

# Synthesis and Supramolecular Organization of 5-(4-Alkylphenyl)isatin

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Supporting Information

**ABSTRACT:** The synthesis of a homologous series of 5-(4-alkylphenyl)isatin derivatives, as well as the crystal structure and DFT studies of the respective hexyl derivative are presented, constituting the first examples of a new family of supramolecular bilayer forming isatin derivatives, which reveal a new type of molecular strand—a molecular arrangement also supported by quantum chemical calculations.



## INTRODUCTION

Supramolecular organization of chromophores is essential for many high-tech applications, such as laser technology,<sup>1</sup> non-linear optics,<sup>2,3</sup> or supramolecular photochemistry.<sup>4</sup>

Common approaches to achieve a desired supramolecular alignment are the following: embedding of chromophoric guests in polymeric, crystalline, or liquid-crystalline host matrices, as well as covalent insertion of chromophoric monomers into the main-chain or into side-chains of polymers.<sup>2,3</sup>

Within our interest in the anisotropic order of nonpolymeric, chromophoric molecules in their condensed phases, we synthesized a number of new isatin derivatives with the aim to elucidate the nature of the supramolecular architecture and interactions in this new chromophoric family.

With respect to its molecular structure, isatin is best suited to serve as a highly variable tecton<sup>5,6</sup> for the construction of supramolecular assemblies because of its remarkable hydrogen bond acceptor/donor abilities and a comparably large molecular dipole moment. Two chemically different carbonyl oxygens resemble two hydrogen bond acceptor functions pointing toward different spatial directions, and the hydrogen attached to the amide nitrogen constitutes the hydrogen bond donor.

From a synthetic point of view, it is advantageous that all four peripheral positions of the isatin phenyl ring can be addressed by substitution in a straightforward way, each starting from the respective regioisomer of, for example, bromoisatin. The latter are synthetically easily accessible.<sup>7–9</sup> All the above-mentioned features make isatin exceedingly interesting for supramolecular engineering. In this contribution, we describe the synthesis and an unconventional crystal structure with a hydrogen bond supported chain formation of 5-(4-alkylphenyl)isatin derivatives. By analyzing its interesting crystal structure, we can cautiously

draw analogy conclusions about the situation in the liquid crystal phase of similar but slightly different isatin derivatives published earlier.<sup>10</sup> Though the prediction of the supramolecular architecture of a compound in its liquid crystalline phase on the basis of its crystal structure cannot be done, it is nonetheless reasonable to assume that dominant molecular interactions such as H-bonds, which are present in the crystal phase, may also exist in the mesophase.<sup>11</sup>

## EXPERIMENTAL SECTION

Syntheses. The synthesis of the new 5-(4-alkylphenyl)isatin derivatives 3a-e (Scheme 1) was accomplished in a straightforward manner: To probe an alternative approach to 1-bromo-4-alkylbenzenes, which usually are synthesized by a sequence of Friedel-Crafts acylation and subsequent Wolff-Kishner reduction,<sup>12</sup> we applied a modern iron mediated cross-coupling reaction<sup>13</sup> of alkyl bromides with phenyl magnesium chloride followed by bromination. This sequence leads to 1:3 mixtures of the respective ortho- and para-bromo alkyl benzenes, the tedious separation of which was omitted at this point. Rather, the products were converted to the respective boronic acids via bromine lithium exchange and quenching with trimethyl borate. At this stage, the 4-alkylphenyl boronic acids 2a-e could be separated by column chromatography. However, considering the selectivity problems and the chromatographic separation of the 4-alkylphenyl boronic acids, our new method provides no significant advantage compared to the traditional sequence. The boronic acid intermediates 2a-e were coupled with 5-bromoisatin (1) under Suzuki-Miyaura conditions to the desired 5-(4-alkylphenyl)isatins 3a-e.

