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Review Commentary

Calculation of NMR parameters in van der Waals complexes involving organic systems and xenon†

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ABSTRACT: Some of our recent results concerning the prediction of NMR parameters for van der Waals (vdW) complexes are reviewed. Through-space coupling constants, in organic molecules stabilized by CH–π interaction, are calculated to be of the order of 0.3 Hz, therefore above the current experimental resolution. Through-space coupling constants between hydrocarbons and xenon are also calculated to be relatively large, of the order of a few Hz at the vdW contact distance. Finally, we present some preliminary data on the dependence of the chemical shift of xenon in vdW complexes with alkyl chains. These results will serve as a tool in molecular dynamics simulations of xenon dissolved in membranes. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: NMR; through-space; spin–spin coupling; CH–π interaction; DFT calculations

INTRODUCTION

The calculation of the molecular properties that determine the NMR spectrum of molecular species is a flourishing area of computational chemistry.[1] To this aim, both major quantum-chemical methodological frameworks for the study of molecular properties have been adopted, i.e. *ab initio* and Density Functional Theory (DFT) methods. In this respect, whereas *ab initio* methods have proved to be very accurate, and often superior to DFT,[2] the rapid increase in their computational cost with molecular size in fact prohibits many applications of interest to practical NMR spectroscopy, which are generally concerned with molecular systems of substantial size. On the other hand, DFT has also proved to be a very accurate method for the calculation of NMR parameters for molecules containing light atoms.[3] Thus, recently, a complete prediction of the ^{1}H NMR spectrum[4] and ^{13}C heterocorrelated 2D spectra[5] of simple molecules has been reported. A quantitative accuracy is obtained for molecules composed of first-row atoms at a relatively low level of theory (B3LYP/cc-pVTZ), while the presence of heavy atoms requires a more specific treatment of electron correlation and relativistic effects.[1,5–7] Because of the relatively low computational cost of DFT, the protocol presented in Refs 4 and 5 is a very useful tool for structure elucidation.

As an extension of the protocol, applied therein to covalent compounds, the prediction of NMR properties in van der Waals complexes is also of interest due to the large number of cases, also of biological relevance (e.g. proteins and DNA), where a given structure is stabilized by dispersive interactions between two moieties. Therefore, we selected several simple organic van der Waals complexes and covalent compounds having a structure where dispersive interaction plays an important role in the stabilization of a given conformer.[8–10]

Another example where NMR properties of van der Waals systems is of paramount importance is ^{129}Xe NMR spectroscopy. This technique is widely used to probe various environments where xenon is dissolved, thanks to the great sensitivity of the xenon chemical shift to the chemical environment. Wherever heavy atoms are present, electron correlation and/or relativistic effects have to be carefully investigated for a quantitative calculation of NMR parameters. This indeed applies to the case of xenon. Thus a relativistic DFT approach was used for the calculation of NMR properties of xenon in various covalent compounds as well as model van der Waals complexes with methane, benzene and a silicate residue.[11]

In this paper we will firstly review some of the above results on calculation of NMR parameters for van der Waals systems, and then we will present new results obtained for the chemical shift of xenon interacting with

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alkyl chains. The latter data might be used to model, by means of an empirical function, the dependence of the chemical shift of xenon when dissolved in polyethylene membranes. Thus, molecular dynamic (MD) simulations will be able to simulate the chemical shift of xenon dissolved in the membrane and to draw microscopic information on the structure of the membrane itself.

DISCUSSION

Through-space coupling in organic systems

The importance of *J*-couplings in the structure determination of covalent compounds is well known: the strength of the couplings is related to the number of bonds between the coupled nuclei, depends on *cis–trans* isomerism and is related to the dihedral angle for ^3J (Karplus relationship).

