Solvent Effects on Nuclear Magnetic Resonance $^2J(C,H_f)$ and $^1J(C,H_f)$ Spin–Spin Coupling Constants in Acetaldehyde

Daniel Zaccari,[1] Verónica Barone,[2] Juan E. Peralta,[2] Rubén H. Contreras*,[2] Oscar E. Taurian,[1] Ernesto Díez[3] and Angel Esteban[4]

[1] Departamento de Química y Física, FCEF-QyN Universidad Nacional de Río Cuarto, Ruta Nac. 36, Km 601, (5800) Río Cuarto, Argentina.

[2] Departamento de Física, FCEyN, Universidad de Buenos Aires and CONICET, Ciudad Universitaria, Pab. 1, (1428), Buenos Aires, Argentina.

[3] Departamento de Química Física Aplicada, Facultad de Ciencias C2. Universidad Autónoma de Madrid, E-28049, Madrid, Spain;

[4] Departamento de Química Física, Facultad de Ciencias, Universidad de Alicante, E-03080 Alicante, Spain.

* Corresponding author. Tel.: +54 11 4576 3353, Fax: +54 11 4576-3357, E-mail: contrera@df.uba.ar, URL: http://www.df.uba.ar/~juanp/

Abstract: The known solvent dependence of $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings in acetaldehyde is studied from a theoretical viewpoint based on the density functional theory approach where the dielectric solvent effect is taken into account with the polarizable continuum model. The four terms of scalar couplings, Fermi contact, paramagnetic spin orbital, diamagnetic spin orbital and spin dipolar, are calculated but the solvent effect analysis is restricted to the first term since for both couplings it is by far the dominant contribution. Experimental trends of $\Delta^1J(C_c,H_f)$ and $\Delta^2J(C_1,H_f)$ Vs ε (the solvent dielectric constant) are correctly reproduced although they are somewhat underestimated. Specific interactions between solute and solvent molecules are studied for dimethylsulfoxide, DMSO, solutions considering two different one-to-one molecular complexes between acetaldehyde and DMSO. They are determined by interactions of type C=O---H—C and S=O---H—C, and the effects of such interactions on $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings are analyzed. Even though only in a semiquantitative way, it is shown that the effect of such interactions on the solvent effects, of $\Delta^1J(C_c,H_f)$ and $\Delta^2J(C_1,H_f)$, tend to improve the agreement between calculated and experimental values. These results seem to indicate that a continuum dielectric model has not enough flexibility for describing quantitatively solvent

effects on spin-spin couplings. Apparently, even for relatively weak hydrogen bonding, the contribution from "direct" interactions is of the same order of magnitude as the "dielectric" effect.

Introduction

Two-bond coupling constants, $^2J(X,Y)$, across a carbonyl carbon atom, C_c, are known [1] to be positive (provided the magnetogyric ratios of both coupled nuclei are of the same sign) and their absolute values are uncommonly large. Such features were rationalized in previous work [2] as originating mainly in the strong charge transfer interactions between the carbonyl oxygen lone pair of purely p character, $n(p)$, and the C_c—X and C_c—Y antibonds, $n(p) \rightarrow (C_c—X,Y)^*$. This suggests that this type of couplings should be sensitive to interactions that either enhance or inhibit such charge transfers; the former increasing the corresponding two-bond coupling, while the latter decreasing it. As an example, it can be cited the observed trend for $^2J(C_1,H_f)$ in benzaldehyde and salicylaldehyde, 24.11 Hz and 20.13 Hz respectively [3]. Such a trend suggests that similar intramolecular couplings can be potentially interesting probes to complement the information provided by trans-hydrogen bond couplings to study intermolecular interactions. As the dielectric solvent effect could mask the effects of specific interactions, it seems interesting to verify how well they can be described using an efficient approach like DFT (Density Functional Theory) to study them. The known experimental values of the dependence of $^2J(C_1,H_f)$ and $^1J(C_c,H_f)$ couplings in acetaldehyde on the dielectric solvent [4] makes it an adequate model compound to study what can be expected for larger molecular systems like proteins and nucleic acid bases.

Until few years ago theoretical studies of dielectric solvent effects on spin-spin couplings were based on the semiempirical INDO (Intermediate Neglect of Differential Overlap) approach [5], where different models were used to describe the solvent dielectric properties [6-9]. Recently, in concordance with the important breakthrough in theoretical approaches to calculate spin-spin coupling constants [10-12] that took place during the last decade, non-empirical Multi-Configurational Self Consistent field, MCSCF, calculations of solvent effects on spin-spin couplings were reported like, for instance, in SeH_2 [13], SH_2 [14] and the $H_2O\cdots H_2O$ dimer [15].

Present methodological approaches for calculating coupling constants based on the DFT framework [16-24] can be used to perform systematic studies in medium-sized compounds [25] using modest computational facilities. Besides, they can be used in conjunction with the solvent representation given by the Polarizable Continuum Model, PCM [26-27], to obtain a powerful tool to evaluate NMR couplings in compounds where solvation effects cannot be neglected [28]. Although in this work all four terms of coupling constants, Fermi contact, FC, Spin-Dipolar, SD, Paramagnetic Spin Orbit, PSO,

