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Synthesis and Spectroscopic Investigation of Aggregation through Cooperative π–π and C–H···O Interactions in a Novel Pyrene Octaaldehyde Derivative[†]

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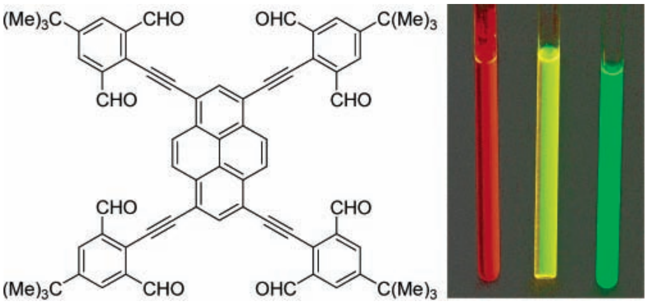
ABSTRACT



Synthesis of a pyrene octaaldehyde derivative and its aggregation through π–π and C–H···O interactions in solution and in the solid state probed by fluorescence emission and other spectroscopic methods are reported. The effect of solvent, concentration, and temperature on the aggregation is investigated.

Weak noncovalent intermolecular interactions such as hydrogen bonding and $\pi-\pi$ and van der Waals interactions, to name a few, are important in chemistry, materials science, and biology.[1] Conventional hydrogen bonds of the type X−H···Y are widely found in chemical and biochemical systems and have been thoroughly studied from both experimental and theoretical perspectives.[2] Supramolecular aggregation through $\pi-\pi$ interactions is found in many polycyclic aromatic hydrocarbons and superacenes.[3] The much weaker C−H···X and C−H···π interactions are now being increasingly observed and accepted.[4] For example, C−H···O interactions have been recognized to play an important role in the stabilization and function of biological

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[†] Dedicated to Professor Dr. Henning Hopf on the occasion of his 65th birthday.

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(1) (a) Desiraju, G. R.; Steiner, T. *The Weak Hydrogen Bond in Structural Chemistry and Biology*; Oxford University Press: Oxford, 1999. (b) Lehn, J.-M. *Supramolecular Chemistry: Concepts and Perspectives*; VCH: Weinheim, 1995. (c) Müller-Dethlefs, K.; Hobza, P. *Chem. Rev.* **2000**, *100*, 143−167.

(2) (a) Desiraju, G. R. *Crystal Engineering: The Design of Organic Solids*; Elseiver: Amsterdam, 1989; Chapter 5, pp 115−165. (b) Jeffrey, G. A.; Saenger, W. *Hydrogen Bonding in Biological Structures*; Springer-Verlag: Berlin, 1991. (c) Scheiner, S. *Hydrogen Bonding: A Theoretical Perspective*; Oxford University Press: Oxford, 1997. (d) For H-bonding interactions in globular proteins, see: Baker, E. N.; Hubbard, R. E. *Prog. Biophys. Mol. Biol.* **1984**, *44*, 97−197.

(3) (a) Bendikov, M.; Wudl, F.; Perepichka, D. F. *Chem. Rev.* **2004**, *104*, 4891−4945. (b) Watson, M. D.; Fechtenkötter, A.; Müllen, K. *Chem. Rev.* **2001**, *101*, 1267−1300. (c) Sokolov, A. N.; Friscic, T.; MacGillivray, L. R. *J. Am. Chem. Soc.* **2006**, *128*, 2806−2807. (d) Claessens, C. G.; Stoddart, J. F. *J. Phys. Org. Chem.* **1997**, *10*, 254−272.

(4) (a) Moorthy, J. N.; Natarajan, R.; Venugopalan, P. *J. Mol. Struct.* **2005**, *741*, 107−114. (b) Moorthy, J. N.; Natarajan, R.; Mal, P.; Venugopalan, P. *J. Am. Chem. Soc.* **2002**, *124*, 6530−6531. (c) Desiraju, G. R. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2311−2327.