Although through-hydrogen-bond couplings have been known for some time in few specific systems,[12] it is only recently that such couplings have been observed in widespread and important systems such as proteins and DNA.[13] These are very important since, for example, the secondary structure of proteins, as well as the structure of DNA is largely determined by hydrogen bonds. This observation has spawned a large amount of experimental and theoretical work, e.g. the modeling of $^{3h}J_{NC'}$ couplings in amide–carbonyl hydrogen bonds.[13,14]

The next logical step, following covalent and hydrogen bonds, is to look for *J* couplings in even weaker bonds, such as van der Waals systems. A few such papers have appeared recently: Salsbury and Harris found a small (10^{-3} Hz) coupling in the Xe···Xe and Xe···H dimers using DFT,[15] and Pecul calculated a relatively large coupling constant of 1.3 Hz for the He···He dimer using a full Configuration Interaction (CI) *ab initio* method.[16] These seminal theoretical studies indicate that nuclei can be *J*-coupled even if no covalent bond exists between them. However, the systems investigated by these workers are not of general interest in organic chemistry. It is desirable to extend such studies to organic systems stabilized by van der Waals interactions. Indeed, several molecules, ranging from small organic compounds to large proteins, are stabilized by dispersive interactions. Among the various types of molecular configurations giving rise to a van der Waals interaction, the so called CH–π interaction,[17] where a C—H bond points perpendicularly towards a π-system, seems to be of special interest as far as the through-space coupling is concerned. Here, in fact, a proton and a carbon atom are located sufficiently close in space that a spin–spin J_{CH} coupling between them could be expected. In addition to being suitable for the search of a through-space coupling in organic systems, the CH–π interaction is also a very common one in organic and biological chemistry. As an example, we will mention the work of Burley and Petsko[18] and Hunter *et al.*[19] on the distribution of orientations of two phenylalanine rings in proteins: when they are in close contact the relative orientation is never face-to-face but it can be either T-shaped or slipped, the T-shaped corresponding to a CH–π arrangement. Quantum-chemical calculations indicate the latter two structures to be energy minima and the face-to-face structure to be a saddle point on the potential energy surface.[20] Several other systems are stabilized by CH–π interaction and we refer the interested reader to Ref. 17.

We therefore selected small organic van der Waals complexes to run a series of test calculations, both at the DFT level as well as at other highly correlated *ab initio* levels.[8–10] As examples, we mention here the methane–ethylene and the acetylene dimer vdW complexes. The DFT calculations were run at the VWN/IGLO-III level of theory with the software DeMon-NMR,[21] which calculates the three most important contributions to the coupling constant (the Fermi-contact, diamagnetic and paramagnetic spin-orbit terms), but does not calculate the spin-dipole term, which is often negligible and very time-consuming.[1] The results for the methane–ethylene complex, in the CH–π arrangement, are shown in Fig. 1. We note that, in the region where the interaction is stabilizing, the through-space J_{CH} between the carbon atom of the π-system and the hydrogen atom of the CH bond involved in the CH–π interaction is not negligible, ca 0.3 Hz. This value, albeit small, lies above the present limit of NMR resolution.[22] In contrast, the J_{HH} coupling between the ethylenic protons and the proton of the CH bond is essentially zero around the equilibrium distance. A very similar result is obtained for the benzene dimer in the stable CH–π configuration: the through-space J_{CH} coupling is ca 0.3 Hz, while the through-space J_{HH} coupling is negligible. Moreover, for the benzene dimer in the face-to-face configuration no significant