Benzaldehyde

Salicylaldehyde

Acetaldehyde
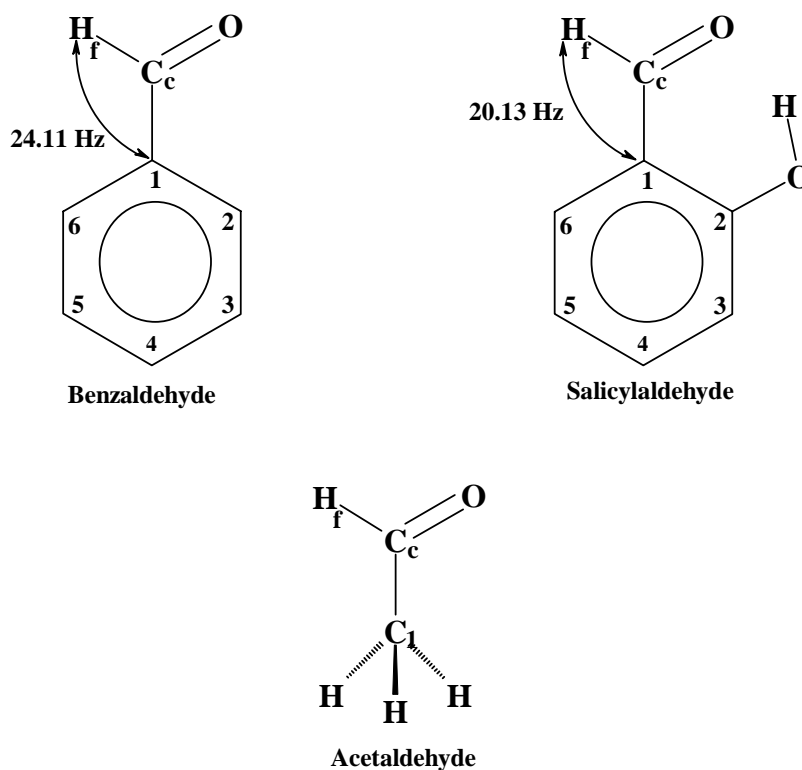
and Diamagnetic Spin Orbit, DSO, are calculated within the DFT framework, the dielectric solvent effect analysis is mainly circumscribed to the FC term because in the two couplings considered in this work, it is by far the largest contribution and, therefore even if non-contact terms, SD, PSO and DSO, are solvent-dependent, their contributions to the total solvent effect should be negligible when compared with that of the FC term. Specific interactions are studied considering DMSO as solvent in one-to-one molecular associations between solute and solvent. The FC term of the above mentioned coupling constants is calculated at the equilibrium geometry of such two-molecule complexes.

Method of Calculation

Molecular geometries were optimized at the DFT/B3LYP [29-31] level with the 6-311G** basis set using the Gaussian 98 suite of programs [32]. The four terms of isotropic spin-spin coupling constants, FC, SD, PSO and DSO, were calculated using a slightly modified version of the Gaussian 98 package of programs [32] according to the following details. The FC and SD terms are calculated using the Finite Perturbation scheme, FPT [33], as described previously [25,34,35], while the PSO term was calculated at the Coupled Perturbed DFT, CP-DFT, approach. The DSO contribution was evaluated as the mean value of the DSO operator in the electronic ground state. One electron integrals required for evaluating the PSO and DSO contributions were calculated in the atomic basis using the DALTON 1.1 package of programs [36]. All four terms of coupling constants were calculated using the 6-311G** basis set. When calculating the FC term tight s functions, taken from Ref. [37], were added at the site of the coupled nuclei.

To estimate the effect of solvent dielectric on couplings unrestricted FPT calculations of the FC and SD terms can be carried out in the context of several of the solvent models available in the Gaussian 98 package of programs [32]. In this work the Tomasi et al. [26-27] PCM model is chosen since it was used previously [28] to study how the anomeric effect on ^{1}J(C,H) coupling depends on solvent dielectric and results thus found look promising. The FC term of both ^{1}J(C$_c$,H$_f$) and ^{2}J(C$_1$,H$_f$) couplings in acetaldehyde are analyzed first by considering it in the isolated molecule, and then by treating it in the presence of the solvent reaction field for different values of the dielectric constant. For a given dielectric constant two different effects were considered, namely, the solvent effect on couplings considering the vacuum optimized geometry, and the solvent effect on couplings considering also how the dielectric solvent affects the geometry. The latter was estimated performing two different geometry optimizations, i.e. considering $\varepsilon = 1$ (isolated molecule) and $\varepsilon = 46.7$ (DMSO solution).

In order to get insight into how the dielectric solvent effect is operating, both calculated FC terms were partitioned into bond contributions using the Natural J Coupling, NJC, scheme, which was described previously [38,39]. Bond, lone-pair and core orbitals are obtained through the Natural Localized Molecular Orbitals, NLMO, localization procedure [40] as implemented [41] in the Gaussian package [32]. Charge transfer interactions were estimated using the NBO method [40,41]. The effect of the n(p)→(C$_c$—H$_f$)* charge transfer interaction on ^{1}J(C$_c$,H$_f$) and ^{2}J(C$_1$,H$_f$) couplings were estimated according to the Neglect of Charge Transfer Interaction, NCTI, [39] procedure, i. e. two calculations of the same FC term were carried out, the standard one and another where such a charge transfer interaction was deleted [41].

Results and Discussion

In Table 1 values for the FC, SD, PSO and DSO terms of ^{1}J(C$_c$,H$_f$) and ^{2}J(C$_1$,H$_f$) coupling constants calculated with $\varepsilon = 1$ in acetaldehyde (using the optimized geometry taking $\varepsilon = 1$) are compared with the respective experimental values measured in gas phase [4]. In the same Table 1 values for the FC, SD and DSO terms for such coupling constants calculated considering the dielectric solvent effect for $\varepsilon = 46.7$ (DMSO) (using the optimized geometry taking $\varepsilon = 46.7$) are displayed. The modifications introduced in the Gaussian 98 program to calculate the PSO term are not adequate to calculate such a term taking into account the dielectric solvent effect. For this reason total couplings including the solvent effect were calculated considering the FC, SD and DSO terms obtained for $\varepsilon = 46.7$, while the PSO is that calculated taking $\varepsilon = 1$.

