

Porphyrin Aggregation

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Folding and Hydrodynamic Forces in J-Aggregates of 5-Phenyl-10,15,20-tris-(4-sulfophenyl)porphyrin***Carlos Escudero, Joaquim Crusats,* Ismael Díez-Pérez, Zoubir El-Hachemi, and Josep M. Ribó**

Amphiphilic anionic porphyrins self-assemble to J-aggregates with spontaneous breaking of mirror symmetry.^[1] In the case of **2** (Scheme 1) it has been statistically shown that a stirring vortex can select the resulting chirality sign.^[1b-c] Although a similar result has been described in another system,^[2] the

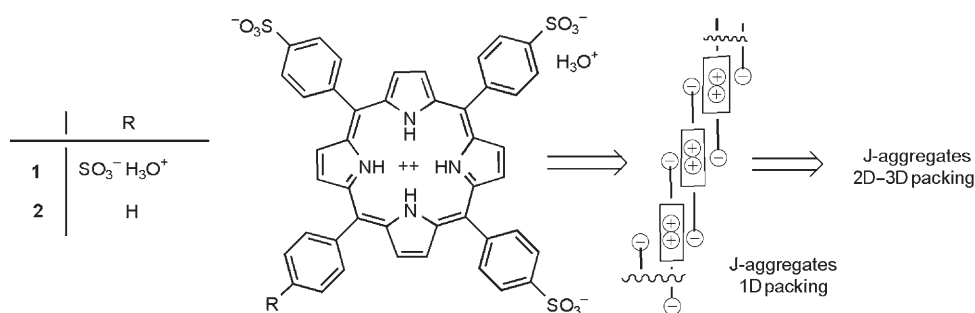
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Supporting information for this article is available on the WWW under <http://www.angewandte.org> or from the author.



Scheme 1. Constitutional formulas of **1**, **2**, and their 1D J-aggregate structures.

origin and cause of such a singular effect is not yet understood. Here we report on new experimental results that show how the title J-aggregates undergo spontaneous folding that can be driven to helical folded tapes by hydrodynamic forces. Thereby, selection of the chirality sign, as detected by circular dichroism (CD), would be an effect of the mechanical forces of chiral hydrodynamic gradients on the formation of mesophases by way of structural transmission of chirality.

The aggregation of diprotonated 4-sulfonato-substituted *meso*-tetraphenylporphyrins is a well-studied topic.^[3] All J-aggregates of this homologous series show very similar UV/Vis spectra^[3f] corresponding to a basic one-dimensional (1D) structure of zwitterions stabilized by intermolecular electrostatic bonding and hydrophobic interactions (Scheme 1). However, the shape of the resulting colloidal particles depends on the *meso*-substitution pattern of the porphyrin.^[1c] We have worked with pure water solutions of the free sulfonic acid forms of **1** and **2**,^[3n] so that the porphyrin has only protons as counterions (absence of ion-pairing effects) in a medium of low ionic strength. Therefore, porphyrin aggregation depends only on its own concentration, which determines both the pH value of the solution (protonation of the porphyrin ring) and self-assembly to J-aggregates. Freshly prepared solutions of

these porphyrins (ca. 1 mM or 0.1 mM) show fast initial J-aggregation of the monomeric zwitterions (detected by the characteristic absorption band at ca. 490 nm). Then, aggregation steadily increases in the course of weeks, in agreement with a hierarchical self-assembly process. This dramatic difference in the time evolution of the initial particles of J-

aggregates compared to acidified solutions of the sodium salts of the porphyrins^[1,3] has allowed us to follow the shape evolution of the mesophases during the aggregation process by tapping-mode atomic force microscopy (AFM).