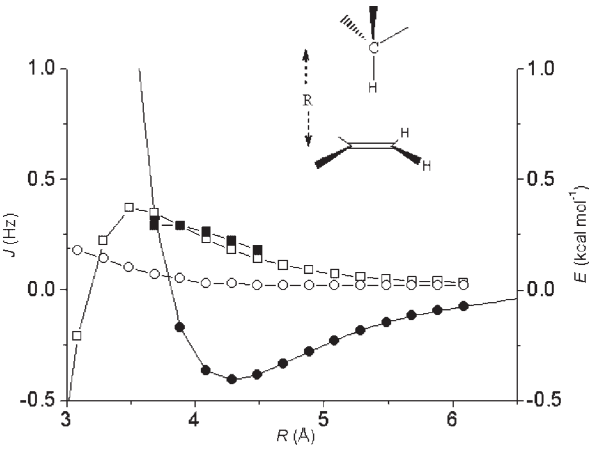


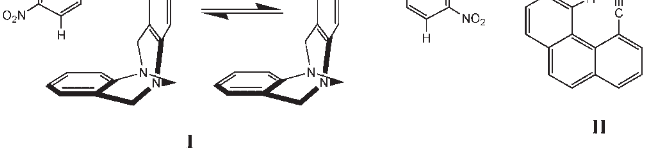
Figure 1. Methane–ethylene dimer. Interaction energy at the MP2/cc-pVTZ level (BSSE-corrected) (solid circles); J_{CH}, DFT WVN/IGLO-III level (empty squares); J_{HH}, DFT WVN/IGLO-III level (empty circles); J_{CH}, *ab initio* SOPPA/aug-cc-pVDZ-su1 level (solid squares)

through-space coupling was calculated. This is mainly due to the fact that the CH–π interaction brings the atoms closer together.

However, it is well known that DFT does not describe adequately the energetics of the dispersive interaction in van der Waals complexes. As, by the same token, one might argue that DFT calculations cannot yield reliable through-space coupling constants, it is sensible to validate the DFT results with those obtained with a highly correlated *ab initio* method. For the smaller methane–ethylene dimer it was possible to calculate the coupling constant using two different approaches: thus, RASSCF (Restricted Active Space Self-Consistent Field)[23] and SOPPA (Second Order Polarization Propagator Approximation)[24] were used to calculate the J_{CH} coupling using the software DALTON.[25] We used the basis set aug-cc-pVDZ-su1 previously used by Pecul in a similar study on the HF–CH_4 complex.[26] The software package DALTON allows for the calculation of all four contributions to the coupling constant. RASSCF and SOPPA results are almost coincident, and the value of the SD contribution is indeed calculated to be very small. A large contribution comes, instead, from an incomplete cancellation of the spin–orbit terms. The total J_{CH} coupling constant calculated at the SOPPA level is also reported in Fig. 1. It is comforting to see the two curves (DFT and SOPPA calculations) are almost superimposed. This confirms the reliability of DFT methods for the calculations of the through-space coupling constant, at least in these systems.

We therefore proceeded to calculate the J_{CH} coupling in a larger molecule,[9] by necessity only at the DFT level (VWN/IGLO-III on the x-ray structure), i.e. the molecular balance of Wilcox and co-workers[27] **I** (Scheme 1).

The molecule was, in fact, designed to measure the strength of the CH–π interaction. In fact, in solution there are two conformers, the folded one and the unfolded one which interconvert slowly on the NMR time scale.[27] The structural difference between the two is that the folded conformer has a CH–π interaction (indicated by the explicit hydrogen in **I**), which is absent in the unfolded conformer. The results of the calculations totally agree with the results obtained for the model dimers: a through-space J_{CH} coupling of 0.3 Hz is calculated between the proton of the CH bond and the carbons of the underlying π-system for the folded conformer. The same J_{CH} coupling constant is calculated to be essentially zero for the unfolded conformer, where the proton is very far away from the π-system. An experimental NMR investigation of this system is currently in progress.



Scheme 1. Organic compounds showing a CH–π interaction where a non-negligible J_{CH} through-space coupling constant has been calculated

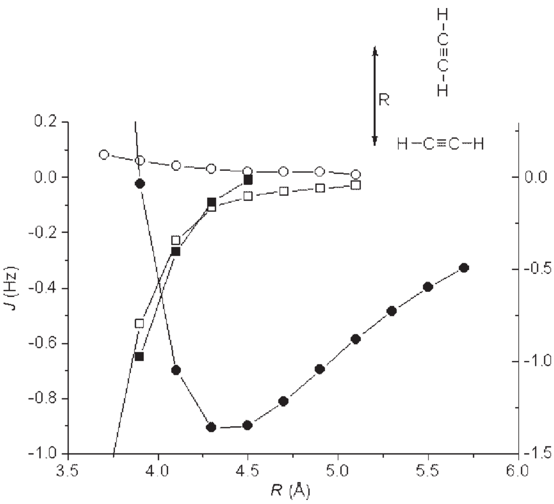


Figure 2. Acetylene dimer. Interaction energy at the MP2/cc-pVTZ level (BSSE-corrected) (solid circles); J_{CH}, DFT WVN/IGLO-III level (empty squares); J_{HH}, DFT WVN/IGLO-III level (empty circles); J_{CH}, *ab initio* SOPPA/aug-cc-pVDZ-su1 level (solid squares)