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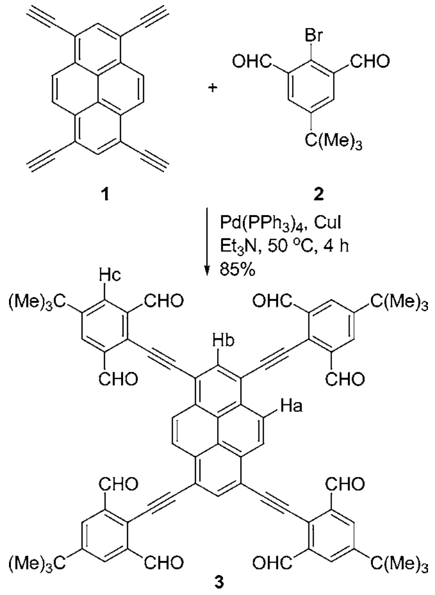
macromolecules.[5] It has been estimated that in some protein–protein complexes the contribution of C–H···O interactions can reach as high as 40–50% to the overall stabilization of the intermolecular interactions.[6] Although very weak in nature, their presence in sheer large numbers can result in the overall stabilization of molecular aggregates. Herein, we report the cooperative effect of π–π and C–H···O interactions in a novel pyrene octaaldehyde derivative resulting in molecular aggregation evidenced by various spectroscopic techniques.

Recently, we have reported a methodology for the synthesis of polyal dendrimers.[7] In this connection, we now report the synthesis of a pyrene-based octaaldehyde **3** starting from 1,3,6,8-tetraethynylpyrene (**1**)[8] and 2-bromo-5-*tert*-butylisophthalaldehyde (**2**)[7] using Sonogashira coupling (Scheme 1). Compound **3** is a dark red fluorescent solid.

Scheme 1. Synthesis of Octaaldehyde **3**



The ^{1}H NMR spectrum showed three singlets in the aromatic region (Ha, Hb, Hc), one singlet for the aldehyde protons, and one singlet for the *tert*-butyl protons in the ratio 1:2:4:4:18, consistent with the symmetrical tetra-substituted structure of **3**. Its color in solution depended on the solvent and concentration. For example, in cyclohexane (10^{-5} M) the solution was dark red and in acetonitrile and methanol it was yellow. In dichloromethane, the color depended on the concentration (see Supporting Information). The UV–vis spectra of **3** in two solvents are shown in Figure 1. In CH_2Cl_2, three absorption bands were observed for **3** at λ_{max} of 360, 465 (sh), and 488 nm. More importantly, in CH_2Cl_2, the cutoff of the absorption was very sharp and beyond 525 nm there was no absorption. A similar pattern was observed in CH_3CN and MeOH. In cyclohexane, the absorption bands were broader and only two bands were observed at λ_{max} of 364 and 481 nm along with a long tail absorption extending up to 600 nm. At higher concentrations of **3**, this tail band appeared as a shoulder more clearly. This striking difference in the color and the absorption spectrum of **3** in cyclohexane compared to the more polar solvents indicated that **3** might be aggregating in cyclohexane.[9]

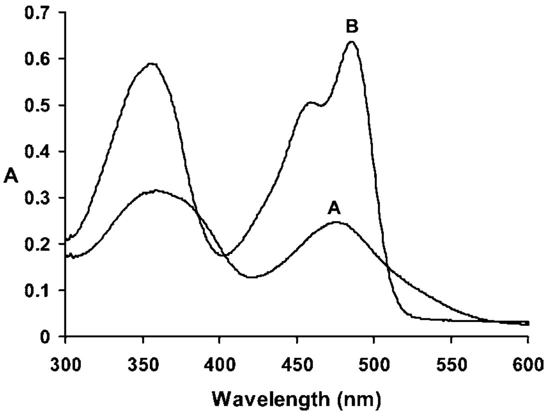


Figure 1. Absorption spectra of **3** in cyclohexane (A) and CH_2Cl_2 (B) at ~10^{-5} M concentration.

Investigation of the fluorescence emission of **3** in various solvents gave more insight. Visibly, the fluorescence of **3** under room light in cyclohexane was orange–red, which was again strikingly different from the more polar solvents. For example, in CH_2Cl_2, MeOH, and CH_3CN, compound **3** gave a greenish fluorescence emission. In CH_2Cl_2, the fluorescence emission of **3** (10^{-5} M) appeared at λ_{max} = 510 nm with a shoulder band at 542 nm (Figure 2). This pattern is very characteristic of several 1,3,6,8-tetraethynylpyrene derivatives reported recently from our laboratory.[8] It corresponds to the monomer emission of the pyrene chromophore.[10] The emission spectrum was invariant with the wavelength of excitation. The spectra obtained in CH_3CN and MeOH were very similar to the that in CH_2Cl_2. However, in cyclohexane (10^{-5} M), besides the monomer emission which appeared at λ_{max} = 500 nm, a broad band at λ_{max} = 612 nm also appeared (Figure 2). Compound **3** showed fluorescence emission in the solid state as well (Figure 2). The spectrum obtained in the solid state showed only one emission band at λ_{max} = 638 nm. The long wavelength band in cyclohexane and in the solid state is assigned to the emission of the excimer.

