Natural bond orbital dissection of fluorine–fluorine through-space NMR coupling ($J_{F,F}$) in polycyclic organic molecules

J. E. Peralta,[a] **R. H. Contreras***[b] **and J. P. Snyder***[a]

[a] *Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Argentina*
[b] *Department of Chemistry, Emory University, Atlanta, GA 30322, USA. E-mail: snyder@euch4e.chem.emory.edu*

A new approach to deconvolute DFT and *ab initio* Fermi contact-derived NMR coupling constants into conceptually familiar localized orbital contributions (NJC analysis) is exemplified by analysis of through-space *J*(F,F) couplings in a few illustrative cases.

Large NMR spin–spin coupling between two proximate atoms that are otherwise separated by a considerable number of formal bonds, through-space coupling, has been observed for many years. Very early, the idea that spin polarization associated with the Fermi contact coupling mechanism can be transmitted between such atoms was advanced.[1] Since that time, both experimental and theoretical evaluations of through-space coupling has stimulated useful insights on how such a mechanism operates.[2–6] Most known theoretical approaches are semiempirical in nature. They partition the total coupling according to the electronic mechanisms involved in spin polarization transmission.[7–9] One attempt to extend the IPPP[9] method to the *ab initio* level proved to be intractable for systematic study of practical problems.[10]

Recently, very efficient and reliable implementations of Finite Perturbation Theory[11] within the Gaussian suite of programs[12] permit calculation of the Fermi contact contribution to spin–spin couplings, $J^{FC}(A,B)$. Both single (FPT-1) and double perturbation (FPT-2) approaches have been reported and reviewed.[13,14] For calculating $J^{FC}(A,B)$ within the FPT-1 method, the Fermi contact operator is introduced as a perturbation placed at only one of the two coupled nuclei, *e.g.* A. The resulting interaction spin-polarizes the electronic environment to define a spin density at nucleus B proportional to $J^{FC}(A,B)$.

Ordinarily, the spin density is written in terms of canonical molecular orbitals. However, if localized molecular orbitals are employed instead, then each localized orbital contribution to $J^{FC}(A,B)$ can be rationalized in terms of familiar chemical concepts. In this way, a practical and intuitive theoretical approach to dissecting $J^{FC}(A,B)$ couplings into different transmission mechanisms is achieved.

In the present work, natural localized molecular orbitals (NLMO) provided by natural bond orbital analysis, NBO,[15] are utilized to express the spin density. The latter and, consequently, $J^{FC}(A,B)$ can then be rewritten as a sum of contributions in terms of core orbitals, CR, non-bonding electron pairs, LP, and bonding orbitals, BD, as in eqn. (1). We refer to the method as natural *J*-coupling (NJC) analysis and consider it a complement to natural chemical shielding analysis (NCS).[16] All calculations of Fermi contact terms reported here were carried out with the Gaussian 98 suite of programs[12] at the DFT B3LYP/6-311G** level.

$$J^{FC}(A,B) = J_{CR}(A,B) + J_{LP}(A,B) + J_{BD}(A,B) \qquad (1)$$

Eqn. (1) is particularly suited to the study of through-space *J*-coupling originating from lone-pair overlap between atoms which are proximate in space, a problem of considerable current interest.[6,17] Three examples illustrate mechanistic insights obtained from the approach. The first case concerns the hydrogen fluoride dimer as a model for pure intermolecular F–F