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Table 1. Yields of the Suzuki-Miyaura Coupling and Thermal Data<sup>*a*</sup> of the Fusion Point of the Products 3a-e

| compd   | R                              | yield (%) | mp (°C) | ΔH <sub>fus</sub><br>(kJ/mol) | $\Delta S_{\rm fus}$<br>(J/(K mol)) |  |  |  |
|---|--------------------------------|-----------|---------|-------------------------------|-------------------------------------|--|--|--|
| 3a  | C <sub>6</sub> H <sub>13</sub> | 32        | 174.2   | 17.7                          | 39.6                                |  |  |  |
| 3b  | $C_8 H_{17}$                   | 39        | 169.3   | 19.9                          | 45.0                                |  |  |  |
| 3c  | $C_{10}H_{21}$                 | 32        | 165.9   | 20.6                          | 46.9                                |  |  |  |
| 3d  | $C_{12}H_{25}$                 | 34        | 159.6   | 21.0                          | 48.5                                |  |  |  |
| 3e  | $C_{14}H_{29}$                 | 24        | 154.8   | 22.1                          | 51.6                                |  |  |  |
| <sup><i>a</i></sup> Thermal data obtained by differential scanning calorimetry. |                                |           |         |                               |                                     |  |  |  |

As can be seen from Table 1, the yields of this Suzuki-Miyaura coupling were only moderate but delivered enough material for the further studies. The complete reaction sequence and all relevant analytical data are compiled in the Supporting Information.

Experimental Molecular and Crystal Structures. To our initial disappointment, the 5-(4-alkylphenyl)isatins 3a-e do not show enantiotropic liquid crystalline behavior.<sup>14</sup> Rather, they melt directly into the isotropic liquid with the phase transition parameters given in Table 1, but to our edification they permit a detailed insight into the supramolecular organization principles of this class of compounds, which is discussed below and which could not be obtained from other derivatives, e.g. from their alkoxy analogues. Apart from a new form of strand formation, hitherto not observed with isatin derivatives, this insight is valuable for the interpretation and understanding of the liquid crystalline behavior of the respective previously published 5-(4-alkyloxyphenyl)isatin derivatives, from which it was not possible to grow single crystals suitable for X-ray analysis.<sup>10</sup>

Figure 1 shows the highly interesting crystal structure<sup>15</sup> of 5-(4hexylphenyl)isatin (3a), which could be resolved and related to density functional theory calculations. The crystals were obtained by slow evaporation from a saturated chloroform solution.

The crystals of 3a are organized in layers, and these are formed by antiparallel arranged, slightly tilted strands of molecules. According to the Cambridge Structural Database (CSD),16 the supramolecular strands found in the case of 3a constitute a new type with respect to isatin derivatives.<sup>17</sup> Both half strands are very slightly different. But due to the only tiny differences, it is reasonable to discuss the structure with averaged values (standard deviation based on entire population given in parentheses).

The crystal structure of 3a reveals five different factors determining the three-dimensional crystal architecture: three different types of hydrogen bonds, dipole compensation, and  $\pi$ - $\pi$ -interactions.

For the topological description of hydrogen bond networks in organic crystals, a nomenclature based on graph theory has been developed and proven as a powerful tool to describe and compare them.<sup>18,19</sup> Following this



Figure 1. (a) Molecular strand in the crystal structure of 3a. Dotted lines represent hydrogen bonds ( $d_{\rm NH-O}$  = 1.94(2) Å, yellow, forming the C(4) motif, and  $d_{CH-O} = 2.29(1)$  Å, blue, forming the C(7) motif). (b) Crystal structure of 3a showing parts of two adjacent strands. The molecules of both chains are associated via  $\pi - \pi$ -interactions and by weak hydrogen bonds between the lateral phenyl groups with a hydrogen-centroid distance of 2.96(3) Å (green dashed lines). In this

nomenclature, a layer in the crystals of 3a would be called a network, made up mainly by two different motifs forming a basic graph set of  $N_1 = C(4)C(7)$ , describing the chains including either four or seven atoms before iteration (i.e., walking through the chain following the yellow dotted lines for C(4) or the blue dotted lines for C(7), respectively, in Figure 1). Both motifs combine to a complex graph set of  $N_2 = R_3^3(14)$ , which describes a ring structure of H-bonds between three donors and three acceptors involving 14 atoms.

way, each of the lateral phenyl rings is linked with both adjacent chains

(in the front and in the back).

The determining factor for the first dimension-the formation of the strand (cf. Figure 1a)—is the C(4)<sup>18,19</sup> hydrogen bond motif formed between the amide hydrogen and the 2-carbonyle function of the next molecule  $(d_{\rm NH-O} = 1.94(2)$  Å, yellow in Figure 1). At this hydrogen bond supported interface of the strand, the molecules are arranged syndiotactically; that is, their hydrophobic tails point out of the strand alternating to the opposite sides.

In such a strand, all the isatin headgroups point in the same direction; that is, in Figure 1a, all carbonyl functions point to the right while all the amine nitrogen atoms point to the left. This leads to an anticlinic setup causing a polar character of each strand.