In the case of **2**, freshly prepared solutions show straight tapes with constant height (3.2 ± 0.1 nm), widths of 35–60 nm, and lengths of 200–400 nm. In concentrated solutions, these initial tapes of **2** mostly adhered one to another. In some of the particles the borders and the corners show a thickness of only 1.5 nm, which points to a double-layer structure for the particle (Figure 1). A thickness of 1.5–1.6 nm agrees with that of a molecule tilted 45° (total length ca. 2.2 nm, i.e., 1.95 nm for the porphyrin molecule plus the water layers necessary to solvate the protons acting as counterions of the anionic sulfonato groups). This bilayer structure (Scheme 2) implies a hydrophobic central region. Stagnant solutions show increasing aggregation with time (UV/Vis) that corresponds to an increase in number and length of the deposited particles, which have similar width and the same thickness as the initial particles. However, after one day, the straight tapes begin to fold. This folding is accelerated by temperature (solutions in the refrigerator show folding much later than samples at room temperature). Stirring the solution also accelerates aggrega-

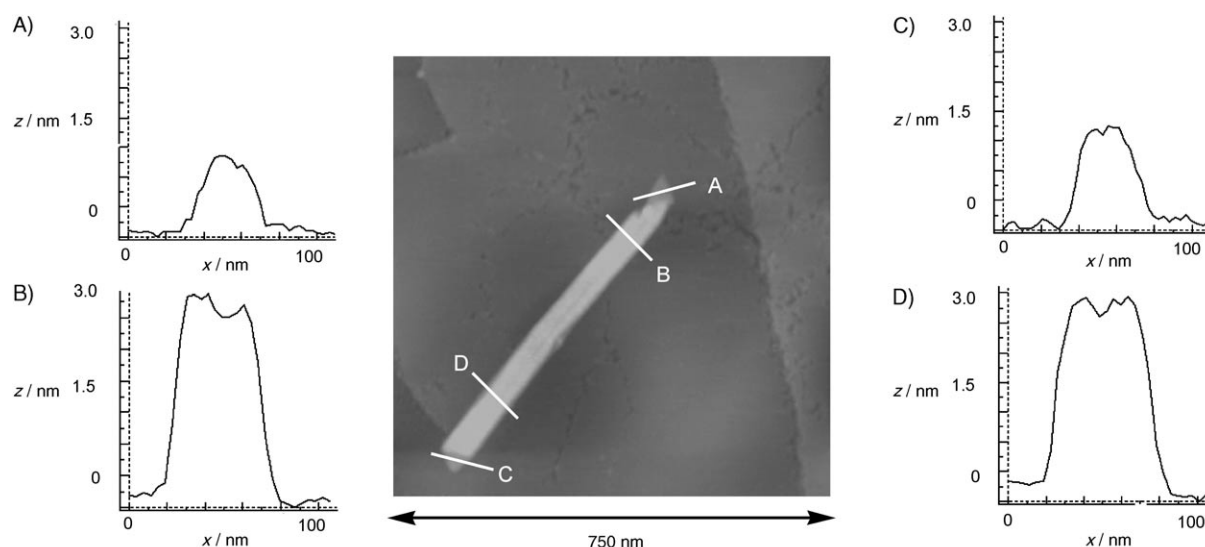
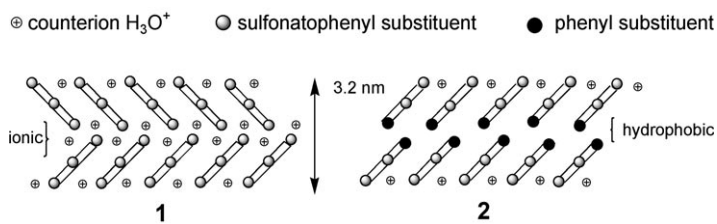


Figure 1. AFM topography image of a J-aggregate of **2**. 1.3 mM freshly prepared solution deposited on highly oriented pyrolytic graphite (HOPG; see Supporting Information). The indentation effect, manifested by differences in step height, highlights the bilayer nature of the particles. A–D) Height profiles of the indicated segments of the topography image.



