DFT Calculation of Intermolecular Nuclear Spin–Spin Coupling in van der Waals Dimers[**]

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Nuclear magnetic resonance is probably the most powerful technique for the determination of molecular structure and conformation in solution; a wide array of experimental methods is available, which exploit scalar (spin–spin) or dipolar (nuclear Overhauser effect) coupling. Spin–spin couplings are normally thought of as probes of connectivities through covalent bonds only. Lately, however, it has been demonstrated that spin–spin coupling can also be transmitted through various types of hydrogen bonds (HBs).[1–6] Most notably, the sensitivity of NMR experiments has made it possible to detect through-HB coupling constants as low as 0.14 Hz.[3] These findings have stimulated much theoretical work aimed at understanding the factors affecting such coupling constants.[1, 7–11]

An obvious extension is that spin–spin coupling might be detectable even in the case of dispersion-bound van der Waals complexes. In fact, Salsbury and Harris calculated a very small ($<10^{-3}$ Hz) coupling for Xe$\cdots$Xe and Xe$\cdots$H.[12] Apart from fundamental implications, exploitation of such couplings might become important in at least two areas, namely the use of optically pumped Xe as a spin probe[12] and structural investigations of host–guest complexes, which often owe their stability to favorable dispersive interactions.[13] Hence, we have carried out a computational investigation of intermolecular spin–spin couplings in methane–benzene and benzene–benzene dimers as models.

The stabilization energy for the two dimers has been calculated using Gaussian 98[14] at the MP2/cc-pVTZ level,[15–17] corrected for the basis-set superposition error.[18] The geometry of the individual monomers was kept fixed.

Spin–spin coupling constants were calculated with deMon-NMR,[19] which allows the calculation of the three major contributions to the nuclear spin–spin coupling: the Fermi contact (FC), the paramagnetic spin-orbit (PSO), and the diamagnetic spin-orbit (DSO) contributions. The spin–dipole term is often negligible, especially for simple hydrocarbons[20] and when the nuclei are separated by relatively large distances.[19e]

The local Vosko-Wilk-Nusair (VWN) exchange correlation functional[21] was used with the IGLO-III basis set.[22] A preliminary set of calculations on the methane–methane dimer (not reported here) showed that VWN gives essentially the same results as the gradient-corrected Perdew functional (PWP), which is preferred for couplings involving covalent bonds.[19e] Moreover, the VWN functional requires a much more coarse integration grid than the PWP while maintaining the same accuracy,[19] thus reducing the computational time by a factor of five. For these reasons, we have used the VWN functional for the calculations presented here. The perturbation ($\lambda = 0.001$)[19e] was placed on the lighter (hydrogen) atom of a methane or benzene molecule, as shown in Figure 1; this yields the couplings with all the essentially equivalent hydrogen and carbon atoms of the other molecule. The same computational scheme was adopted[7] for through-HB couplings in peptide models, in which a very good accuracy was obtained. Further validation is provided by the values of direct couplings ($^1J_{C,H}$) in the methane, ethylene, and benzene molecules at the PWP/IGLO-III level, which are less than 4% smaller than experimental values. All results are compiled in Table 1.

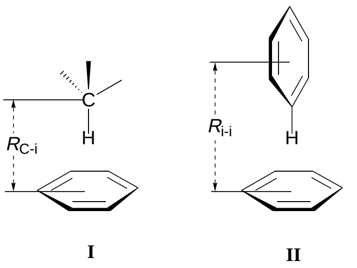

Figure 1. Schematic representation of the two dimers.

Table 1. Main contributions to the intermolecular spin–spin couplings at some selected distances.

	R [Å]	J_{HH} [Hz]			$J_{C,H}$ [Hz]		
		FC	PSO	DSO	FC	PSO	DSO
CH_4–C_6H_6 (**I**)							
	4.485	0.00	−0.21	0.21	0.02	−0.19	0.26
	3.685	0.00	−0.13	0.12	0.11	−0.30	0.41
	3.285	0.01	−0.02	0.00	0.19	−0.42	0.53
C_6H_6–C_6H_6 (**II**)							
	5.100	0.00	−0.33	0.32	0.08	−0.36	0.46
	4.900	0.00	−0.30	0.28	0.11	−0.42	0.52
	4.400	0.04	−0.16	0.13	0.07	−0.64	0.73

