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NMR spectroscopy

A Molecular Level Approach To Elucidate the Supramolecular Packing of Light-Harvesting Antenna Systems

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Abstract: The molecular geometry and supramolecular packing of two bichromophoric prototypic light harvesting compounds **D1A2** and **D2A2**, consisting of two naphthylimide energy donors that were attached to the 1,7 bay positions of a perylene monoimide diester energy acceptor, have been determined by a hybrid approach using magic angle spinning NMR spectroscopy and electron nano-crystallography (ENC), followed by modelling. NMR shift constraints, combined with the $P\bar{1}$ space group obtained from ENC, were used to generate a centrosymmetric dimer of truncated perylene fragments. This racemic packing motif is used in a biased molecular replacement approach to generate a partial 3D electrostatic scattering potential map. Resolving the structure of the bay substituents is guided by the inversion symmetry, and the distance constraints obtained from heteronuclear correlation spectra. The antenna molecules form a pseudocrystalline lattice of antiparallel centrosymmetric dimers with pockets of partially disordered bay substituents. The two molecules in a unit cell form a butterfly-type arrangement. The hybrid methodology that has been developed is robust and widely applicable for critical structural underpinning of self-assembling structures of large organic molecules.

Introduction

About halfway into the transition to a sustainable energy system, our societies are running up against a wall with solar energy conversion. While photovoltaics is expected to grow rapidly from the current 0.5 %, its production needs to be balanced with the demand by fuels. Currently the only sustainable route to renewable fuels is from photosynthesis via biomass, which contributes 10 % to the energy mix and is the benchmark by a wide margin. Although it is both sustainable and affordable, it is not scalable and therefore insufficient. The compelling advantage of natural photosynthesis is that proteins perform non-adiabatic conversions at avoided crossings, to minimize thermodynamic losses when breaking and making chemical bonds. These losses are detrimental in adiabatic conversion cascades where equilibrium is maintained, such as in separate photovoltaic (PV) and electrolysis, or photoelectrochemical (PEC) conversion. To mimic the primary processes of photosynthesis in artificial systems is a prime challenge on the way to an energy efficient zero or negative carbon emission energy system. It requires engineering novel pseudocrystalline chiral nanomaterials, based on chemically robust molecular building blocks with structural control over the conformational dynamics.[1] The rational design of such biomimetic artificial responsive matrix materials cannot proceed without knowledge of their 3D structure.[2]

Here we introduce a novel hybrid approach for determining packings of pseudocrystalline materials that combines magic angle spinning (MAS) NMR spectroscopy with electron nanocrystallography (ENC). It selectively averages the static and dynamic heterogeneity and allows the extrapolation of the short and medium range order. To demonstrate its use, we elucidate the first 3D packings of a set of perylene monoimide diester light-harvesting antenna molecules. These are large molecules that consist of a central perylene energy acceptor to which two naphthylimide energy donors were attached by phenoxy spacers at the 1,7 bay positions of the perylene core (Figure 1).[3–5] The non-conjugated phenoxy bridge provides very little electronic communication between the constituent chromophores, which is necessary to suppress intramolecular electron transfer that would shorten the life time of the excited state and compromise the light harvesting antenna function.[6] Perylenes are very stable and have a high fluorescence quantum

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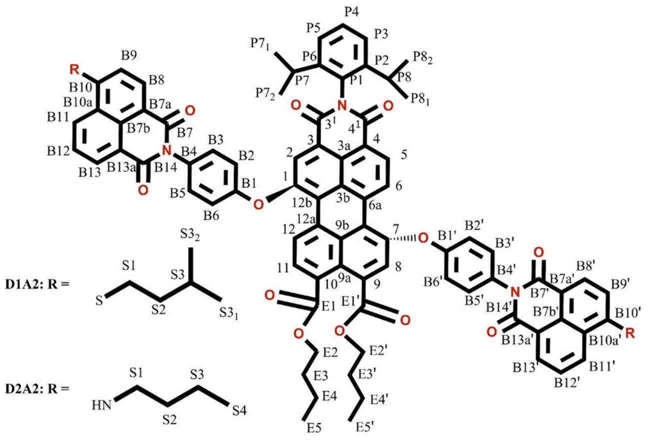