A second, weak hydrogen bond motif is formed between the 6-hydrogen of 3a and the 3-carbonyl function of the next but one

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molecule of the same strand, which is the next molecule on the same side of the strand ( $d_{CH-O} = 2.29(1)$  Å, blue in Figure 1a). This second C(7) hydrogen bond motif additionally stabilizes the strand.

Both motifs together lead to a complex graph set describing a  $R_3^3(14)$  ring structure in which the C(4) motif contributes two H-bonds, while the C(7) motif participates with only one H-bond.

The second dimension of the supramolecular setup of 3a is opened by the formation of layers by juxtaposition of the above-discussed strands, cf. Figure 1b. Here, the organizing factors are the shape anisotropy of the strands, nanophase segregation of the polar aromatic heads from the apolar alkyl chains, and the polarity of each strand. The latter leads to an antiparallel alignment of adjacent strands so that their polarities cancel out and the overall layer is macroscopically not dipolar. In the adjacent strands of one layer, the molecules lie on top of each other (but with the above-described opposite orientation) with a face-to-face distance between the isatin head groups of 3.26(1) Å, which is close enough to allow  $\pi - \pi$ -interactions between them.

While the planes of all the isatin bicycles in the crystal structure of **3a** are arranged parallel to each other, the lateral phenyl rings organize in a fishbone-like manner in such a way that two (partially positively charged) hydrogen atoms of each phenyl ring point toward the (negatively charged)  $\pi$ -electron cloud of the lateral phenyl ring of a neighbored molecule in an adjacent strand. This third, weak hydrogen bond motif is a further cross-linking factor between adjacent chains and was not considered in the graph set analysis performed above.

The third dimension of the crystal is formed by stacking the abovedescribed bilayers on top of each other. At the interface between these layers, the alkyl chains point toward each other in a synclinic manner.

Within the layers, the plane of the strands is tilted by 14° with respect to the layer normal. Together with the polar order of the strand, this could lead to supramolecular chirality even from achiral molecules. Examples for such spontaneous formation of chirality are the so-called "banan"- or "bent-core"-liquid crystals.<sup>20–23</sup> However, since in the case of **3a** the neighboring polar strands are oriented into opposite directions, a supramolecular racemic situation is developed within the layers. But, the supramolecular chiral character of each tilted single strand in this crystal architecture possibly opens an opportunity to discriminate between both polar orientations (i.e., the "enantiomers") by introducing a *molecular* chirality and thus converting the *enantiomeric* situation of the antiparallel tilted strands into a *diastereomeric* and, thus, energetically distinct situation.

The formation of such hydrogen bond supported bilayers strongly recalls the formation of bilayers in smectic liquid crystals. Thus, we are confident that the experimental and theoretical findings described here for the 5-(4-alkylphenyl)isatins 3a-e can be applied to the rational design of isatin derived liquid crystals as well.

Despite the numerous isatin derivatives described in the literature,<sup>24</sup> only 16 crystal structures of 8 different compounds are registered in the CSD.<sup>16</sup> The tendency of isatin derivatives to form polymorphs is well described for the case of 7-fluoroisatin, exhibiting three different crystal structures with dimeric and tetrameric hydrogen bond motifs.<sup>25</sup> From the above-mentioned 16 crystal structures, the vast majority of 10 structures describe dimers; also, the stem compound isatin shows this type of organization.<sup>26</sup> In general, such homodromic dimers with a  $R_2^2(8)$  graph set, as, for example, the well-known dimers of carboxylic acids, are of frequent occurrence in nature.<sup>18,19</sup> Among the remaining six crystal structures, only one describes a strand, but which is of a different type compared to the one described here. In this other type of strand, the hydrogen bond linkage proceeds from the NH-group to the 3-carbonyl, forming a C(5) motif.<sup>27</sup>

**Computational Structures.** All calculations have been performed by employing the Becke three-parameter hybrid functional<sup>28</sup> with the correlation functional of Lee, Yang, and Parr<sup>29</sup> (B3LYP) in combination with the 6-311G(d) basis set as implemented in the Gaussian  $03^{30}$  (G03)



Figure 2. (a) Section of a molecular strand of 3a calculated under periodic boundary conditions (PBC), showing the C(4) hydrogen bond motif but lacking the C(7) one found in the crystal structure, cf. Figure 1a. (b) Calculated dimer of 3a showing the same hydrogen bond motif as found in the crystal structure<sup>26</sup> of unsubstituted isatin.