Although the solvent effect on the SD term in ^{1}J(C$_c$,H$_f$) is in percentage non-negligible, the SD term as well as the PSO and DSO terms are much smaller than the FC contribution. For this reason the following considerations refer only to the solvent effect on the FC term. In both ^{1}J(C$_c$,H$_f$) and ^{2}J(C$_1$,H$_f$) couplings the calculated solvent effects follow the experimental trend although the respective ΔJ(C,H$_f$)

Table 1. Comparison between the sum of the four calculated terms, FC, SD, PSO, and DSO, and experimental values for $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ coupling constants in acetaldehyde. Dielectric solvent effects on the FC, SD and DSO terms are also shown comparing results obtained taking $\varepsilon = 1$ (isolated molecule) and $\varepsilon = 46.7$ (DMSO).[a]

	FC	SD	PSO	DSO	Total	Exp.[b]
$^1J(C_c,H_f)$ ($\varepsilon = 1$)	177.53	0.29	-0.94	0.90	177.78	169.68
$^1J(C_c,H_f)$ ($\varepsilon = 46.7$)	179.91	0.36	nc[c]	0.89	180.22[d]	173.34
$^2J(C_1,H_f)$ ($\varepsilon = 1$)	32.47	0.04	-0.02	-0.33	32.16	29.54
$^2J(C_1,H_f)$ ($\varepsilon = 46.7$)	30.45	0.04	nc[c]	-0.34	29.95[d]	26.25

a) H_f stands for the formyl proton. Calculations for $\varepsilon = 1$ and $\varepsilon = 46.7$ were carried out using the corresponding optimized geometry using the respective dielectric constant in the optimization procedure. All couplings are in Hz.

b) Taken from Ref. [4].

c) PSO terms including solvent effects were not calculated, nc.

d) Total value obtained taking the respective PSO term calculated with $\varepsilon = 1$.

values are somewhat smaller than their experimental counterpart $[\Delta J(C,H_f) = J(C,H_f)(\varepsilon) - J(C,H_f)(\varepsilon=1);$ $C=C_1$ and $C_c]$. In Fig. 1 $\Delta^1J(C_c,H_f)$ is plotted Vs ε for the experimental values, taken from Ref. [4], and for those couplings calculated using two different geometries, i. e. that optimized for acetaldehyde taken as an isolated molecule, $\varepsilon = 1$, and that optimized taking it in presence of a solvent with dielectric constant ε. These calculations were carried out in order to appreciate how important geometry solvent effects are in comparison with the direct solvent effect on the FC term. In general the experimental and theoretical trends are in good qualitative agreement, although theoretical values somewhat underestimate the experimental solvent dielectric effects. It is worth noting that the inclusion of the geometry solvent effect for $\Delta^1J(C_c,H_f)$ worsens slightly the agreement with experimental values.

Similar plots for $\Delta^2J(C_1,H_f)$ are shown in Fig. 2, where it is observed that, in this case, the inclusion of geometric solvent effects improves somewhat the agreement with experimental values. However, as observed in results displayed in Fig. 1, solvent effects for $\Delta^2J(C_1,H_f)$ are also somewhat underestimated. These differences between theoretical and experimental values seem to originate in a poor representation of the dielectric solvent effect given by the PCM model to describe solvent effects on spin-spin coupling constants. At this point it is important to recall that this type of NMR parameters present a strong local character and therefore a continuum model like PCM could not be flexible enough to take into account very local differences which could be important for coupling constants. These small differences could originate in weak specific solute-solvent interactions. In this work the effects of such specific interactions are qualitatively estimated considering the structures of two one-to-one complexes between acetaldehyde and DMSO, **1** and **2**. Taking into account the Basis Set
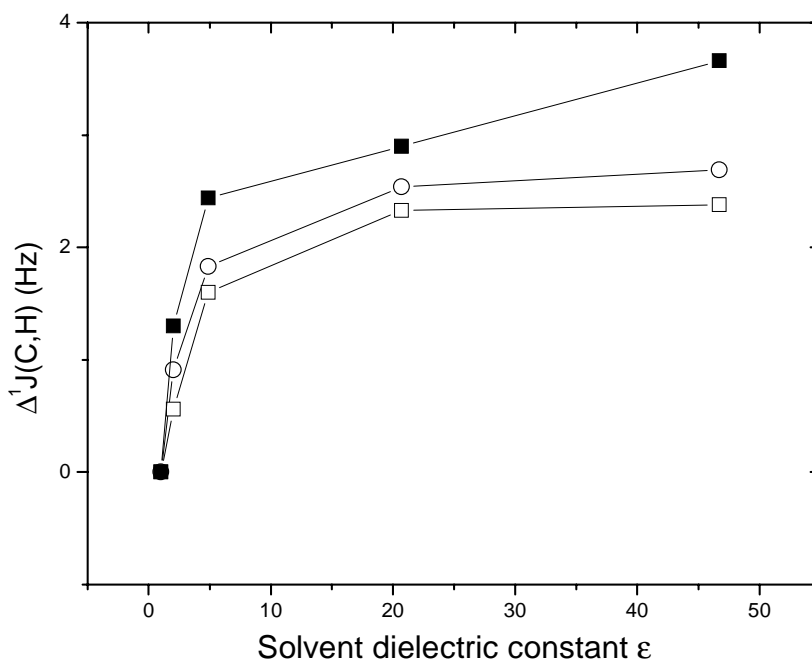
Figure 1. Comparison between experimental, (-■-), and theoretical solvent effects on $^1J(C_c,H_f)$, $\Delta^1J(C_c,H_f) = {}^1J^{(\varepsilon=1)}(C_c,H_f) - {}^1J^{\varepsilon}(C_c,H_f)$. Calculated values include only the FC term and, for each solvent, two different geometries were used to carry out the FC calculation, namely, that optimized considering $\varepsilon = 1$, (-o-), and that optimized considering ε (-□-).