Figure 1. Chemical structure of **D1A2** and **D2A2**, which is an asymmetric perylene with a phenoxy derivative of napthalenemonoimide as bay substituents. Here the perylene core is numbered based on the conventional numbering scheme while the bay substituents are numbered starting with B1 and B1′. Similarly, imide substituents as P1 and ester alkyl groups as E1 and E1′.

yield. In toluene solution it was shown that these two antenna molecules exhibited ultrafast energy transfer from the naphthylimide donor to the perylene acceptor within 1 ps, while charge transfer within the antenna molecules was absent.[3] This implies that ideal antenna behaviour is achieved for these multiple antenna molecules that absorb strongly in the visible region of the solar spectrum.

Results and Discussion

For the two bichromophoric light harvesting donor-acceptor molecules **D1A2** and **D2A2**, the space group was obtained from the ENC diffraction data (Table 1). Centrosymmetric perylene dimer cores were resolved with MAS NMR shift and distance constraints obtained from heteronuclear ^{1}H-^{13}C dipolar correlation (HETCOR) data collected from samples with ^{13}C at natural abundance. While the perylene core does not possess any stereogenic centre, core chirality is induced by steric interactions between the bay substituents and the bay hydrogens at C6 and C12.[6f] The perylene dimer motif was used to phase the limited diffraction response and resolve the electron density in the unit cell by molecular replacement. In addition, intermolecular ^{1}H-^{13}C correlations between aliphatic tails and naphthalene monoimide were used to position the *N*-phenoxy naphthylimide energy donors, which are disordered beyond diffraction.

Table 1. Data processing statistics XDS: electron diffraction data of **D1A2** and **D2A2** was successfully indexed using the XDS software package.[a]

	D1A2	D2A2
space group	$P\bar{1}$	$P\bar{1}$
cell dimensions		
a, b, c [Å]	14.53, 15.55, 19.53	11.76, 17.12, 20.13
α, β, γ [°]	96.36, 107.15, 108.89	111.47, 90.88, 104.72
resolution [Å]	5.38–1.92 (2.03–1.92)	2.0 (2.12–2.00)
R_{sym} [%]	13.3 (21.2)	8.4 (49.9)
I [σ]	3.13 (1.72)	4.05 (1.94)
R_{meas} [%]	18.8 (30.0)	11.8 (7.06)
$CC_{1/2}$	97.9 (96.2)	99.2 (32.4)
completeness [%]	25.2 (26.1)	49.2 (49.2)
redundancy	1.93 (1.88)	1.27 (1.27)

[a] Highest resolution shell is shown in parenthesis.