Table 2. Calculated (B3LYP/6-311G(d)) Energetic Data of 5-(4-Hexylphenyl)isatin (3a) and Isatin<sup>*a*</sup>

| compd  |         | $E_{\rm tot}$ (Hartree) | $\Delta E_{\rm tot}  ({\rm kJ/mol})$ |
|--------|---------|-------------------------|--------------------------------------|
| 3a     | monomer | -980.223062416          | 0                                    |
| 3a     | dimer   | -1960.47197137          | -67.9                                |
| 3a     | strand  | -1960.48711830          | -107.6                               |
| isatin | monomer | -513.18639588           | 0                                    |
| isatin | dimer   | -1026.39866586          | -67.9                                |
| isatin | strand  | -1026.41370584          | -107.4                               |

<sup>*a*</sup> In each case of the calculated structures of **3a**, several conformers are possible with respect to, for example, the orientation of the alkyl chain at the heterocycle or the relative arrangement of different molecules. Only the energetically most favored one is reported here.

program. For the monomers and dimers, the ground state character of the stationary points has been proven by frequency calculations, confirming the absence of any negative eigenvalues in the Hessian matrix. Unfortunately, the latter type of calculation is not possible with G03 under periodic boundary conditions (PBC), which were employed for the calculations of the strand. All computed structures are listed in detail in the Supporting Information.

In a preliminary theoretical DFT study, both primary organization models, the C(4)-strand (Figure 2a) and  $R_2^2(8)$  dimers (Figure 2b), could be reproduced.

For 5-(4-hexylphenyl)isatin (3a) and isatin, both types of organization constitute local minima. For both compounds, the energy gain  $\Delta E$  is calculated to be about -68 kJ/mol for the dimerization and about -107 kJ/mol for the strand formation (see Table 2); that is, in both cases, the strands are calculated to be favored by about  $\Delta\Delta E \approx 40$  kJ/mol compared to the dimers in these "gas-phase structures" (all values refer to the simple difference of the computed total energy without consideration of zero point energies or basis set superposition errors—which are not available for the PBC structures). That the energetic results for 3a and isatin are so similar is not surprising, since the computable intermolecular interactions are very similar in both cases and the only difference, the additional residue in 3a, is located far away from the direct molecular interaction.

However, regarding the experimental crystal structure of isatin, the calculated result is obviously untenable. But it has to be kept in mind that in these provisional calculations still a lot of molecular interactions are Table 3. Characteristic Measures from Computed (B3LYP/ 6-311G(d)) and X-ray Structures of the Different Aggregates of 5-(4-Hexylphenyl)isatin (3a) and Isatin<sup>*a*</sup>

| compd  |                            | d <sub>NH-O</sub><br>(Å) | d <sub>N-O</sub><br>(Å) | d <sub>со–н</sub><br>(Å) | d <sub>C2-N</sub><br>(Å) |
|--------|----------------------------|--------------------------|-------------------------|--------------------------|--------------------------|
| 3a     | strand, X-ray              | 1.94                     | 2.79                    | 2.29                     | 6.84                     |
| 3a     | strand, computed           | 1.85                     | 2.84                    | 2.51                     | 6.80                     |
| 3a     | dimer, computed            | 1.89                     | 2.89                    |                          | 3.62                     |
| isatin | dimer, X-ray <sup>26</sup> | 2.04                     | 2.93                    |                          | 3.58                     |
| isatin | strand, computed           | 1.84                     | 2.83                    | 2.54                     | 6.82                     |
| isatin | dimer, computed            | 1.88                     | 2.89                    |                          | 3.62                     |

<sup>*a*</sup>  $d_{\text{NH-O}}$ , distance between the hydrogen atom of the H-bond and the acceptor oxygen;  $d_{\text{N-O}}$ , distance between the donor group nitrogen and the acceptor oxygen of the next molecule;  $d_{\text{CO-H}}$ , distance between the 3-carbonyl oxygen and the phenyl 6-hydrogen of the adjacent molecule;  $d_{\text{C2-N}}$ , distance between C-2 and the nitrogen of the neighboring molecule located at the same half side.

not considered, e.g. the dipolar interactions between adjacent strains or dimers, van der Waals interactions, as well as any entropic influences or crystal packing effects (e.g., minimization of excluded volume etc.).