Superposition Error, BSSE, through the counterpoise [42] approach, the association energies are, respectively, 5.7 and 5.0 kcal/mol. In both cases molecular associations take place through contacts of types C=O---H—C and S=O---H—C; in **1** there are three of them while in **2** there are two. Such contacts are at present very well known [43] and they are classified as "weak hydrogen bonds" [44]. Their main attractive interaction corresponds to an electrostatic effect [45] although in some cases there could also be some charge transfer interaction of type $n(O)\rightarrow(C—H)^*$ [2]. For $C(sp^3)$—H and $C(sp^2)$—H bonds the electrostatic part of this proximate effect causes an increase in its corresponding $^1J(C,H)$ coupling [46-47] while the charge transfer contribution causes a decrease in such a coupling [2].

Structures for **1** and **2** were optimized considering $\varepsilon = 1$, **1a** and **2a**, and $\varepsilon = 46.7$, **1b** and **2b**; in both cases the C—H---O distances were shorter for the latter optimization, i.e. such associations are stronger in a polar solvent. Such a trend is in line with the known decrease of electron transfer interactions involving the non-bonding electron pairs owing to the dielectric solvent effect [28]. Using such structures for complexes **1** and **2** the FC terms of $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ were calculated and results thus found are shown in Table 2. As it is expected, in **1** the S=O---H$_f$—C$_c$ interaction causes an important increase in $^1J(C_c,H_f)$, which is smaller in about 4 Hz for **1b** than for **1a**. The corresponding effect on $^2J(C_1,H_f)$ depends also on solvent, but it is not very significant. Complex **2** causes a decrease in both $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings which are also smaller when the FC term is calculated in **2b** than in **2a**.
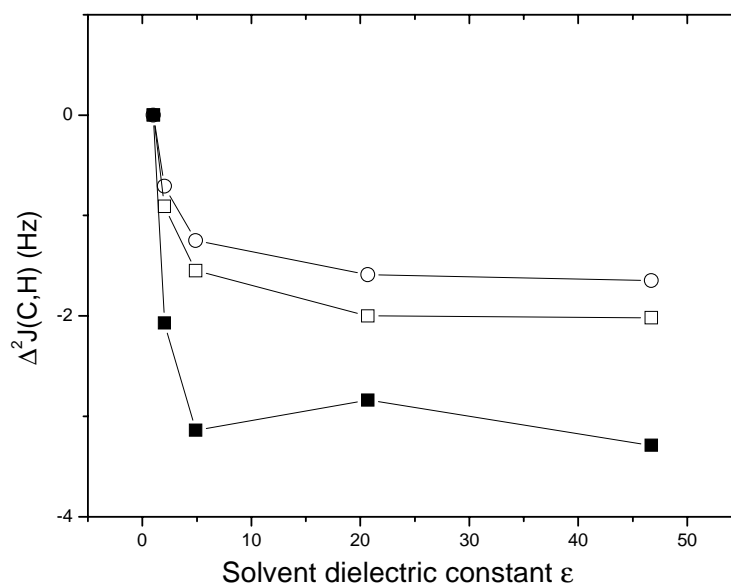
Figure 2. Comparison between experimental, (-■-), and theoretical solvent effects on $^2J(C_1,H_f)$, $\Delta^2J(C_1,H_f) = {}^2J^{(\varepsilon=1)}(C_1,H_f) - {}^2J^{\varepsilon}(C_1,H_f)$. Calculated values only include the FC term and, for each solvent, two different geometries were used to carry out the FC calculation, namely, that optimized considering $\varepsilon =1$, (-o-), and that optimized considering ε (-□-).

1a   **1b**

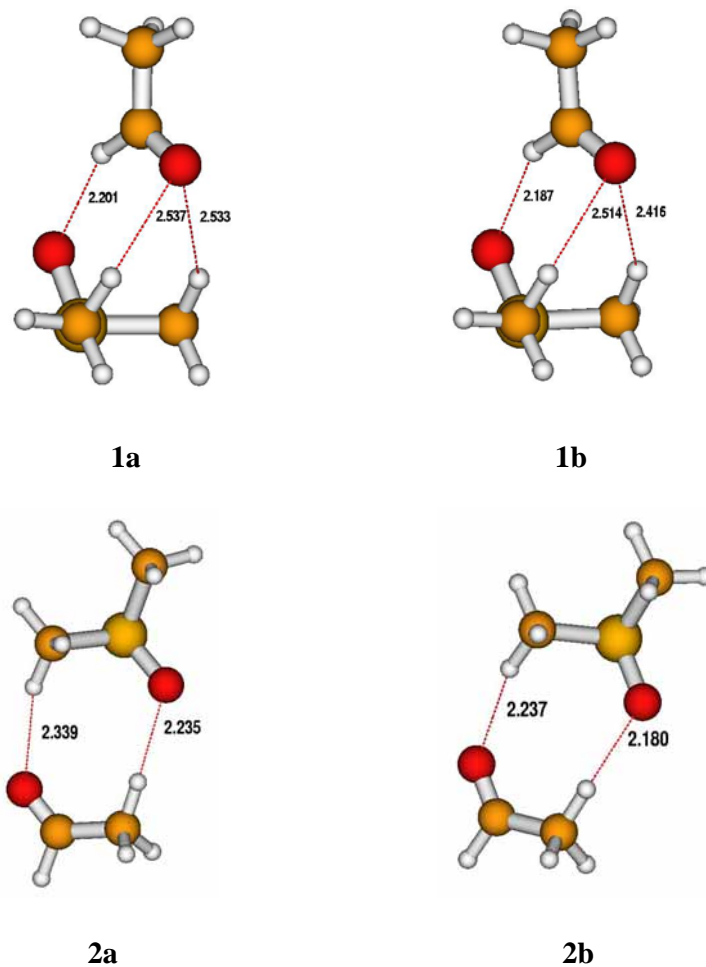**2a**   **2b**

Table 2. Effect of specific interactions between DMSO and acetaldehyde on $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings (in Hz) as calculated in complexes **1a**, **1b**, and **2a** and **2b**, $\Delta(\mathbf{1})$ and $\Delta(\mathbf{2})$, respectively (only the FC term is taken into account). It is also shown how dielectric solvent effects affect these effects.[a]