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(5) (a) Egli, M.; Gessner, R. V. *Proc. Natl. Acad. Sci. U.S.A.* **1995**, *92*, 180–184. (b) Berger, I.; Egli, M.; Rich, A. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 12116–12121. (c) Ornstein, R. L.; Zheng, Y. J. *J. Biomol. Struct. Dyn.* **1997**, *14*, 657–665. (d) Takahara, P. M.; Frederick, C. A.; Lippard, S. J. *J. Am. Chem. Soc.* **1996**, *118*, 12309–12321.

(6) Jiang, L.; Lai, L. *J. Biol. Chem.* **2002**, *277*, 37732–37740.

(7) Narayanan, V.; Sankararaman, S.; Hopf, H. *Eur. J. Org. Chem.* **2005**, 2740–2746.

(8) Venkataramana, G.; Sankararaman, S. *Eur. J. Org. Chem.* **2005**, 4162–4166.

(9) For the effect of concentration on the color and absorption spectrum of perylene biamide dyes, see: (a) Würthner, F. *Chem. Commun.* **2004**, 1564–1579. (b) Würthner, F.; Thalacker, C.; Diele, S.; Tschierske, C. *Chem.–Eur. J.* **2001**, *7*, 2245–2253.

(10) (a) Berlman, I. B. *Handbook of Fluorescence Spectra of Aromatic Molecules*; Academic Press: New York, 1965; p 173. (b) Winnik, F. M. *Chem. Rev.* **1993**, *93*, 587–614.

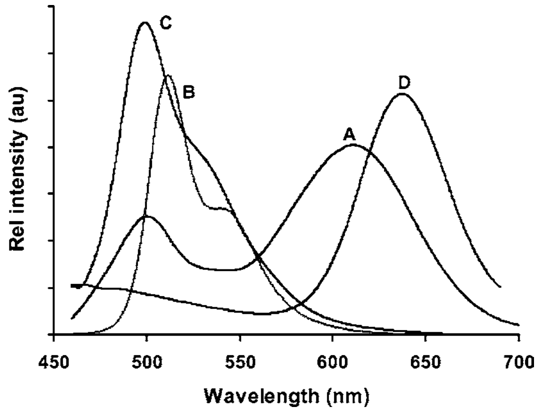

Figure 2. Fluorescence emission spectra of **3** (1×10^{-5} M) in cyclohexane (A), CH_2Cl_2 (B), MeOH (C), and in the solid state (D). $\lambda_{ex} = 362$ nm.

The effect of concentration on the fluorescence emission is shown in Figure 3. At very low concentrations (10^{-8} M), the emission corresponding to only the monomer was observed. With increasing concentration of **3**, the intensity of the emission band at 612 nm increased, indicating that this band is due to the excimer emission.[11]

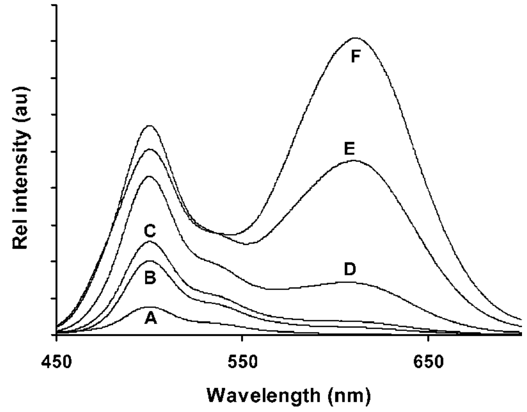

Figure 3. Effect of concentration on the fluorescence emission of **3** in cyclohexane. (A) 5×10^{-8} M, (B) 1×10^{-7} M, (C) 5×10^{-7} M, (D) 1×10^{-6} M, (E) 5×10^{-5} M, (F) 1×10^{-5} M. $\lambda_{ex} = 362$ nm.