As a second example, in Fig. 2 we report the results, both at the DFT and the SOPPA levels of theory, for the acetylene dimer.[10b] Again we note that, in the region where the interaction is stabilizing, a non-negligible J_{CH} coupling constant between the proton of the C—H bond and the carbon of the acetylenic π-system is calculated, while the J_{HH} coupling constant is essentially zero. As for the case of the methane–ethylene dimer, the results of the *ab initio* calculations are in good agreement with the DFT ones. Also in this case, therefore, it is confirmed that DFT is a useful tool for the prediction of through-space coupling constants in CH–π interacting complexes.

The acetylene dimer system was investigated as a model of 4-ethynylphenanthrene **II** (Scheme 1): here, an aromatic proton is very close in space (2.3 Å as obtained by optimization at the B3LYP/6-31G** level) to the triple bond, and therefore a non-negligible J_{CH} is expected. In fact, the calculation at the DFT (WVN/IGLO-III) level predicted a coupling constant J_{CH} of −0.35 Hz. For this system, an experimental verification is also in progress.

Through-space coupling in xenon dimers

In parallel with the study of through-space coupling in organic systems, we have also investigated the through-space coupling in van der Waals dimers involving xenon.[11] Very recently, a new NMR technique, based on SQUID (Superconducting QUantum Interference

Device) detection of magnetization from laser-hyperpolarized xenon, has been developed by Romalis and coworkers,[28] which is not based on the detection of peak splittings and, quoting the Authors, '*is promising for the detection of intermolecular scalar spin–spin couplings*'. This work sheds new light on our recent results of calculations of through-space *J* couplings between ^{129}Xe and ^{1}H or ^{13}C nuclei of simple hydrocarbons such as methane and benzene, or ^{29}Si and ^{17}O in a silicate residue. In fact, in Ref. 11 we considered the van der Waals dimers made of Xe and hydrocarbons or silicate to be useful models of real compounds where Xe is trapped inside cavities as, for example, in zeolites, membranes, liquid crystals, cryptands. However, no conventional technique would be able to measure the through-space coupling in the dimers themselves, owing to their short lifetime. In contrast, the new SQUID-NMR technique can, in principle, detect scalar couplings between atoms in a van der Waals dimer even in the fast exchange regime.

As a first step, we ran a set of calculations of shielding constants and spin–spin coupling constants for an ensemble of simple xenon covalent molecules, for which the chemical shift and the *J* couplings were known. These were mainly xenon fluorides and oxides [XeF_2, XeF_4, $XeOF_4$, XeO_3, XeO_2F_2, $FXeOSO_2F$, $FXeN(SO_2F)_2$, XeF_6, XeF^+, $XeCl^+$]. Apart from XeF_6, XeF^+ and $XeCl^+$, whose the structure is unknown or questionable, a good correlation of chemical shifts and coupling constants was found at the relativistic scalar ZORA/TZ2P level of theory, both for the ^{129}Xe chemical shift and for the spin–spin coupling constants, using the software code ADF.[29] We therefore proceeded to calculate the through-space coupling constants of xenon with protons and carbon atoms in simple van der Waals complexes such as xenon–methane, xenon–benzene and xenon with a silicate residue. The results are encouraging: as an example, in the $Xe—CH_4$ complex the J_{XeH} coupling can be as large as about 3 Hz at the van der Waals contact distance (3.9 Å). The van der Waals contact distance is taken here as a limit of the shortest approach that xenon and methane (or any other molecule) can have in the complex. This is because, in contrast to the case of the CH–π complexes, we could not calculate the interaction energy and its distance dependence at the MP2 level with a large basis sets for xenon systems, due to their large size. Therefore we could not determine accurately the equilibrium separation of the $Xe—CH_4$ complex. However, for this complex, the coupling constant is still of the order of 1 Hz even if the separation is increased, with respect to the contact distance, by 0.5 Å. This renders such xenon–hydrocarbon complexes as favourable systems where through-space couplings could be detected by means of the SQUID-NMR technique. In fact, the mixture of liquid xenon–cyclopentane has been suggested for an experimental verification.[28] Currently we are investigating, by means of molecular dynamics simulations, the effect of the composition and degree of hyperpolarization of xenon on the outcome of the experiments.