	$^1J(C_c,H_f)$		$^2J(C_1,H_f)$	
	$\varepsilon = 1$[b]	$\varepsilon = 46.7$[c]	$\varepsilon = 1$[b]	$\varepsilon = 46.7$[c]
Exp.	169.68	173.34	29.54	26.25
Acet.	177.53	179.91	32.47	30.45
1	194.09	192.79	32.25	31.15
$\Delta(\mathbf{1})$	16.56	12.88	-0.22	0.70
2	173.36	175.99	27.37	26.31
$\Delta(\mathbf{2})$	-4.17	-3.72	-5.20	-4.14

[a] The BSSE on the calculated couplings in **1** and **2** were estimated using the counterpoise approach [26]. In all cases it was found smaller than 5 % of the complex formation effect.

[b] Coupling constants calculated using optimized geometries with $\varepsilon = 1$.

[c] Coupling constants calculated using optimized geometries with $\varepsilon = 46.7$.

Without attempting a quantitative analysis of the dynamic process that takes place in liquid phase, the following semiquantitative estimates can be made. The complex formation energy is not significantly different for **1** and **2** and therefore it can be assumed that these two molecular associations have similar life times. Complex **1** tends to increase the solvent effect on $^1J(C_c,H_f)$, but it affects only slightly the solvent effect on $^2J(C_1,H_f)$. On the other hand, complex **2** tends to decrease the solvent effect on both of them. However, for $^1J(C_c,H_f)$ the absolute value of $\Delta(\mathbf{1})$ is larger than that of $\Delta(\mathbf{2})$, and therefore it can be expected that these specific interactions yield a net increase in the solvent effect in acetaldehyde, improving the agreement with experimental values displayed in Figure 1. Similarly, for $^2J(C_1,H_f)$ these two specific interactions yield a decrease in the solvent effect, improving also the agreement between calculated and experimental values displayed in Figure 2.

The effects of the $n(p)\rightarrow(C_c\!\!-\!\!H_f)^*$ charge transfer interaction on the NLMO bond contributions to $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings as given by the NCTI approach [38] are displayed in Table 3. It is observed that, when deleting such an interaction, $^1J(C_c,H_f)$ is increased in ca. 4 Hz and it only depends on solvent slightly, although the effect on the different NLMO contributions does depend on solvent. For $\varepsilon = 46.7$ the $C_c\!\!-\!\!H_f$ bond contribution is the largest. On the other hand, such a deletion causes a decrease on the $^2J(C_1,H_f)$ coupling whose amount depends on the solvent dielectric constant.

The effects of the $n(p)\rightarrow(C_c\!\!-\!\!C_1)^*$ charge transfer interaction on the NLMO bond contributions to $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings as given by the NCTI approach are displayed in Table 4. The deletion of such an interaction causes an important decrease in the total $^1J(C_c,H_f)$ coupling which is notably reduced when this calculation is carried out considering $\varepsilon = 46.7$. On the other hand, such a deletion causes a decrease in $^2J(C_1,H_f)$, which becomes more important for a polar solvent. It is interesting to point out that all these NCTI results are in agreement with the qualitative description of electronic charge transfer interactions on one- and two-bond coupling constants given previously [2].

Table 3. Effect of deleting the $n(p) \rightarrow (C_c\text{—}H_f)^*$ interaction on NLMO bond contributions, J(NLMO), to $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings in acetaldehyde, $\Delta[NLMO] = J(NLMO)_{NCTI} - J(NLMO)$ (in Hz).

NLMO	$\Delta[NLMO]$ for $^1J(C_c,H_f)$		$\Delta[NLMO]$ for $^2J(C_1,H_f)$	
	$\varepsilon = 1$	$\varepsilon = 46.7$	$\varepsilon = 1$	$\varepsilon = 46.7$
C_c-C_1	0.9	0.3	-0.2	-0.2
C_c-O	0.1	0.4	0.0	0.0
Core(C)[a]	1.3	-0.2	-0.5	-0.3
C_c-H_f	0.8	2.6	-1.5	-1.2
C_{Me}—H[b]	-0.1	0.0	0.0	0.3
n(sp)	-0.5	-0.2	0.0	0.0
n(p)	1.5	0.7	0.6	-1.6
TOTAL	4.0	3.6	-1.6	-3.0

[a] C stands for C_c in $^1J(C_c,H_f)$ and for C_1 in $^2J(C_1,H_f)$.

[b] It corresponds to the sum of the three C_{Me}—H bond contributions.

Table 4. Effect of deleting the $n(p) \rightarrow (C_c\text{—}C_1)^*$ interaction on NLMO bond contributions, J(NLMO), to $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings in acetaldehyde, $\Delta[NLMO] = J(NLMO)_{NCTI} - J(NLMO)$ (in Hz).