The NMR shifts are sensitive to molecular conformation and (pseudo-)symmetry. As the two halves of the molecule provide nearly identical chemical shifts, this helps to constrain the packing. Also, there is little difference between solution and solid-state shifts, which implies that partial disorder or non-periodicity may be essential to relax the packing on the mesoscale. The ^{13}C CP/MAS spectrum for **D1A2** is shown in Figure S1 (Supporting Information). The two compounds only differ in the 4- and 4′ substituents at the naphthylimides, noted by B10 and B10′ in Figure 1, and the CP/MAS NMR responses for the **D1A2** and **D2A2** homologues are very similar. Diverse functionalities present in the molecule lead to a good dispersion of resonances and the ^{13}C shifts were assigned by comparison with the solution NMR assignment (Table S1 and S2 in Supporting Information). With solid-state dipolar heteronuclear ^{1}H-^{13}C correlation spectra collected from the **D1A2** system with a short mixing time of 256 μs, directly bonded ^{13}C-^{1}H pairs can be resolved (Figure S2–Figure S4). Although the two naphthalene monoimides are attached to different bay positions, their NMR responses overlap, revealing similar environments for the two donors, due to a pseudosymmetric packing. In Figure 2, dipolar heteronuclear ^{1}H-^{13}C correlation data collected from the **D1A2** with a longer mixing time of 1 ms are shown. The assignments of the intermolecular ^{1}H-^{13}C correlations are indicated in the figure. The cross peak at 0.94 ppm ^{1}H shift and 127.35 ppm ^{13}C shift between the B12 or B12′ ^{13}C and the E5 or E5′ ^{1}H is attributed to intermolecular transfer. The B12 and B12′ ^{13}C are located at the naphthalene monoimide of the bay substituent and the E5 and E5′ ^{1}H are at the terminal methyl of the aliphatic chain attached to the perylene core. Intramolecular long-range transfer across the same molecule would require a pronounced conformational change with respect to the relaxed, extended state that would compromise the general similarity between solution and solid-state shifts. Similarly, a correlation signal between the E4 or E4′ ^{1}H and the B9 or B9′ ^{13}C is assigned to intermolecular transfer, since naphthalene monoimide is too far from the alkyl chain attached to the perylene core for intramolecular transfer. In addition, a long-range correlation signal can be observed between aromatic protons and aliphatic carbons, represented as E3′, E3 ^{13}C and B8′, B8 ^{1}H in Figure 2, which is also an intermolecular correlation. Figure S4 shows the related dipolar heteronuclear ^{1}H-^{13}C correlation data collected with a long mixing time of 1 ms for the **D2A2** homologue. For both systems a correlation between 2H and 8C in the perylene core is attributed to intermolecular transfer, since the intramolecular distance of 8 Å is too large to detect a dipolar transfer event. This correlation points to centrosymmetric dimers of perylenes with opposite core chirality. Extensive investigation of perylene bisimides has provided convincing evidence that packing-induced core chirality

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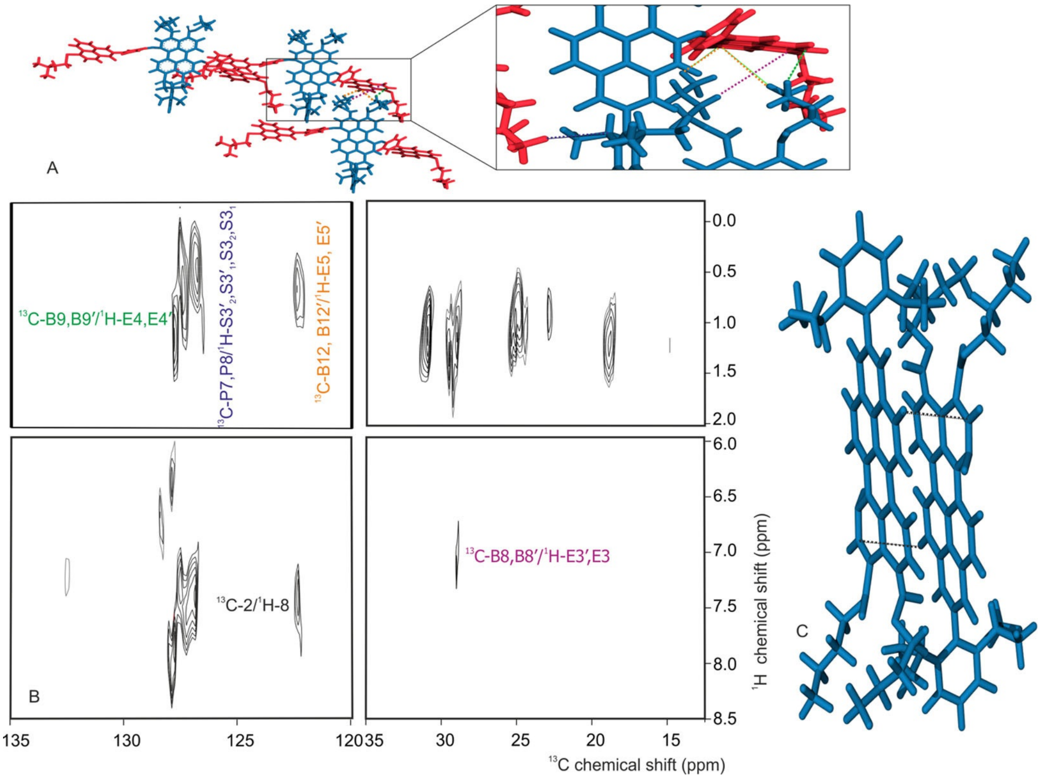