^{129}Xe Chemical shifts in organic vdW complexes

As we mentioned in the previous section, ^{129}Xe NMR spectroscopy is largely used to obtain information about the structure of the environment where the xenon is dissolved, because the xenon chemical shift is strongly affected by the surroundings. As an example, we recall the variation of 1.19 ppm observed for xenon encapsulated into a cryptand on deuteration of the cryptand itself.[30] In this case, the deuterium atoms alter the vibrational modes of the cage containing the xenon atom, and this change is detected as a shift in the ^{129}Xe NMR spectrum. Xenon is largely used as a molecular probe in studying the structure of zeolites,[31] membranes[32] and liquid crystals.[33] The chemical shift contains important information about the chemical nature of the environment and its local structure. However, a detailed understanding of the dependence of the chemical shift on the chemical environment is still way ahead.

An important technique to gain information at a microscopic level of a given system is molecular dynamics simulation. However, in order to be able to simulate the NMR spectrum of xenon inside a medium, the dependence of the ^{129}Xe chemical shift as a function of the distance from the various atoms of the host molecule (or host phase) has to be known. Recently, computer simulations of the NMR spectrum of xenon in zeolites have been reported,[34] where the chemical shift dependence on the distance of xenon from the atoms constituting the zeolite cavity have been determined by quantum chemical calculations. We are interested in xenon as a probe as a means of obtaining information about the structure, cavity distribution and degree of order of polymeric membranes. Therefore we considered polyethylene as an example where a similar protocol to the one used for interpreting results of ^{129}Xe NMR in zeolites may be tested. Thus, in this last section we will discuss some new recent results of the dependence of the chemical shift of xenon on the distance from various alkyl chains. The goal of this investigation is to find an empirical pairwise additive function to express the ^{129}Xe chemical shift as the sum of all contributions from the surrounding atoms.

We have therefore selected the linear alkanes C_1–C_5, C_7 and C_9 and built the complexes with xenon placing a xenon atom as in Fig. 3, where some examples are shown, so as to obtain C_{2v} and C_s symmetry for the odd and even chains, respectively. For each complex, we have varied the $Xe—C$ distance in 0.25 Å steps; the calculations have been carried out at the scalar ZORA/TZ2P level.[29] In Fig. 4 we report the results of this preliminary investigation.

The dependence of the chemical shift on the distance is exponential, at least within the range of distances

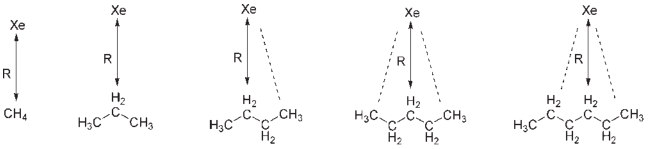


Figure 3. Example of the arrangement of xenon and alkyl chains for the calculation of the chemical shift dependence of $\delta(^{129}Xe)$ in polyethylene for some of the complexes investigated in this work