NLMO	$\Delta[NLMO]$ for $^1J(C_c,H_f)$		$\Delta[NLMO]$ for $^2J(C_1,H_f)$	
	$\varepsilon = 1$	$\varepsilon = 46.7$	$\varepsilon = 1$	$\varepsilon = 46.7$
C_c-C_1	1.0	0.4	-0.3	-0.4
Core(C)[a]	-1.9	-1.0	-0.8	-0.4
C_c-O	-0.2	0.4	0.0	0.0
C_{Me}—H[b]	0.0	0.1	0.1	0.3
C_c-H_f	-5.8	-3.0	-1.6	-1.2
n(sp)	0.3	0.4	0.0	0.0
n(p)	-1.8	0.0	0.1	-1.6
TOTAL	-8.4	-2.7	-2.5	-3.3

[a] C stands for C_c in $^1J(C_c,H_f)$ and for C_1 in $^2J(C_1,H_f)$.

[b] It corresponds to the sum of the three C_{Me}—H bond contributions.

Concluding Remarks

Results presented above suggest that spin-spin couplings strongly affected by negative hyperconjugations (also known as anomeric effects) are adequate probes to study both inter- and intra-molecular interactions that either inhibit or enhance such charge transfer interactions. The ability of such couplings for acting as sensitive probes to study molecular interactions should also strongly depend on how much the chosen couplings depend on negative hyperconjugations. A case in point it that of the $^2J(^{15}N,H_f)$ coupling in formamide, whose value was recently measured both in gas phase

and in a 1 mol % solution of DMSO [48]. The respective reported values are (-) 20.14 Hz (-) 15.30 Hz (signs assumed). The difference between these two values (which could be dubbed the "DMSO solvent effect" on that coupling) amounts to 4.84 Hz. The respective difference for $^2J(C_1,H_f)$ in acetaldehyde amounts to 3.29 Hz (Table 1). However, a sound comparison between the relative sensitivities of these two coupling constants to intermolecular interactions should take into account the notable difference between the ^{15}N and ^{13}C magnetogyric ratios. Thus, for the $^2J(^{15}N,H_f)$ coupling the significant quantity should be $4.84|\gamma(^{13}C)/\gamma(^{15}N)|$ Hz = 12.00 Hz, and it must be compared with 3.29 Hz for $^2J(C_1,H_f)$ in acetaldehyde.

The notably larger sensitivity of $^2J(^{15}N,H_f)$ in formamide than $^2J(C_1,H_f)$ in acetaldehyde to interactions affecting the strong negative hyperconjugative interactions within the carbonyl group can be easily rationalized on the following grounds. In formamide the $(C_c—N)*$ antibond is notably better electron acceptor than the $(C_c—C_1)*$ antibond in acetaldehyde since, on the one hand, the electronegativity for the N atom is larger than for the C atom. On the other hand, the partial double bond character of the $C_c—N$ bond in formamide causes the corresponding $\sigma(C_c—N)*$ to have a better electron acceptor character. All in all, these comparisons suggest that a *geminal* coupling through a carbonyl carbon atom involving a nitrogen nucleus could be an interesting probe to gauge intermolecular interactions involving the non-bonding electron pairs of the carbonyl oxygen atom.

It is also worth noting that the present results suggest that the B3LYP/DFT approach used in conjunction with the PCM model to describe the dielectric solvent effect on couplings between nuclei belonging to a carbonyl moiety yields results that are qualitatively in line with the experimental trends although they are underestimated. This could indicate that a solvent continuous model is not flexible enough to take into account fine details that could be of relevance for coupling constants owing to their local character. However, it should be recalled that in the present work no attempt was made to calculate the effects of nuclear motions on $^1J(C_c,H_f)$ and $^2J(C_1,H_f)$ couplings in acetaldehyde. A rough estimation of such effects in gas phase can be obtained from the detailed calculations reported recently by Wigglesworth et al. [49] for acetylene, $\Delta^1J(C,H)$ = 4.866 Hz and $\Delta^2J(C,H)$ = - 3.703 Hz, since the respective $^1J(C,H)$ and $^2J(C,H)$ couplings resemble somewhat those in acetaldehyde. In the latter compound similar nuclear motion corrections would worsen for the former and would improve for the latter the agreement between gas phase calculated and experimental values. These are the same trends as Wigglesworth et al. [32] observed for high level ab initio calculations of such couplings in acetylene. If nuclear motion corrections would increase with the solvent dielectric constant, then the agreement between calculated and experimental trends depicted in Figures 1 and 2 would improve, displaying a better performance for the PCM model when applied to coupling constants.