Figure 2. (A) ^{13}C-^{1}H 2D HETCOR spectra of **D1A2** with ^{13}C at natural abundance collected at room temperature with 1 ms mixing time. The MAS frequency and the number of scans are 13 kHz and 1 k, respectively. Intermolecular correlations for resolving the packing are indicated. The HETCOR spectrum is divided into four panels. The left bottom part indicates the interaction of the aromatic region with aromatic protons, whereas the left top indicates the interaction of aliphatic protons with aromatic carbons and the right bottom indicates the interaction between aromatic protons and aliphatic carbons that are unique to find the position of tails. Intermolecular correlations are labelled following the numbering scheme in Figure 1. The $P\bar{1}$ symmetry obtained from ENC reveals an antiparallel arrangement, which validates the C2-H8 correlation derived from the MAS NMR.

can lead to centrosymmetric dimers in a racemic material or J-aggregate formation for the pure enantiomer.[6f] A long-range correlation between the 2, 6-diisopropyl phenyl P7 and P8 ^{13}C in **D1A2**, with the proton response associated with the terminal S3$_1$, S3$_2$, S3$_1$′ and S3$_2$′ methyl groups on the isopentyl thiol, should be intermolecular. The B7b, B7′ ^{13}C in the naphthalene monoimide correlate with aliphatic protons on the isopentyl chain of **D1A2**. Additional information on the arrangement of the tails in the packing is obtained from correlations between ^{13}C nuclei at the aliphatic S2/S2′ and E4/E4′ positions with aromatic protons (Figure 2).

ENC was applied to collect electron diffraction data from single flat nanocrystals of **D1A2** and **D2A2** (Figure 3 and Figures S5,S6). Compound **D2A2** shows more reflections than for **D1A2**, due to less disorder in the **D2A2** crystal structure. To resolve the principle elements of the packing, rather than solving a structure at high resolution, which is meaningless in a heterogeneous environment, we use the sparse diffraction in reciprocal space to average the static and dynamic heterogeneity. This parallels the computational integration of MAS NMR spectra and Fourier transforms of plain cryo-TEM images that was recently developed to elucidate supramolecular packings in more favourable cases, where distinct diffraction conditions such as a layer line or systematic absences facilitate resolving the symmetry.[7] An ENC experiment allows direct observation of the scattering intensity in 3D reciprocal space, to determine the unit cell parameters and the Laue class of the packing. We used the different building blocks of the supramolecular structure as trial models to determine that mainly the perylene part is diffracting, and that phenoxy and naphthyl monoimide fragments are partially disordered or mobile and do not give rise to nonzero structure factors in the ENC. The density of perylene type solids is ≈1.25 g cm^{-3}.[8] Based on the unit cell volume and the space group $P\bar{1}$, there should be two molecules in the unit cell, that is, $Z=2$. The model bias in the mo-

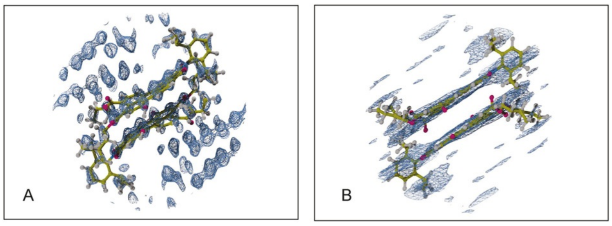

Figure 3. Reconstruction of electron density maps in real space from ENC recorded diffraction data of **D2A2** (A) and **D1A2** (B) in reciprocal space by integration with MAS NMR. The density map obtained by molecular replacement reveals the dimeric centrosymmetric perylene motifs in the unit cell. This is well in line with the NMR distance constraint between 8H and 2C. Hence, perylene dimers with pseudo C_2 symmetry form the basic building block on which the bay substituents are grafted.