Scheme 2. Bilayer of **1** and **2** mesophases. The J-aggregation axis (Scheme 1) goes from back to front and forms an angle of about 70° to the paper plane. The present data do not allow one to infer whether the two monolayers are parallel or oblique.

tion: Freshly prepared solutions after 6 h of uniform magnetic stirring in a small tube (Supporting Information) show a degree of aggregation similar to those found in one-day-old stagnant solutions. However, the folding behavior in stagnant solutions differs dramatically from that of vortex-stirred solutions (Figure 2). In the latter, a very large proportion of

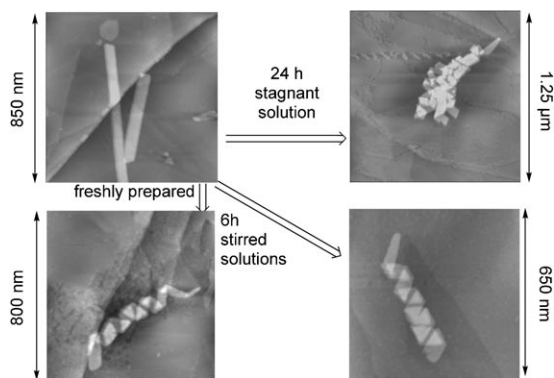


Figure 2. AFM topography images of particles of **2** (1.3 μm , deposited on HOPG) showing the onset of folding in stagnant and stirred solutions. After 6 h the stagnant solutions did not show folding. Stirring for 6 h results mostly in nonadhering long-order folded ribbons. In stagnant solutions, folding appears later and yields irregularly folded ribbons mostly adhering in bundles.

the tapes displays long-range folding order (helical ribbons), while irregular folding and bundles of tapes are rarely detected. The absence of bundles must be attributed to the effect of squeezing flows (see below), which would avoid aggregation between tapes. Furthermore, the stirred solutions show good correlation between the chirality sign of their CD spectra and the direction of stirring (Supporting Information).^[4] Note that in previous studies on acidified solutions of the sodium salts,^[1b-d] such a relationship could only be obtained by rotary evaporation of very dilute solutions of porphyrin, and that here the slow aggregation rates allow us to perform such experiments at constant porphyrin concentration.

Freshly prepared solutions of **1** (1.0–1.6 mM) initially show straight tapes similar to those of **2** (35–60 nm wide, 300–800 nm long, and 3.2 ± 0.2 nm in height: Supporting Information),^[5] but they do not evolve to folded particles. Stagnant solutions show increased J-aggregation after one week, which according to AFM corresponds to an increase in the number

of particles and in their length (micrometer size order), but with similar width and the same thickness as the initial particles. After two months, the particles can be longer than 10 μm , but no folding can be observed. Stirring increases the rate of aggregation but, in contrast to **2**, it does not lead to folding. However, the final particles in strongly stirred solutions show a narrow distribution of lengths ($\leq 2 \mu\text{m}$), which points to a mechanical breaking of the long whiskers by hydrodynamic shear forces or by impact with the stirring bar.

A recent theoretical model^[6] that treats the transition from straight tubes to helices in solution as an entropically driven process can be applied to the folding observed here. In this model, the straight tube interacts with spherical particles in solution, so that folding decreases the volume available for the interaction and a free-energy gain is thus generated by the release of particles to the bulk of the solution. The entropy gain depends on the number of depleted spherical particles, their size, the dimensions of the tape, and the curvature of folding. In our case, the folding is possible for J-aggregates of **2** (hydrophobic interaction between the two layers) but not for those of **1** (ionic structure between the two layers; Scheme 2). The latter compound has only one possible planar arrangement between the two monolayers, and therefore only breaking of the tapes is possible. However, in the case of **2** the hydrophobically bonded monolayers show a plethora of structural states differing only slightly in enthalpy. In this respect, it is significant that folding only occurs when the width becomes greater than about 28 nm (Figure 3). This