References

1. Hansen, P. E. In *The Chemistry of Double-bonded Functional Groups*, Patai, S., Ed.; Wiley, New York, 1989, Ch. 3.
2. Contreras, R. H.; Peralta, J. E. Angular Dependence of Spin-spin Coupling Constants. *Prog NMR Spectrosc.* **2000**, *37*, 321-425.
3. Hansen, P. E. Carbon-hydrogen spin-spin coupling constants. *Prog. NMR Spectrosc.* **1981**, *14*, 175-295.
4. Ando, I.; Inoue, Y.; Watanabe, S.; Sakamoto, Y.; Webb, G. A. The Effects of Solvent Dielectrics on Some NMR Spin-spin Couplings. A Study of Acetaldehyde in the Gaseous Phase and in Various Solvents. *J. Mol Liquids* **1984**, *27*, 179-200.
5. Ando, I. In *Encyclopedia of Nuclear Magnetic Resonance*, Grant D. M.; Harris, R. K. Eds. Wiley, Chichester, 1996, p. 2512.
6. Ando, I.; Webb, G. A. Some Quantm Chemical Aspects of Solvent Effects on NMR Parameters. *Org. Magn. Reson.* **1981**, *15*, 111-130.
7. Ando, I.; Webb, G. A. *Theory of NMR Parameters*: Academic, New York, 1983.
8. Ruiz-López, M., Rinaldi, D.; Rivail, J-L. Electrostatic Solvent Effect on Spin-spin Nuclear Coupling Constants. *J. Chem. Res. (M)* **1982**, 3369-3391.
9. Facelli, J. C.; Giribet, C. G.; Contreras, R. H. A theoretical studies of medium effects on the transmission mechanisms of the Fermi contact term of spin-spin coupling constants in the acetamide molecule. *Int. J. Quantum Chem.* **1984**, *25*, 515-525.
10. Helgaker, T.; Jaszunski, M.; Ruud, K.; Ab initio Methods for the Calculation of NMR Shielding and Indirect Spin-spin Coupling Constants. *Chem. Rev.* **1999**, *99*, 293-352.
11. Fukui, H. Theory and calculation of nuclear spin-spin coupling constants. *Prog. NMR. Spectrosc.* **1999**, *35*, 267-294.
12. Contreras, R. H.; Peralta, J. E.; Giribet, C. G.; Ruiz de Azúa, M. C.; Facelli, J. C. Advances in Theoretical and Physical Aspects of Spin-spin Coupling Constants. *Ann. Rep. NMR Spectrosc.* **2000**, *41*, 55-184.
13. Åstrand, P-O.; Mikkelsen, K. V.; Jørgensen, P.; Ruud, K.; Helgaker, T. Solvent Effects on Nuclear Shieldings and Spin-spin Couplings of Hydrogen Selenide. *J. Chem. Phys.* **1998**, *108*, 2528-2537.
14. Mikkelsen, K. V.; Ruud, K.; Helgaker, T. Solvent Effects on the NMR Parameters of H_2S and HCN. *J. Comput. Chem.* **1999**, *20*, 1281-1291.
15. Pecul, M..; Sadlej, J. The nuclear spin-spin coupling constants in the water dimer. *Chem. Phys. Lett.* **1999**, *308*, 486-494.

16. Malkin, V. G.; Malkina, O. L.; Salahub, D. R. Calculation of spin-spin coupling constants using density functional theory. *Chem. Phys. Lett*. **1994**, *221*, 91-99.

17. Grayce, C. J.; Harris, R. A. A density functional theory of the Fermi contact contribution to the nuclear spin-spin coupling constant. *Chem. Phys. Lett*. **1995**, *234*, 319-322.

18. Stahl, M.; Schopfer, U.; Frenking, G.; Hoffmann, R. W. Conformational Analysis with Carbon-Carbon Coupling Constants. A Density Functional and Molecular Mechanics Study. *J. Org. Chem.* **1997**, *62*, 3702-3704.

19. Dickson, R. M.; Ziegler, T. NMR Spin-Spin Coupling Constants from Density Functional Theory with Slater-Type Basis Functions. *J. Phys. Chem*. **1996**, *100*, 5286-5290.

20. Cloran, F.; Carmichael, I.; Seriani, A. S. ^{13}C-^1H and ^{13}C-^{13}C Spin Coupling Behavior in Aldofuranosyl Rings from Density Functional Theory. *J. Phys. Chem. A* **1999**, *103*, 3783-3795.

21. Bouř, P.; Buděšínský, M.. Sum-over-states Calculation of the Nuclear Spin–spin Coupling Constants. *J. Chem. Phys*. **1999**, *110*, 2836-2843.

22. Dingley, A. J.; Masse, J. E.; Peterson, R. D.; Barfield, M.; Feigon, J.; Grzesiek, S. Internucleotide Scalar Couplings Across Hydrogen Bonds in Warson-Crick and Hoogsten Base pairs of a DNA Triplex. *J. Am. Chem. Soc*. **1999**, *121*, 6019-6027.

23. Helgaker, T.; Watson, M.; Handy, N. C. Analytical Calculation of Nuclear Magnetic Resonance Indirect Spin–spin Coupling Constants at the Generalized Gradient Approximation and Hybrid Levels of Density-Functional Theory. *J. Chem. Phys*. **2000**, *113*, 9402-9409.

24. Sychrovský; V.; Gräfenstein, J.; Cremer, D.; Nuclear Magnetic Resonance Spin–spin Coupling Constants from Coupled Perturbed Density Functional Theory. *J. Chem. Phys.* **2000**, *113*, 3530-3547.

25. Cuevas, G.; Juaristi, E.; Vela, A. Density Functional Calculation of $^1J_{C-H}$ Coupling Constants in Cyclohehane and Diheterocyclohehanes. Repercussion of Stereoelectronic Effects on Couping Constants. *J. Phys. Chem. A* **1999**, *103*, 932-937.

26. Mertius, S.; Scrocco, E.; Tomasi, J. Electrostatic Interaction of a Solute with a Continuum. A Direct Utilization of ab initio Molecular Potentials for the Prevision of Solvent Effects. *Chem. Phys.* **1981**, *55*, 117-129.

27. Mertius, S.; Tomasi, J. Approximate Evaluations of the Electrostatic Free Energy and Internal Energy Changes in Solution Processes. *Chem. Phys.* **1982**, *65*, 239-245.

28. Zaccari, D. G.; Snyder, J. P.; Peralta, J. E.; Taurian, O. E.; Contreras, R. H.; Barone, V. Natural J Coupling (NJC) Analysis of the Electron Lone Pair Effect on NMR Couplings. 2: The Anomeric Effect on $^1J(C,H)$ Couplings and its Dependence on Solvent. *Mol. Phys.* **2002**, *100*, 705-715.

29. Becke, A. D. Density-Functional Exchange-Energy Approximation with Correct Asymptotic Behavior. *Phys. Rev. A* **1988**, *38*, 3098-3100.

30. Lee; C.; Yang W.; Parr, R. G. Development of the Colle-Salvetti Correlation-Energy Formula Into a Functional of the Electron Density. *Phys. Rev. B* **1988**, *37*, 785-789.