coupling. In this very simple system evaluated for different planar configurations (**1**), the coupling mechanisms can be
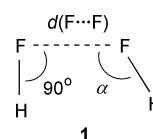
understood on intuitive grounds. Fig. 1 displays the total $J^{FC}(F,F)$ coupling and the $J_{LP}(F,F)$, $J_{CR}(F,F)$ and $J_{BD}(F,F)$ contributions as a function of F···F distance for $\alpha = 90°$. Several features of the plots are noteworthy. The total $J^{FC}(F,F)$ coupling decreases rapidly with increasing $d(F\cdots F)$ following the same trend as the absolute values for the different components. The $J_{LP}(F,F)$ and $J_{CR}(F,F)$ contributions correspond to positive decrements, while $J_{BD}(F,F)$ is negative. In agreement, several experimental reports on *J*(H,H) and *J*(F,H) couplings offer evidence that through-space transmission as a result of direct overlap between two bonds elicits a negative contribution.[3,18] With respect to different lone pairs within the HF dimer, the $J_{LP}(F,F)$ breakdown suggests that (a) the lone pairs of both fluorine atoms whose NLMOs are of π-symmetry do not participate in through-space transmission; (b) the NLMOs of lowest energy yield the largest and positive contribution to $J^{FC}(F,F)$; and (c) the *J*-contribution of the lone pairs of highest energy are negative but of notably smaller absolute value than that described in (b). However, actual values of each component depend strongly on α for a given $d(F\cdots F)$ distance. Thus, for $d(F\cdots F) = 2.3$ Å and $\alpha = 90°$, $J^{FC}(F,F)$, $J_{LP}(F,F)$, $J_{CR}(F,F)$ and $J_{BD}(F,F)$ are calculated to be 245, 210, 53 and −18 Hz, respectively. On the other hand, for $\alpha = 120°$ at the same distance, the values are 351, 330, 90 and −70 Hz, respectively. These NJC variations call for caution when *J*(F,F) couplings dominated by a through-space mechanism are correlated with only the $d(F\cdots F)$ parameter.

Our second example is taken from compound **2**, in which $^4J(F_a,F_b)$ and $^4J(F_a,F_c)$ were reported to be 37 and 24 Hz, respectively.[19] In order to study the behavior of the through-
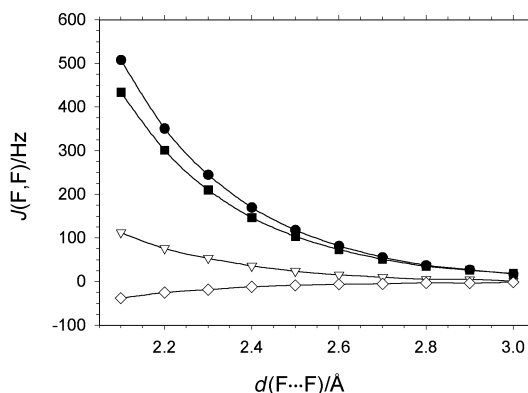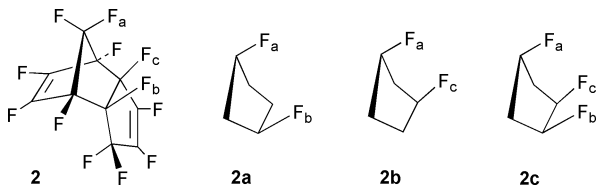
Fig. 1 Plots of $J^{FC}(F,F)$, ●, in the hydrogen fluoride dimer **1** and its $J_{LP}(F,F)$, ■, $J_{CR}(F,F)$, ▽, and $J_{BD}(F,F)$, ◇, contributions as a function of $d(F\cdots F)$; $\alpha = 90°$.

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

space components of the two couplings for fluorine atoms with the same configuration, the structure of **2** was first optimized with the MM3*/MacroModel.[20] The five-membered ring structures **2a**–**c** were then constructed from optimized **2** by preserving local heavy atom geometries; that is, both distance and angular relationships between the fluorine atoms are unchanged. The lone pair contributions to $^4J^{FC}(F_a,F_b)$ and $^4J^{FC}(F_a,F_c)$ in **2a**–**c** are compared with their respective total $^4J^{FC}(F,F)$ couplings in Table 1. While the latter calculated values do not accurately reproduce the corresponding experimental values in **2**, a number of qualitative trends are evident. $^4J_{LP}(F,F)$ and $^4J_{CR}(F,F)$ are positive and correspond to contributions transmitted through-space. On the other hand, the negative term $\Delta^4J(F,F)$ is composed of both through-space and through-bond contributions, the former originating in the direct superposition of two C–F bonds. Not surprisingly, the absolute value of $\Delta^4J(F_a,F_b)$ (16–20 Hz) is considerably larger than that for $\Delta^4J(F_a,F_c)$ (3–5 Hz) (Table 1). To interpret the difference, we note that the fluorine pairs F_a/F_b and F_a/F_c are linked by four bonds, while the fluorine atoms in each pair are separated by 2.56 and 2.92 Å, respectively. A reasonable assumption is that the −3 to −5 Hz exhibited by $\Delta^4J(F_a,F_c)$ is an upper limit for through-bond coupling. Thus, the −16 to −20 Hz calculated for $\Delta^4J(F_a,F_b)$ can be viewed primarily as a C–F bond through-space effect, a result in harmony with the HF dimer model calculations.