Pyrene itself does not exhibit excimer emission at concentrations of 10^{-5} M and below. *It must also be emphasized here that neither 1-phenylethynylpyrene*[12] *nor the various derivatives of 1,3,6,8-tetraethynylpyrene*[8] *(including 1,3,6,8-tetraphenylethynlpyrene) showed excimer emission at 10^{-5} M and even higher concentrations*. Compound **3**, despite bearing bulky *tert*-butyl groups on the periphery,[13] showed excimer emission even at concentrations as low as 10^{-6} M (Figure 3). Therefore, we conclude that in compound **3** the eight aldehyde functional groups placed symmetrically in the molecule must play a role in promoting the intermolecular interactions. One possible explanation is that in the solid state as well as in nonpolar solvents such as cyclohexane there are intermolecular $\pi-\pi$ and C$-$H···O interactions that bring two molecules of **3** close enough to result in excimer emission.

Although a very weak hydrogen bond, the presence of several aldehyde groups can result in the formation of multiple C$-$H···O interactions resulting in the stabilization of a molecular dimer or an aggregate. It is also possible that in the solid state there are extensive intermolecular interactions in the crystal lattice arising from extended C$-$H···O and $\pi-\pi$ interactions. The larger bandwidth and the tail absorption extending up to 600 nm in cyclohexane support the notion that strong intermolecular interactions exist even in the ground state.[9]

Calculations have shown that C$-$H···O interactions occur favorably at a distance of ~3.3 Å which is also an ideal distance for intermolecular $\pi-\pi$ interaction.[14] In compound **3**, perhaps a combination of several intermolecular C$-$H···O interactions and $\pi-\pi$ interactions results in the formation of molecular aggregates in the solid state and in a nonpolar solvent such as cyclohexane. Solvents of high polarity and strong hydrogen bonding solvents disrupt the weak C$-$H···O interactions resulting in the dissociation of the molecular aggregates, and hence, only monomer emission occurs from such solvents. In the present study, also only a monomer emission was observed in more polar solvents. Further evidence for molecular aggregation comes from the dependency of proton NMR chemical shifts of **3** on the concentration and the temperature. Upon increasing the temperature from 25 to 60 °C, the pyrene protons were gradually shifted to higher δ values from 8.21 (Ha) and 7.98 (Hb) to 8.33 and 8.12 ppm, respectively (Scheme 1) (Figure 4). The

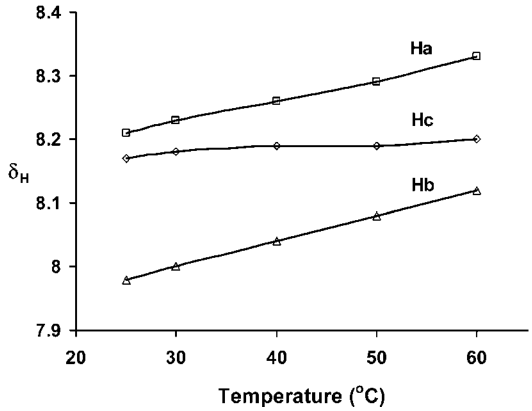

Figure 4. Effect of temperature on proton NMR chemical shifts of **3**.

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(11) For examples of π-stacking interactions in pyrene and excimer emission, see: (a) Vero, A.; Suzuki, I.; Osa, T. *J. Am. Chem. Soc.* **1989**, *111*, 6391−6397. (b) Chou, T.-C.; Hwa, C.-L.; Lin, J.-J.; Liao, K.-C.; Tseng, J.-C. *J. Org. Chem.* **2005**, *70*, 9717−9726. (c) Yuasa, H.; Miyagawa, N.; Izumi, T.; Nakatani, M.; Izumi, M.; Hashimoto, H. *Org. Lett.* **2004**, *6*, 1489−1492. (d) Nishizawa, S.; Kaot, Y.; Teramae, N. *J. Am. Chem. Soc.* **1999**, *121*, 9463−9464. (e) Lee, S. H.; Kim, S. H.; Kim, S. K.; Jung, J. H.; Kim, J. S. *J. Org. Chem.* **2005**, *70*, 9288−9295.