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lecular replacement allows us to add relevant phase angles to the scattering intensities and generate a low resolution electrostatic scattering potential map in the unit cell for positioning of molecules with NMR shift and distance constraints (Figure 3).

In molecular replacement analyses with naphthalene monoimide and isopentylthio fragments, the match with the electron density map was rather poor, compared to the perylene core trial structure. For the naphthalene monoimide, which is a rigid object with a molecular weight of 197 Da, the molecular replacement reproduces an electron density of the centrosymmetric perylene dimer. On the one hand this gives confidence that molecular bias helps to converge upon the desired result, whereas on the other hand it confirms that the diffracting species is primarily the perylene. In contrast, naphthalene monoimide predominantly represents the disordered or mobile fraction not involved in coherent scattering. With the principal scattering component positioned in the unit cell (Figure 3 B), the bay substituents can be attached with naphthalene monoimide positioned in between perylene dimers for geometry optimization by classical molecular mechanics in the periodic lattice (Figure 4). Propeller-shaped centrosymmetric dimers with P and M chirality are positioned diagonally across the unit cell, with the 2,6-diisopropylphenyl group approximately orthogonal to the perylene plane, to reduce steric hindrance.[9] A 3D network is formed by the stretched phenoxy and naphthalene monoimide bay substituents, which extend towards the second row of perylene dimers, and positioning the naphthalene monoimide donor blocks that are subject to static and dynamic disorder in the NMR, and do not contribute to the electron density map from the ENC, in between the more rigid perylene dimers of the first next row (Figure 4). In this way both rigidity and softness can be realized within the same scaffolding, which paves the way for the design and engineering of advanced, responsive matrix type artificial photosynthesis materials. The molecules self-assemble in a racemic packing of P and M enantiomers with core-induced handedness. In the electron density map and the model structure, the distance between perylene planes in the dimer is ≈0.41 nm after modelling, which compares well with the short distance of 0.34 nm that has been reported before in X-ray structures for perylene dimers without bay substituents.[10]

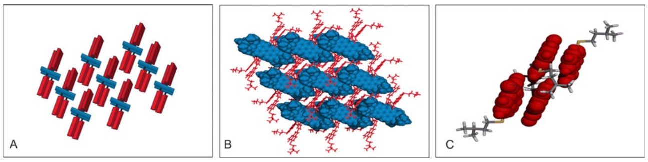

Figure 4. Schematic representation of the packing of **D1A2** (A). The channels of perylene dimers with NMI projecting outwards (B). (C) Columns of NMI form a matrix around the perylene.

In solution, it has been demonstrated that for both **D1A2** and **D2A2**, the blue light-absorbing naphthalene monoimide energy donors harvest the photons and transfer the energy quantitatively to the green-light-absorbing perylene energy acceptors. This energy transfer is through fluorescence resonance energy transfer (FRET) since there is a good overlap between the donor's emission and the acceptor's absorption, and electronic communication between donor and acceptor moieties is absent.[3] In the solid state, discrete perylene dimers form rods along the *a*-axis with an edge-to-edge distance of 0.28 nm between dimers. Both along the *b*-axis and along the *c*-axis, the edge-to-edge distances are longer, ≈0.8 nm and ≈1 nm, respectively. This packing structure can be further studied and engineered for optimal antenna function.

Conclusion

In conclusion, we have used computational integration of ENC and MAS NMR data, with a molecular replacement approach to determine the molecular packing of two bichromophoric light-harvesting donor-acceptor antenna systems, **D1A2** and **D2A2**, that form a racemic packing of centrosymmetric P and M dimers due to core induced chirality in the solid state. In this approach, the NMR distance constraints are used to solve the phase problem and to find the orientation of the molecule in the unit cell. Our results enable a direct molecular level approach to elucidate the supramolecular packing of light-harvesting antenna systems with naphthalene monoimide and perylene monoimide diester as molecular entities. The rod-type morphology of chromophores in the solid state leads to a contiguous column of acceptors, with naphthalene monoimide donors orienting outwards to harvest photons and feed into the perylene system. Our methodology opens the way for the studies of pseudocrystalline supramolecular systems, using compounds with ^{13}C at natural abundance, and could be used for underpinning the design of complex self-assembling responsive matrix systems for artificial photosynthesis.