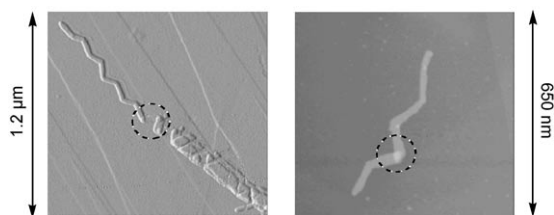


Figure 3. AFM topography (right) and amplitude (left) images of J-aggregate particles of **2** obtained by stirring. Folding (circled) only appears above a critical width (ca. 28 nm). Below this width only a zigzag shape was detected (stirred solutions).

implies that the depletion interaction occurs with rather large particles and excludes a pure hydrophobic effect as the origin of folding. These particles must be small-sized J-aggregates, oligomers, and the already relatively large monomeric porphyrin (ca. 2.5 nm³). Since the tapes of J-aggregates and the interacting particles are both electrically charged species, the interactions between them are those acting in colloidal systems.

The role of stirring in the folding of the tapes of **2** points to the influence of hydrodynamic effects on the folding kinetics. A liquid plays a crucial role in selecting and achieving equilibrium structures in soft-matter components: It allows transition states to be reached and thereby modifies kinetic pathways.^[7] The role of water in protein folding is a paradigm for this. In this respect, Brownian dynamics act as a thermal bath that provides the necessary activation energy to cross transition states. This would explain the folding in our

stagnant solutions. Conversely, the long-order folding in vortex-stirred solutions must be the signature of hydrodynamic interactions with laminar flow (turbulent flow would have a similar effect to that of Brownian dynamics). However, a rough estimation of the Reynolds number Re of our experimental setup indicated that the system is not stirring in a low- Re regime, that is, a turbulent vortex is implied. Nevertheless, it is well known that laminar flow at the wall of the container cannot be suppressed. Thus, the long-order effect on folding is expected to have its origin in the laminar flow at the wall of the container, that is, in the return flow from the bottom to the top of the tube. Note that the helical sign of the vortex created by a stirring bar from the top to the bottom (e.g., P) changes its sign (i.e., M) in the fluid returning to the surface (same sense of circular rotation but inverse direction of progress). The fact that the previously reported selection of chirality sign in rotary evaporation experiments^[1b,c] was opposite to that reported here under magnetic stirring agrees with the argument that the chirality-inducing flow is that originating at the walls: In the rotary evaporator flask the significant flow is the progress of the fluid from the top to the bottom of the flask in the last stages of the evaporation process. However, a laminar flow alone cannot explain the chiral-selection effect, because at low stirring speeds, that is, smaller Re , chiral selection disappears (Supporting Information). In consequence, the important point is the presence of sufficiently large hydrodynamic gradients in the boundary layer of the laminar flow created at the wall surface.

Enantiomorphic objects in a circular flow exhibit enantiotropic trajectories, as has been shown both experimentally (hemihedric crystals, 30 years ago!)[^{8]} and theoretically (helices).^[9] In our case, the resulting trajectories for enantiomorphic helices must be diastereotropic, because the shear flow is already chiral. All this suggests an evolutionary selection of one of the two helix senses, that is, particles with a given helical sense can follow the trajectory of the laminar flow while the others will be ejected towards the chaotic flow regions where “recycling” to the monomer via small oligomeric species will be more pronounced. Note that a such mechanism is only possible for chiral-shaped objects that can be classified into two homochiral classes (e.g., helices).^[10]

The present results are an experimental example of how shear flows^[7] can select among different pathways in a hierarchical self-assembly, and therefore between supramolecular polymorphs. This is of interest not only in the field of biopolymers, but also in supramolecular chemistry, for example, in the self-assembly of porphyrinoids mimicking natural systems.^[11] In fact, previous experimental results on the influence of gravity on the mesophase structures obtained by self-assembly^[12] also have their origin in hydrodynamic effects.

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