In the final example, we perform an NJC analysis for the *peri*-$^4J^{FC}(F,F)$ coupling in compounds **3a** and **3b**. The total $J^{FC}(F,F)$

3a **3b**
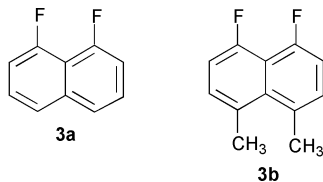
coupling and the $J_{LP}(F,F)$, $J_{CR}(F,F)$ and $J_{BD}(F,F)$ contributions to these *peri*-$^4J^{FC}(F,F)$ couplings are compared in Table 2. While the total $J^{FC}(F,F)$ couplings are underestimated by 12–15%, they follow experiment nicely. All contributions are in agreement with expectations based on molecular geometry. For instance, the larger absolute values of $^4J_{LP}(F,F)$, $^4J_{CR}(F,F)$ and $\Delta^4J(F,F)$ in **3b** with the smaller $d(F\cdots F)$ (Table 2), parallel the trends described above for the FH dimer (Fig. 1). Similar to **2a**–**c**, the combined and negative through-bond and through-space term, $\Delta^4J(F,F)$, is larger for the shorter distance. As before, we assume a similar ^4J through-bond coupling (both σ and π) for **3a** and **3b**. The calculated difference of −11.8 Hz can thus be

Table 2 Becke3LYP/6-311G**/NBO and experimental values for $^4J^{FC}(F,F)$ (Hz) and component couplings in **3a** and **3b**

Coupling	3a	3b
$^4J^{FC}(F,F)$	52.1	73.2
$^4J_{LP}(F,F)$	58.2	86.4
$^4J_{CR}(F,F)$	10.8	15.5
$\Delta^4J(F,F)^a$	−16.9	−28.7
Jexp^b	59.0	85.2
$d(F\cdots F)^c$	2.580	2.508

^{a} $\Delta^4J(F,F) = {}^4J^{FC}(F,F) - [^4J_{LP}(F,F) + {}^4J_{CR}(F,F)]$. ^{b} Taken from F. B. Mallory, *et al*.[17] ^{c} MM3*/MacroModel optimized **3a** and **3b** (Å). X-ray of 1,8-difluoronaphthalene, $d(F\cdots F) = 2.584$ Å; P. A. Meresse, C. Courseille, F. Leroy and N. B. Chanh, *Acta Crytallogr. B*, 1975, **31**, 1236.

attributed to the C–F bonds contribution to coupling in the latter compound.

In summary, the main features of dissection of $J(F,F)$ couplings transmitted through-space in compounds such as **2–3** are in good agreement with currently accepted mechanisms, especially the lone-pair overlap proposal of Mallory and co-workers.[17] However, in addition to presenting a novel tool for J-analysis, we also highlight the previously unrecognized importance of angular effects and X–F bond–bond coupling contributions. Future NJC analyses will explore these phenomena in detail.