31. Becke, A. D. Density-Functional Thermochemistry. III. The Role of Exact Exchange. *J. Chem. Phys.* **1993**, *98*, 5648-5652.

32. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.;

Zakrzewski, V. G.; Montgomery, Jr., J. A.; 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.; 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., Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M; Replogle, E.S.; Pople, J. A.; *Gaussian 98*, Revision A.7, Gaussian Inc., Pittsburgh PA, 1998.

33. Pople, J. A.; Beveridge, D. L. *Approximate Molecular Orbital Theory*; McGraw-Hill: New York, 1970.

34. Peralta, J. E.; Ruiz de Azúa, M. C.; Contreras, R. H. On the Convergence of FPT-DFT Calculations of the Fermi Contact Contribution to NMR Coupling Constants. *Theoret. Chem. Acc*. **2000**, *105*, 156-164.

35. Peralta, J. E.; Barone, V.; Ruiz de Azúa; M. C.; Contreras, R. H. Finite Perturbation Theory-Density Functional Theory (FPT-DFT) Calculation of the Spin Dipolar Contribution to NMR Spin-spin Coupling Constant. *Mol. Phys.* **2001**, *99*, 655-661.

36. Helgaker, T.; Jensen, P. Jørgensen, H. J. A., Olsen, J.; Ruud, K.; Ågren, H.; Andersen, T.; Bak, K. L.; Bakken, V.; Christiansen, O.; Dahle, P.; Dalskov, E. K.; Enevoldsen, T.; Fernandez, B.; Heiberg, H.; Hettema, H.; Jonsson, D.; Kirpekar, S.; Kobayashi, R.; Koch, H.; Mikkelsen, K. V.; Norman, P.; Packer, M. J.; Saue, T.; Taylor, P. R.; Vahtras, O. *Dalton: An Electronic Structure Program*, Release 1.0, 1997.

37. Guilleme, J.; San Fabián, J. Basis Sets and Active Space in Multiconfigurational Self-Consistent Field Calculations of Nuclear Magnetic Resonance Spin–spin Coupling Constants. *J. Chem. Phys*. **1998**, *109*, 8168-8181.

38. Peralta, J. E.; Contreras, R. H.; Snyder, and J. P. Natural Bond Orbital Disecction of Fluorine-Fluorine Through-space NMR Coupling ($J_{F,F}$) in Polycyclic Organic Molecules. *J. Chem. Soc. Chem. Commun.* **2000**, *20*, 2025-2026.

39. Barone, V.; Peralta, J. E.; Contreras, R. H.; Sosnin, A. V.; Krivdin, L. B. Natural J Coupling (NJC) Analysis of the Electron Lone Pair Effect on NMR Couplings: Part 1. The Lone Pair Orientation Effect of an -Nitrogen Atom on ^{1}J(C,C) Couplings. *Magn. Reson. Chem.* **2001**, *39*, 600-606.

40. Reed, A. E.; Curtiss, L. A.; Weinhold, F. Intermolecular Interactions from a Natural Bond Orbital, Donor-acceptor Viewpoint. *Chem. Rev*. **1988**, *88*, 899-926.

41. Glendening, E. D.; Reed, A. E.; Carpenter, J. E.; Weinhold, F. *NBO version 3.1* (Included in the Gaussian 98 package of programs).

42. Boys, S. F.; Bernardi, F. The Calculation of Small Molecular Interactions by the Differences of Separate Total Energies. Some Procedures With Reduced Errors. *Mol. Phys.* **1970**, *19*, 553-566.

43. Turi, L.; Dannenberg, J. J. Molecular Orbital Studies of C-H...O Hydrogen-bonded Complexes. *J. Phys. Chem.* **1993**, *97*, 7899.

44. Desiraju, G. R.; Steiner, T. *The Weak Hydrogen Bond in Structural Chemistry and Biology*, Oxford

University Press, Oxford, 1999.

45. Kowalewski, D. G.; Kowalewski, V. J.; Peralta, J. E.; Eskuche, G.; Contreras, R. H.; Esteban, A. L.; Galache, M. P.; Díez, E. Intramolecular Electric Field Effect on a [1]J(C,H) NMR Spin-spin Coupling Constant. an Experimental and Theoretical Study. *Magn. Reson. Chem.* **1999**, *37*, 227-231.

46. Vizioli, C.; Ruiz de Azúa, M. C.; Giribet, C. G.; Contreras, R. H.; Turi, L.; Dannenberg, J. J.; Rae, I. D.; Weigold, J. A.; Malagoli, M., Zanasi R.; Lazzeretti, P. Proximity Effects on Nuclear Spin-spin Coupling Constants. 1. [1]J(CH) Couplings in the Vicinity of an Atom Bearing Lone Pairs. *J. Phys. Chem.* **1994**, *98*, 8858-8861.

47. Giribet, C. G.; Vizioli, C. V.; Ruiz de Azúa, M. C.; Contreras, R. H.; Dannenberg, J. J.; and Masunov, A. Proximity Effects on Nuclear Spin-spin Coupling Constants. Part 2. The Electric Field Effect on [1]J(CH) Couplings. *J. Chem. Soc. Faraday Trans.* **1996**, *92*, 3029-3030.

48. Taha, A. N.; True, N. S. Experimental ^{1}H NMR and Computational Studies of Internal Rotation of Solvated Formamide. *J. Phys. Chem, A* **2000**, *104*, 2985-2993.

49. Wigglesworth, R. D., Raynes, W. T., Kirpekar, S., Oddershede, J., Sauer, S. P. A. Nuclear spin-spin coupling in the acetylene isotopomers calculated from ab initio correlated surfaces for [1]J(C,H), [1]J(C,C), [2]J(C,H) and [3]J(H,H). *J. Chem. Phys.* **2000**, *112*, 3735-3746.