–31G* level and LORG/6–31G*//HF/6–31G* magnetic shielding constants for the respective $^{13}C_\beta$ nuclei, together with their weighted average values for the *s-cis* and *s-trans* rotamers and comparison with the experimental difference[a]

Parameter	*s-cis*-A[b]	*s-cis*-(+ 83.5)[c]	*s-trans*-A[b]	*s-trans*-(+92.8)[c]
Energies	0.00	0.00	5.97	5.66
Shielding	204.15	214.04	202.04	205.73
Average shielding[d]	210.74		204.89	
s-cis–*s-trans* difference		5.85		
Experimental[e]		4.10		

[a] Energies in kcal mol^{-1} and magnetic shielding constants in ppm.

[b] A corresponds to the conformation with the $C_\alpha—C_\beta$ bond antiperiplanar to the $C_c—O_e$ bond.

[c] Values in parentheses are the $C_\beta—C_\alpha—O_e—C_c$ dihedral angle (in degrees).

[d] Average value weighted with the energies displayed in the first row.

[e] The different sign conventions for chemical shifts and shielding constants were properly taken into account.

conformer one of the two C_α—H bonds is close enough to a *cis* configuration with respect to the in-plane O_e lone pair to undergo an important Perlin effect. For the *s-trans* conformer, *s-trans*-(+92.8) is still the preferred conformation at the MP2/6–31G**//HF/6–31G* level. It seems that the increase in the corresponding C_β—C_α—O_e—C_c dihedral angle is sufficient to inhibit the Perlin effect in the *s-trans* rotamer.

With the HF/6–31G* optimized geometries for the four conformers of **2**, LORG[10] calculations were carried out for the $^{13}C_\beta$ magnetic shielding constants using the same basis set as that employed in the optimization processes. The values thus obtained are also given in Table 5. It is interesting that the LORG-calculated $^{13}C_\beta$ magnetic shielding constants depend strongly on the two *s-cis* conformations, that of the *s-cis*-(+83.5) rotamer being *ca.* 10 ppm more shielded than the *s-cis*-A rotamer. This change seems to originate in a proximity effect, as can be expected on physico-chemical grounds. The comparison with the experimental values should take into account that in this work only one *s-cis* and only one *s-trans* rotamer could be observed. Therefore, average LORG $^{13}C_\beta$ chemical shift calculations, weighted according to the MP2/6–31G*//HF/6–31G* energies, are also given in Table 5 and compared with the experimental values taken from Table 3. Fair agreement between them is observed. In this comparison it was taken into account that magnetic shielding constants and chemical shifts go in opposite directions. This good agreement suggests that the proximity effect present in the *s-cis*-(+83.5) rotamer is properly described using this modest basis set. This observation is in line with similar conclusions presented previously, using semi-empirical methods, for both magnetic shielding constants[34] and spin–spin coupling constants.[39]

CONCLUSION

The conspicuous difference observed (Table 1) for ^1J(C=O,H) and ^1J(C_α,H) between the *s-cis* and *s-trans* rotamers are similar for both types of couplings and in both cases they are rationalized as originating in the Perlin effect, which is present only in the *s-cis* rotamers. Such a similarity is surprising since both carbon atoms are differently hybridized, i.e. whereas the former is sp^2, the latter is sp^3. This different hybridization yields different values for the two types of couplings. Also, the respective C—O bond lengths are different. Another interesting feature of the Perlin effect observed in this work, is the absence of this effect in the *s-trans* rotamer of **2**, where the H_α—C_α—O_e—lone pair dihedral angle is only *ca.* 10° larger than the corresponding value in the *s-cis* rotamer. This suggests that the Perlin effect depends strongly on that dihedral angle.

The important shielding effect observed on the C_β carbon atom in **2**–**7** suggests that in all these cases a similar effect is operating. Apparently, this should be a proximity effect which can be used as a probe to detect an attractive interaction between C_β and the carbonyl π electronic system. According to calculations performed on **2**, this interaction renders as preferential a C_β—C_α—O_e—C_c dihedral angle of *ca.* 83°. It is important to recall that C_β in **7** is an sp^2 carbon atom.

Another point that is important to stress is that the results presented in this paper suggest that the LORG approach can describe adequately proximate interactions when using only a modest basis set.

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