As an example of an alkyl–aromatic interaction, we have considered the methane–benzene dimer in the configuration **I** (Figure 1). The geometry of both monomers has been optimized at the MP2/cc-pVTZ level. The interaction energy is reported in Figure 2 as a function of the intermolecular separation $R_{C\text{-}i}$ between the carbon atom of the methane and the center of symmetry of the benzene molecule. The MP2 interaction energy has a minimum at $R_{C\text{-}i} = 3.685$ Å with a stabilization energy of 1.40 kcal mol^{-1}. The $J_{H,H}$ coupling is essentially zero over the distances investigated. On the contrary, a weak but detectable coupling exists between the hydrogen of the methane and the carbon atoms of the benzene molecule, about 0.3 Hz at $R_{C\text{-}i} \approx 3.3$ Å. For $J_{H,H}$ we have a large compensation between the PSO and DSO terms (Table 1), as previously noted in covalent species,[23] whereas for $J_{C,H}$ the compensation is incomplete.

An arrangement of atoms similar to **I** has been found, for example, in the inclusion complex of *tert*-butylcalix[4]arene

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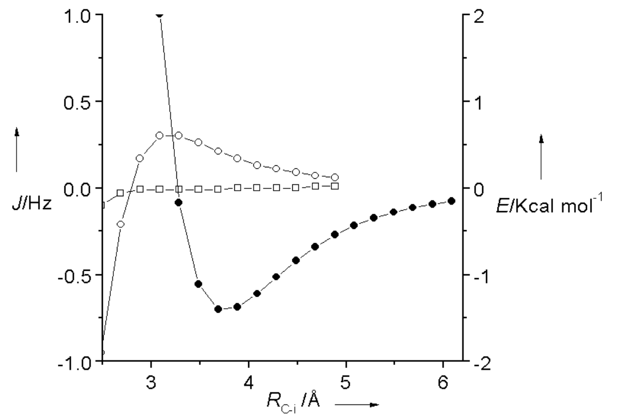

Figure 2. Interaction energies and coupling constants for the $CH_4-C_6H_6$ dimer **I** as a function of the $R_{C\text{-}i}$ distance (VWN/IGLO-III). MP2 interaction energy (●); $J_{H,H}$ couplings (□); $J_{C,H}$ couplings (○).

and acetonitrile.[24] In that case, the $R_{C\text{-}i}$ distance between the methyl carbon and the center of symmetry of one of the benzene rings was 3.71 Å, that is, almost exactly the distance corresponding to the energy minimum in Figure 2.

We have chosen the T-shaped configuration **II** of the benzene–benzene dimer in Figure 1 using the experimental geometries for the benzene monomers.[25] The interaction energies are reported in Figure 3 as a function of the intermolecular separation $R_{i\text{-}i}$ between the centers of symmetry of the benzene molecules. The MP2 energy has a deeper minimum ($3.02\,\text{kcal}\,\text{mol}^{-1}$ at $R_{i\text{-}i} = 4.90$ Å). As for **I**, $J_{H,H}$ couplings are again almost zero, whereas $J_{C,H}$ couplings are about 0.2 Hz at the equilibrium distance. In Figure 3 we also report the FC contribution to $J_{C,H}$ calculated with the MPWPW91 functional[26, 27] and the cc-pVTZ basis set. We observe the same qualitative behaviour of the spin–spin coupling as a function of the intermolecular separation despite the differences in the functional and basis set used.

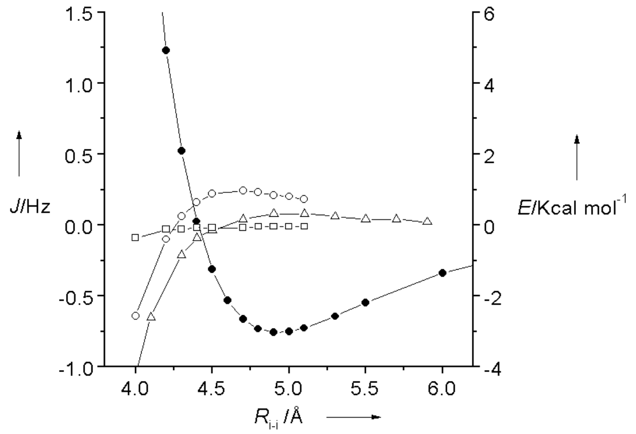

Figure 3. Interaction energies and coupling constants for the $C_6H_6-C_6H_6$ dimer **II** as a function of the $R_{i\text{-}i}$ distance (VWN/IGLO-III). MP2 interaction energy (●); $J_{H,H}$ couplings (□); $J_{C,H}$ couplings (○); FC contribution to $J_{C,H}$ couplings (MPWPW91/cc-pVTZ) (△).

In some rotaxane complexes,[28] the distance between the centroids of the aromatic rings, roughly arranged as in **II**, were in the range 4.8–5.2 Å, again very close to the distance for which we observe the minimum of the interaction energy.