Experimental Details

Full experimental details including MAS NMR spectroscopy, electron nano-crystallography and computational modelling are included in the Supporting Information.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: electron nano-crystallography · MAS NMR · perylene · self-assembly

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[1] R. L. Purchase, H. J. M. de Groot, *Interface Focus* **2015**, *5*, 20150014.
[2] B. Thomas, J. Rombouts, G. T. Oostergetel, K. B. S. S. Gupta, F. Buda, K. Lammertsma, R. Orru, H. J. M. de Groot, *Chem. Eur. J.* **2017**, *23*, 3280–3284.
[3] R. K. Dubey, D. Inan, S. Sengupta, E. J. R. Sudholter, F. C. Grozema, W. F. Jager, *Chem. Sci.* **2016**, *7*, 3517–3532.
[4] M. Şener, J. Strümpfer, J. Hsin, D. Chandler, S. Scheuring, C. N. Hunter, K. Schulten, *ChemPhysChem* **2011**, *12*, 518–531.
[5] a) S. Sengupta, R. K. Dubey, R. W. M. Hoek, S. P. P. van Eeden, D. D. Gunbaş, F. C. Grozema, E. J. R. Sudhölter, W. F. Jager, *J. Org. Chem.* **2014**, *79*, 6655–6662; b) H. Kashida, T. Takatsu, K. Sekiguchi, H. Asanuma, *Chem. Eur. J.* **2010**, *16*, 2479–2486.
[6] a) D. González-Rodríguez, T. Torres, M. Á. Herranz, L. Echegoyen, E. Carbonell, D. M. Guldi, *Chem. Eur. J.* **2008**, *14*, 7670–7679; b) C. Li, H. Yan, L.-X. Zhao, G.-F. Zhang, Z. Hu, Z.-L. Huang, M.-Q. Zhu, *Nat. Commun.* **2014**, *5*, 5709; c) P. Osswald, F. Würthner, *Chem. Eur. J.* **2007**, *13*, 7395–7409; d) M. M. Safont-Sempere, P. Osswald, K. Radacki, F. Würthner, *Chem. Eur. J.* **2010**, *16*, 7380–7384; e) P. Osswald, M. Reichert, G. Bringmann, F. Würthner, *J. Org. Chem.* **2007**, *72*, 3403–3411; f) M. M. Safont-Sempere, V. Stepanenko, M. Lehmann, F. Wurthner, *J. Mater. Chem.* **2011**, *21*, 7201–7209.
[7] S. Ganapathy, G. T. Oostergetel, P. K. Wawrzyniak, M. Reus, A. Gomez Maqueo Chew, F. Buda, E. J. Boekema, D. A. Bryant, A. R. Holzwarth, H. J. M. de Groot, *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 8525–8530.
[8] S. Budavari, M. J. O'Neil, A. Smith, and P. E. Heckelman, *The Merck Index vol. 1606*, Merck & Co. Inc., Rahway, NJ **1989** .
[9] Y. Shi, H. Qian, Y. Li, W. Yue, Z. Wang, *Org. Lett.* **2008**, *10*, 2337–2340.
[10] a) A. L. Briseno, S. C. B. Mannsfeld, C. Reese, J. M. Hancock, Y. Xiong, S. A. Jenekhe, Z. Bao, Y. Xia, *Nano Lett.* **2007**, *7*, 2847–2853; b) Y. Shao, G.-Z. Yin, X. Ren, X. Zhang, J. Wang, K. Guo, X. Li, C. Wesdemiotis, W.-B. Zhang, S. Yang, M. Zhu, B. Sun, *RSC Adv.* **2017**, *7*, 6530–6537.

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