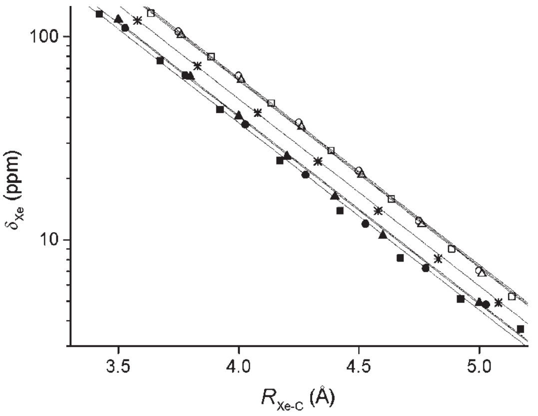


Figure 4. Dependence of the chemical shift of xenon (δ_{Xe}) calculated with respect to free xenon atom ($\sigma_{Xe} = 5660$ ppm) for the various alkyl chains investigated. Note the log scale for the chemical shift. C_1 (solid squares); C_2 (solid circles); C_3 (solid triangles); C_4 (asterisks); C_5 (open circles); C_7 (open squares); C_9 (open triangles); multiple monoexponential fit with shared decay constant (solid lines)

investigated, and all curves can be fitted reasonably well by the same decay constant. This behaviour is different from what was observed in previous theoretical studies where an inverse power law with exponent $n = 6$ was found.[35] In our case it was not possible to fit the dependence of the chemical shift with a power law, although for large separations (>5.5 Å), the chemical shift of xenon in the complexes is found to decay more slowly than a monoexponential curve. This will possibly require some correction to the chemical shift of xenon calculated by means of the pairwise empirical exponential function from MD trajectories but, for large separations, where the radial distribution function is approximately constant, such a correction will only depend on the density of CH_2 groups in the simulation box. The decay of the ^{129}Xe chemical shift for all complexes has, therefore, been fit to a monoexponential curve ($\delta_{Xe} = Ae^{-R/R_D}$), imposing the same exponential decay constant R_D for all and letting the amplitudes A free. The decay constant obtained is $R_D = 0.47$ Å, which indicates a rapid decay of the chemical shift with the distance. The amplitudes, A, obtained from the exponential fitting of $\delta_{Xe}(R)$, for the complexes with C_1, C_2, C_3, C_4, C_5, C_7 and C_9 are (in 10^5 ppm): 1.97, 1.93, 1.81, 2.38, 3.02, 2.96 and 2.92, respectively. Therefore they can be grouped into three groups (C_1–C_3, C_4 and C_5–C_7) depending on the number of CH_2 groups facing towards xenon. This behaviour can be easily explained if we assume an additive contribution of each CH_2 group facing the xenon atom to the ^{129}Xe chemical shift. In fact, what seems to have an effect on the electronic distribution of xenon (and therefore on its chemical shift) is the front pair of hydrogen atoms only (for the geometries we have considered). The back hydrogens do not give a significant contribution, nor do the CH_2 groups separated by more than two C—C bonds from the CH_2 group facing xenon, which are too remote to give a significant contribution. Therefore, for the complexes with C_1–C_3 there is only one CH_2 group, for the C_4 complex there are two CH_2 groups, whereas three CH_2 groups are facing the xenon atom in C_5–C_7 (and longer) chains, as shown schematically in Fig. 3. We also note that the addition of the second CH_2 group increases the amplitude by approximately 0.5–0.6×10^5 ppm, and so does the third CH_2 group.

Table 1. Chemical shift of xenon interacting with one and two methane molecules

	$\delta(^{129}Xe)$ (ppm)	
R (Å)	$CH_4 \cdots Xe$	$CH_4 \cdots Xe \cdots CH_4$
5.0	4.5	11.8
4.0	40.5	87.5
3.0	323	700

We have also calculated $\delta(Xe)$ for the sandwich complex $CH_4 \cdots Xe \cdots CH_4$ at three intermolecular C—Xe separations, and compared the results with those of the $CH_4 \cdots Xe$ complex at the same C—Xe distance in Table 1. The results indicate that $\delta(Xe)$ is roughly twice as large for the sandwich complex than for the simple xenon–methane complex.

These observations confirm that the effects of the various CH_2 groups on the chemical shift are additive, as required to model the chemical shift dependence of xenon in polyethylene membranes by molecular dynamics simulations.