On the other hand, the calculated strand of 3a, computed under periodic boundary conditions, reproduces the structure found in the crystal quite well; a collection of characteristic measures, comparing the DFT calculations with the crystal structures of 3a and isatin is compiled in Table 3.

Differences between the computed and the X-ray determined structures appear with respect to the second, weak C(7) hydrogen bond motif in the strands of **3a**, which is not described properly by the DFT calculations. A second difference is that in the calculations the isatin heads of adjacent molecules (dimers and strands) lie exactly in the same plane, while in the crystal structures an offset occurs, leading to a little "step" between the molecules.

A very good agreement was found regarding the out-of-plane twist of the lateral phenyl groups of **3a**, for which the angle is  $38.4^{\circ}$  in the computed structure and, thus, only  $1.7^{\circ}$  smaller than the measured one.

At this stage of our study we concentrated on the supramolecular organization with respect to the first dimension only. Interactions between adjacent dimers or between adjacent strands have not yet been studied, since conventional DFT is known to perform only poorly with respect to weak intermolecular interactions, such as, for example, van der Waals or  $\pi - \pi$  interactions.<sup>31,32</sup> Therefore, the calculations presented here resemble just a qualitative measure for possible supramolecular aggregates.

Regarding the computed structures, a clear difference between the liquid crystalline alkoxyphenyl-substituted isatin derivatives<sup>10</sup> and the alkylphenyl derivatives of series **3** is that, in the case of the alkoxyphenyl substituents, the alkyloxy chain is situated in plane with the phenyl ring while, in the case of the alkylphenyl derivatives, the alkyl chain is arranged nearly perpendicular to the plane of the phenyl ring. These predilections for the orientation of the alkyl- or alkyloxy-chain can also be one reason for the different behavior of the two series with regard to their thermomesomorphism.

Concerning the melting process, it is reasonable to assume that the weakest H-bond, i.e. the C(7) pattern, breaks first, which gives the molecules a certain rotational freedom and opens the possibility of a dynamic equilibrium between the (almost infinite) C(4) strand, shorter but still linear fragments of it, cyclic structures, and the  $R_2^2(8)$  dimers. All these architectures differ in their degrees of freedom and, thus, in their entropic situation, in which the dimers are most favored.

#### CONCLUSION

The crystal architecture of the newly synthesized 5-(4-hexylphenyl)isatin (3) reveals a number of important intermolecular interactions which are effective between the molecules and which will help for the rational design of new functional materials (e.g., in the field of liquid crystals or crystal engineering) on the basis of this structural motif. The presented DFT studies support the experimentally found supramolecular basic units, i.e. dimers and strands, in a qualitative manner. However, at the level of theory chosen here, only the strongest hydrogen bonds could be reproduced in the calculated structures while all the weaker interactions remained neglected. For this reason, the quantitative energetical results of calculations at this level of theory concerning the supramolecular assemblies of isatin and its derivatives are not expressive for a deeper interpretation of the polymorphic variations.

The parallel spatial alignment of the chromophoric parts of the substituted isatins 3, the formation of supramolecular polar strands, and the high molecular dipole moment of the isatin headgroup might be technically applicable because of their anisotropy, possibly already with such crystalline compounds as 3, but particularly in derivatives which may form liquid crystalline, i.e. fluid, phases. Respective works are ongoing and will be reported elsewhere.

## ASSOCIATED CONTENT

**Supporting Information.** Instrumentation, synthetic procedures and analytical data (refraction index, IR-, <sup>1</sup>H-, <sup>13</sup>C NMR), crystal structure data including crystallographic information files (CIF), and DFT-computed structures. This material is available free of charge via the Internet at http://pubs.acs.org.

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#### REFERENCES

(1) Preiswerk, H. P.; Lubanski, M.; Kneubühl, F. K. Appl. Phys. B: Laser Opt. 1984, 33, 115–131.

(2) Ostroverkhova, O.; Moerner, W. E. Chem. Rev. 2004, 104, 3267-3314.

(3) Kajzar, F.; Lee, K.-S.; Jen, A. K.-Y. Polymeric materials and their orientation techniques for second-order nonlinear optics. In *Polymers for Photonics Applications II*; Springer-Verlag Berlin: Berlin, 2003; Vol. 161, pp 1–85.