Notes and references

1 L. Petrakis and C. H. Sederholm, *J. Chem. Phys.*, 1961, **35**, 1243; D. R. Davis, R. P. Lutz and J. D. Roberts, *J. Am. Chem. Soc.*, 1961, **83**, 246.
2 J. Hilton and L. H. Sutcliffe, *Prog. NMR Spectrosc.*, 1975, **10**, 27.
3 R. H.Contreras, M. A. Natiello and G. E. Scuseria, *Magn. Reson. Rev.*, 1985, **9**, 239.
4 F. B. Mallory and C. W. Mallory, in *Encyclopedia of Nuclear Magnetic Resonance*, ed. D. M. Grant and R. K. Harris, J. Wiley & Sons, Chichester, 1996, vol. 3, p. 1491.
5 R. H. Contreras and J. C. Facelli, *Ann. Rep. NMR Spectrosc.*, 1993, **27**, 255.
6 R. H. Contreras and J. E. Peralta, *Prog. NMR Spectrosc.*, in the press.
7 M. Barfield, *J. Am. Chem. Soc.*, 1980, **102**, 1.
8 A. R. Engelmann, R. H. Contreras and J. C. Facelli, *Theoret. Chim. Acta*, 1981, **59**, 17.
9 A. R. Engelmann and R. H. Contreras, *Int. J. Quantum Chem.*, 1983, **23**, 1033.
10 P. Lazzeretti, M. Malagoli, R. Zanasi, E. W. Della, I. J. Lochert, C. G. Giribet, M. C. Ruiz de Azúa and R. H. Contreras, *J. Chem. Soc., Faraday Trans.*, 1995, **91**, 4031.
11 J. A. Pople and D. L. Beveridge, *Approximate Molecular Orbital Theory*, McGraw–Hill, New York (1970).
12 Gaussian 98, Revision A.7, Gaussian Inc., Pittsburgh, PA, 1998.
13 R. H. Contreras, J. E. Peralta, M. C. Ruiz de Azúa, C. G. Giribet and J. C. Facelli, *Ann. Reps. NMR Spectrosc.*, 2000, **41**, 55.
14 J. E. Peralta, M. C. Ruiz de Azúa and R. H. Contreras, *Theoret. Chem. Acc.*, in the press.
15 J. P. Foster and F. Weinhold, *J. Am. Chem. Soc.*, 1980, **102**, 7211; A. E. Reed, L. A. Curtis and F. Weinhold, *Chem. Rev.*, 1988, **88**, 899; NBO version 3.1, E. D. Glendening, A. E. Reed, J. E. Carpenter and F. Weinhold (in ref. 12).
16 J. A. Bohmann, F. Weinhold and T. C. Farrar, *J. Chem. Phys.*, 1997, **107**, 1173.
17 F. B. Mallory, C. W. Mallory, K. E. Butler, M. B. Lewis, A. Q. Xia, E. D. Luzik Jr., L. E. Fredenburgh, M. M. Ramanjulu, Q. N. Van, M. M. Francl, D. A. Freed, C. C. Wray, C. Hann, M. Nerz-Stormes, P. J. Carroll and L. E. Chirlian, *J. Am. Chem. Soc.*, 2000, **122**, 4108.
18 T. Schaefer, S. Kroeker and D. M. McKinnon, *Can. J. Chem.*, 1995, **73**, 2208.
19 R. Fields, M. Green and A. Jones, *J. Chem. Soc. B*, 1967, 270.
20 MacroModel web site: http://www.schrodinger.com/macromodel.html

Table 1 Becke3LYP/6-311G**/NBO values for $^4J^{FC}(F,F)$ (Hz) and component couplings in **2a**–**c**

Coupling	2a	2b	2c	
	$^4J(F_a,F_b)$	$^4J(F_a,F_c)$	$^4J(F_a,F_b)$	$^4J(F_a,F_c)$
$^4J^{FC}(F,F)$	68.0	7.6	67.7	9.0
$^4J_{LP}(F,F)$	72.9	11.8	71.1	12.6
$^4J_{CR}(F,F)$	14.5	0.4	13.0	0.2
$\Delta^4J(F,F)^a$	−19.4	−4.6	−16.4	−3.8
$d(F\cdots F)^b$	2.56	2.92	2.56	2.92

^{a} $\Delta^4J(F,F) = {}^4J^{FC}(F,F) - [^4J_{LP}(F,F) + {}^4J_{CR}(F,F)]$. ^{b} From MM3*/MacroModel[19] optimized **2** (Å).