CONCLUSIONS

We have shown the reliability of Density Functional Theory for the calculations of NMR parameters of simple organic van der Waals systems. Comparison of the DFT results with those obtained at highly correlated *ab initio* methods shows very good agreement, at least for CH–π interacting model systems. Relativistic DFT has been applied to the study of xenon van der Waals complexes with hydrocarbons, revealing a relatively large through-space coupling constant at the contact distance. The dependence of the xenon chemical shift on the distance in complexes of xenon with alkyl chains have been investigated in order to model the chemical shift dependence of xenon dissolved in membranes. The effect of increasing number of methylene groups interacting with xenon is, to a good approximation, additive.

REFERENCES

1. Helgaker T, Jaszunski M, Ruud K. *Chem. Rev.* 1999; **99**: 293–352.
2. Cheeseman JR, Trucks GW, Keith TA, Frisch MJ. *J. Chem. Phys.* 1996; **104**: 5497–5509.
3. (a) Malkin VG, Malkina OL, Salahub DR. *Chem. Phys. Lett.* 1994; **221**: 91–99; (b) Dickson RM, Ziegler T. *J. Phys. Chem.* 1996; **100**: 5286–5290; (c) Sychrovský V, Gräfenstein J, Cremer D. *J. Chem. Phys*. 2000; **113**: 3530–3547; (d) Helgaker T, Watson M, Handy NC. *J. Chem. Phys.* 2000; **113**: 9402–9409.
4. Bagno A. *Chem. Eur. J.* 2001; **7**: 1652–1661.
5. Bagno A, Saielli G, Rastrelli F. *J. Phys. Chem. A* 2003; **107**: 9964–9973.
6. Bagno A, Bonchio M, Sartorel A, Scorrano G. *Chem. Phys. Chem.* 2003; **4**: 517–519.
7. Autschbach J, Ziegler T. In *Encyclopedia of Nuclear Magnetic Resonance*: *Advances in NMR*, vol. 9, Grant DM, Harris RK (eds). Wiley: Chichester, 2002; 306–323.
8. Bagno A, Saielli G, Scorrano G. *Angew. Chem., Int. Ed. Engl.* 2001; **40**: 2532–2533.
9. Bagno A, Saielli G, Scorrano G. *Chem. Eur. J.* 2002; **8**: 2047–2056.
10. (a) Bagno A, Saielli G, Scorrano G. *ARKIVOC* 2002; **IV**: 38–44; (b) Bagno A, Casella G, Saielli G, Scorrano G. *Int. J. Mol. Sci.* 2003; **4**: 193–202.
11. Bagno A, Saielli G. *Chem. Eur. J.* 2003; **9**: 1486–1495.
12. Golubev NS, Shenderovich IG, Smirnov SN, Denisov GS, Limbach HH. *Chem. Eur. J.* 1999; **5**: 492–497.
13. For a recent leading reference see: Barfield M. *J. Am. Chem. Soc.* 2002; **124**: 4158–4168.
14. Bagno A. *Chem. Eur. J.* 2000; **6**: 2925–2930.
15. Salsbury FR, Harris FA. *Mol. Phys.* 1998; **94**: 307–312.
16. Pecul M. *J. Chem. Phys.* 2000; **113**: 10835–10836.
17. Nishio M, Hirota M, Umezawa Y. *The CH–π Interaction, Evidence, Nature and Consequences*. Wiley-VCH: New York, 1998.
18. Burley SK, Petsko GA. *Science* 1985; **229**: 23–28.
19. Hunter CA, Singh J, Thornton JM. *J. Mol. Biol.* 1991; **218**: 837–846.
20. Sinnokrot MO, Sherrill CD. *J. Phys. Chem. A* 2003; **107**: 8377–8379.