(4) Ariga, K.; Kunitake, T. Supramolecular Chemistry—Fundamentals

and Applications; Springer Verlag: Berlin, Heidelberg, New York, 2006.
(5) Simard, M.; Su, D.; Wuest, J. D. J. Am. Chem. Soc. 1991, 113, 4696–4698.

(6) Su, D.; Wang, X.; Simard, M.; Wuest, J. D. Supramol. Chem. 1995, 6, 171–178.

(7) Borsche, W.; Jacobs, W. Ber. Dtsch. Chem. Ges. 1914, 47, 354–363.

(8) Sandmeyer, T. Helv. Chim. Acta 1919, 2, 234-242.

(9) Sadler, P. W. J. Org. Chem. 1956, 21, 169–170.

(10) Blunk, D.; Porada, J. ChemPhysChem 2009, 10, 3260-3264.

(11) Haase, W.; Athanassopoulou, M. Crystal Structures of LC Mesogens. In *Liquid Crystals I*; Mingos, D., Ed.; Springer: Berlin/ Heidelberg, 1999; Vol. 94, pp 139–197.

(12) Gray, G. W.; Hird, M.; Lacey, D.; Toyne, K. J. J. Chem. Soc., Perkin Trans. 2 1989, 2041–2053.

(13) Nakamura, M.; Matsuo, K.; Ito, S.; Nakamura, B. J. Am. Chem. Soc. **2004**, *126*, 3686–3687.

(14) Using polarization microscopy, we could observe a monotropic liquid crystalline phase far below the respective melting point of the 5-(4-alkylphenyl)isatin homologues with an alkyl chain of octyl or longer. This phase could not be caught by DSC due to preceding recrystallization.

(15) CCDC 722527 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/ data request/cif.

(16) CSD Version 5.30, Update 3.

(17) Unsubstituted isatin and several derivatives form dimers in their crystals. Some halogen substituted isatin derivatives form molecular chains of a different type, in which the amide hydrogen bond is linked to the oxygen atom of the 3-carbonyl group.

(18) Etter, M. C.; Macdonald, J. C.; Bernstein, J. Acta Crystallogr, Sect. B: Struct. Sci. 1990, 46, 256–262.

(19) Bernstein, J.; Davis, R. E.; Shimoni, L.; Chang, N. L. Angew. Chem., Int. Ed. Engl. 1995, 34, 1555–1573.

(20) Link, D. R.; Natale, G.; Shao, R.; Maclennan, J. E.; Clark, N. A.; Korblova, E.; Walba, D. M. Science **1997**, 278, 1924–1927.

(21) Reddy, R. A.; Tschierske, C. J. Mater. Chem. 2006, 16, 907–961.
(22) Takezoe, H.; Takanishi, Y. Jpn. J. Appl. Phys., Part 1 2006,

45, 597–625.
(23) Tschierske, C. Curr. Opin. Colloid Interface Sci. 2002, 7, 69–80.

(24) As of September 2010, CAS lists 1768 isatin derivatives as single compounds in which the heterocycle, both carbonyl functions, and the NH-group are neither substituted nor modified.

(25) Mohamed, S.; Barnett, S. A.; Tocher, D. A.; Price, S. L.; Shankland, K.; Leech, C. K. *CrystEngComm* **2008**, *10*, 399–404.

(26) Palenik, G. J.; Koziol, A. E.; Katritzky, A. R.; Fan, W. Q. J. Chem. Soc., Chem. Commun. 1990, 715–716.

(27) Garden, S. J.; Pinto, A. C.; Wardell, J. L.; Low, J. N.; Glidewell, C. Acta Crystallogr., Sect. C: Cryst. Struct. Commun. 2006, 62, O321–O323.

(28) Becke, A. D. J. Chem. Phys. 1993, 98, 5648-5652.

(29) Lee, C. T.; Yang, W. T.; Parr, R. G. Phys. Rev. B 1988, 37, 785-789.

(30) Frisch, M. J.; et al. *Gaussian 03*, Revision D.02; Gaussian Inc.: Wallingford, CT, 2004.

(31) Szalewicz, K.; Patkowski, K.; Bogumil, J. Intermolecular Interactions via Perturbation Theory: From Diatoms to Biomolecules. In *Intermolecular Forces and Clusters II*; Springer-Verlag: Berlin, Heidelberg, 2005; Vol. 116, pp 43–117.

(32) Wu, X.; Vargas, M. C.; Nayak, S.; Lotrich, V.; Scoles, G. J. Chem. Phys. 2001, 115, 8748–8757.