We also note a nonmonotonic trend followed by $J_{C,H}$ in the stabilizing region, as previously noted for $F^- \cdots (HF)_n$ complexes.[5]

A qualitative picture of the mechanism responsible for the through-space spin–spin coupling in the dimers we have investigated is provided by Figure 4, which shows a molecular orbital of **II** at the equilibrium distance connecting the perturbed hydrogen with the hydrogen and carbon atoms of the other molecule.

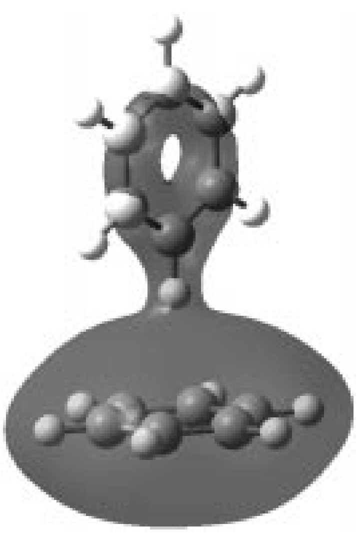

Figure 4. Isosurface at an electron density value of 0.005 for the occupied molecular orbital no. 13 (MP2/cc-pVTZ) for the benzene dimer **II** at the equilibrium distance.

In conclusion, intermolecular spin–spin coupling in these van der Waals dimers is not negligible (0.2–0.3 Hz) for spatial arrangements where the interaction is stabilizing. However, even though such values should lie within the scope of current experimental NMR methods, these model systems are not suitable for an experimental verification, due to their too-large exchange rate compared to the small couplings. On the other hand, some host–guest complexes with similar structural features may have sufficient stabilities and lifetimes. In this respect, our predictions indicate $J_{C,H}$ couplings as the most likely candidates for such experiments.

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A Three-Component Coupling Reaction of Aldehydes, Amines, and Alkynes

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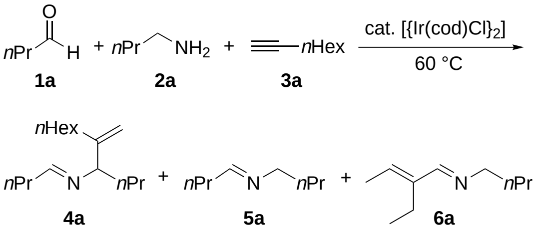
Since the decisive breakthrough in 1993 by Murai et al., who achieved a highly efficient ruthenium-catalyzed addition of aromatic C–H bonds to olefins,[1] carbon–carbon bond formation through the activation of C–H bonds by transition metal complexes is recognized as a new category of chemistry.[2, 3] So far there have been a number of cases of C–C bond formation through activation of the C–H bond adjacent to the heteroatom.[3–5] Recently, it was shown that some iridium complexes cleave the C–H bond of nitriles[6] or 1-naphthols[7] to provide a new C–C bond. To the best of our knowledge, however, no reports have appeared on C–C bond formation by the activation of C–H bonds neighboring the nitrogen atom of imines. In continuation of our studies on iridium-catalyzed reactions of imines,[8] we have now found a new type of C–H bond activation adjacent to the nitrogen atom of imines by an iridium complex, leading to a three-component coupling reaction of aldehydes, amines, and alkynes.

The reaction of *n*-butyraldehyde (**1a**), *n*-butylamine (**2a**), and 1-octyne (**3a**) was selected as a model reaction and examined in the presence of a catalytic amount of [{Ir(cod)Cl}$_2$] (cod = cycloocta-1,5-diene) under various reaction conditions [Eq. (1), Table 1]. To a solution containing [{Ir(cod)Cl}$_2$] in THF was added a 1:1:1 mixture of **1a**, **2a**, and **3a**. The reaction was carried out with stirring at 60 °C for 15 h, giving the coupling products *N*-butyliden(2-hexylpropylallyl)amine (**4a**), imine **5a**, and *α*,*β*-unsaturated imine **6a** in 57 %, 28 % and 11 % yields, respectively (Table 1, run 1). When two equivalents of **1a** and **3a** with respect to **2a** were employed, **4a** was formed in higher yield (72 %, run 2). Interestingly, the reaction took place at 50 °C to give **4a** in moderate yield (56 %, run 4), although the usual catalytic addition of C–H bonds to alkenes and alkynes calls for higher reaction temperatures (> 100 °C).[1–5] When the reaction was terminated after 7 h, a considerable amount of imine **5a** remained unchanged (run 5). This shows that the reaction is



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