21. (a) Salahub DR, Fournier R, Mlynarski P, Papai I, St-Amant A, Ushio J. In *Density Functional Methods in Chemistry*, Labanowski J, Andzelm J (eds). Springer: New York, 1991; (b) St-Amant A, Salahub DR, *Chem. Phys. Lett.* 1990; **169**: 387–392; (c) Malkin VG, Malkina OL, Casida M, Salahub DR. *J. Am. Chem. Soc.* 1994; **116**: 5898–5908; (d) Malkin VG, Malkina OL, Eriksson LA, Salahub DR. In *Modern Density Functional Theory: A Tool For Chemistry*, vol. 2, Seminario JM, Politzer P (eds). Elsevier: Amsterdam, 1995; (e) Malkina OL, Salahub DR, Malkin VG, *J. Chem. Phys.* 1996; **105**: 8793–8800.
22. Liu A, Majumdar A, Hu W, Kettani A, Skripkin E, Patel DJ. *J. Am. Chem. Soc*. 2000; **122**: 3206–3210.
23. Vahtras O, Ågren H, Jorgensen P, Jensen HJA, Padkjær SB, Helgaker T. *J. Chem. Phys.* 1992; **96**: 6120–6125.
24. Enevoldsen T, Oddershede J, Sauer SPA. *Theor. Chem. Acc.* 1998; **100**: 275–284.
25. Helgaker T, Jensen HJAa, Jørgensen P, Olsen J, Ruud K, Ågren H, Auer AA, Bak KL, Bakken V, Christiansen O, Coriani S, Dahle P, Dalskov EK, Enevoldsen T, Fernandez B, Hättig C, Hald K, Halkier A, Heiberg H, Hettema H, Jonsson D, Kirpekar S, Kobayashi R, Koch H, Mikkelsen KV, Norman P, Packer MJ, Pedersen TB, Ruden TA, Sanchez A, Saue T, Sauer SPA, Schimmelpfennig B, Sylvester-Hvid KO, Taylor PR, Vahtras O. *Dalton, a molecular electronic structure program, Release 1.2*. 2001.
26. Pecul M, Sadlej J, Leszczynski J. *J. Chem. Phys.* 2001; **115**: 5498–5506.
27. Paliwal S, Geib S, Wilcox CS. *J. Am. Chem. Soc.* 1994; **116**: 4497–4498.
28. Heckman JJ, Ledbetter MP, Romalis MV. *Phys. Rev. Lett.* 2003; **91**: 0676011–0676014.
29. te Velde G, Bickelhaupt FM, Baerends EJ, Fonseca Guerra C, van Gisbergen SJA, Snijders JG, Ziegler T. *J. Comput. Chem.* 2001; **22**: 931–967. ADF 2002.01: http://www.scm.com.
30. (a) Brotin T, Lesage A, Emsley L, Collet A. *J. Am. Chem. Soc.* 2000; **122**: 1171–1174. (b) Brotin T, Devic T, Lesage A, Emsley L, Collet A. *Chem. Eur. J.* 2001; **7**: 1561–1573.
31. (a) Ito T, Fraissard J. *J. Chem. Phys.* 1982; **76**: 5225–5229. (b) Chen QJ, Fraissard J. *J. Phys. Chem.* 1992; **96**: 1809–1814. (c) Heo NH, Lim WT, Kim BJ, Lee SY, Kim MC, Seff K. *J. Phys. Chem. B* 1999; **103**: 1881–1889. (d) Yang D, Clark LA, Ray GJ, Kim YJ, Du H, Snurr RQ. *J. Phys. Chem. B* 2001; **105**: 4698–4708.
32. Xu Y, Tang P. *Biochim. Biophys. Acta Biomemb.* 1997; **1323**: 154–162.
33. (a) Muenster O, Jokisaari J. *Mol. Cryst. Liq. Cryst.* 1991; **206**: 179–186. (b) Ruohonen J, Jokisaari J. *Phys. Chem. Chem. Phys.* 2001; **3**: 3208–3212.
34. Jameson CJ, de Dios AC. *J. Chem. Phys.* 2002; **116**: 3805–3821.
35. Barszczewicz A, Jaszunski M, Helgaker T, Ruud K. *Chem. Phys. Lett.* 1996; **250**: 1–8.