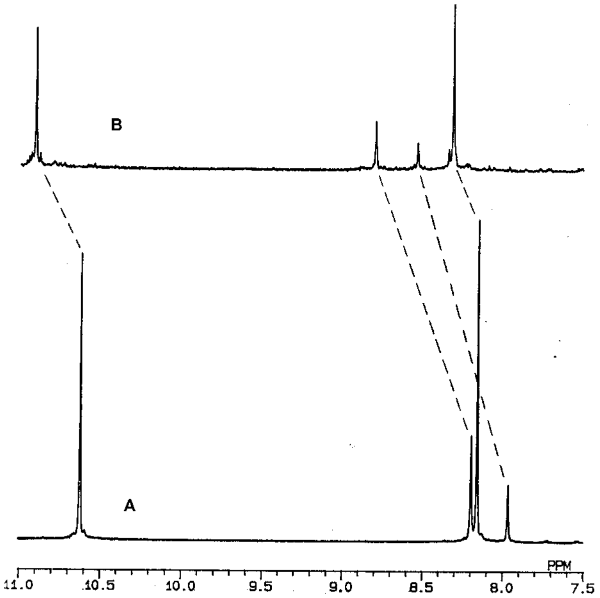

Figure 5. Concentration-dependent ^{1}H NMR spectra of **3** in $CDCl_3$ (400 MHz). (A) 4 × 10^{-2} M, (B) 8 × 10^{-3} M at 25 °C.

aldehyde protons were also shifted from 10.64 at 25 °C to 10.70 at 60 °C. The *tert*-butyl protons and Hc protons were relatively unaffected. *It should be noted that in several of the tetraethynyl-substituted pyrene derivatives the NMR chemical shift values of the pyrene protons were 8.5−8.8 (Ha) and 8.2−8.5 (Hb) ppm, much more deshielded than protons of* ***3***.[8]

The shielding of the pyrene protons in **3** cannot be entirely due to the anisotropic effects of the aldehyde groups because dilution of the NMR sample had the same effect, i.e., the more diluted the solution the higher the δ values for the protons. The chemical shifts of the CHO, Ha, Hb, and Hc protons were 10.64, 8.21, 7.98, and 8.17, respectively, at 4 × 10^{-2} M concentration and were shifted to 10.92, 8.81, 8.55, and 8.33 at 8 × 10^{-3} M concentration in $CDCl_3$ (Figure 5). The chemical shifts of CHO and Ha and Hb were relatively more deshielded than Hc upon dilution. From these results, we infer that the aggregates can be broken up by dilution as well as by raising the temperature. Molecular aggregation through $\pi-\pi$ and other weaker interactions generally results in the shielding of the protons resulting in lower δ values in the NMR spectrum compared to that of the monomeric species.[15]

On the basis of the spectroscopic evidence, we conclude that octaaldehyde **3** is a novel molecule wherein cooperativity of the $\pi-\pi$ and C−H···O interactions results in molecular aggregation in nonpolar solvents as well as in the solid state. In view of its solid-state fluorescence, octaaldehyde **3** and its derivatives might find applications in the field of molecular optoelectronics.

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Supporting Information Available: Experimental procedures, spectral data, copies of ^{1}H and ^{13}C NMR spectra, and temperature-dependent ^{1}H NMR spectra of **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(12) Yang, S.-W.; Elangovan, A.; Hwang, K.-C.; Ho, T.-I. *J. Phys. Chem. B* **2005**, *109*, 16628−16635.

(13) For π-stacking of acenes bearing bulky peripheral substituents, see: Antony, J. E.; Brooks, J. S.; Eaton, D. L.; Perkin, S. R. *J. Am. Chem. Soc.* **2001**, *123*, 9482−9483.

(14) Scheiner, S.; Kar, T.; Gu, Y. *J. Biol. Chem.* **2001**, *276*, 9832−9837.

(15) For temperature-dependent NMR due to π-stacking and aggregation, see: (a) Watson, M. D.; Jäckel, F.; Severin, N.; Rabe, J. P.; Müllen, K. *J. Am. Chem. Soc.* **2004**, *126*, 1402−1407. (b) Fechtenkötter, A.; Saalwächter, K.; Harbison, M. A.; Müllen, K.; Spiess, H. W. *Angew. Chem., Int. Ed.* **1999**, *38*, 3039−3042. (c) Shetty, A. S.; Fischer, P. R.; Storck, K. F.; Bohn, P. W.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 9409−9414.