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Peripheral Stepwise Degradation of a Porphyrin J-Aggregate

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Supporting Information

ABSTRACT: For metalation of the acidic form of tetrakis(4-sulfonatophenyl)porphyrin (dianionic H_4TPPS_4) by Cu(II), the order of reagent mixing determines the rate and mechanism of $CuTPPS_4$ formation. When copper salts are added last, the kinetic profile is fit as a (pseudo)-first-order process. However, J-aggregates of the H_4TPPS_4 porphyrin are rapidly formed at pH ∼ 3 when Cu(II) salts are incorporated in solution *prior* to porphyrin addition. The subsequent porphyrin units metalation leads to the disassembling of these arrays via a *pseudo-zero-order* kinetic profile, suggesting an attack of the metal ion at the rims of the nanostructure.

J-aggregates (J-agg) formed via the self-assembly of porphyrins have attracted the attention of many researchers because of their remarkable structural, electronic, and chiral properties.[1] Much of this effort has been focused on water-soluble tetraanionic tetrakis(4-sulfonatophenyl)porphyrin (H_2TPPS_4). At acidic pH, the diacid H_4TPPS_4 (pK_a = 4.9)[2] is formed, which, in the presence of added salts or at high acid concentration, self-assembles to form nanostructures that are stabilized primarily by electrostatic interactions between the positive protonated core of the macrocycle and the negatively charged sulfonate groups of adjacent porphyrins. A series of studies have suggested the presence in solution of assemblies whose sizes span from the nano- to micrometer scale,[3] and recent investigations have provided evidence for the formation of porphyrin nanotubes.[4] Depending on the mixing protocol,[5] medium properties [pH, ionic strength (IS), etc.], and porphyrin concentration, an interesting "fractal-to-rod" transition of the aggregate mesostructure has also been reported.[6]

While at the mesoscopic scale the description of the aggregation kinetics can be analyzed in terms of current theories for colloidal systems,[7] at the nanoscale, the kinetics of J-agg supramolecular assembly are characterized by a sigmoidal profile with an initial lag period. These two phases correspond to an early nucleation stage, followed by a rapid growth of the aggregates.[8] An analysis of the kinetics has been provided by a complex model proposed by Pasternack et al.[9]

Detailed kinetic studies on the *reverse* reaction for J-agg, i.e., the disassembly process, are far less frequent.[10] However, such processes could prove important in a number of chemical/biochemical applications of J-agg assemblies in which such species serve, for example, as (unreactive) reservoirs of active monomers. Strategies for the stepwise freeing of these small, reactive molecules could be very useful, especially where time release is a factor. Here we describe the disassembly behavior of a J-agg nanostructure by interaction with Cu(II) ions. The selection of Cu(II) as the metal ion for this investigation is based on several factors: it inserts into porphyrins orders of magnitude more rapidly than other metal ions, forms a stable product [unlike Zn(II), whose complexes with porphyrins are labile at low pH], has little tendency to add axial ligands, and shows no (easily accessible) redox behavior.[11]

When a solution of $CuSO_4$ (0.3 M) is added to a preacidified solution of H_4TPPS_4 (pH = 2.6), the B band of the starting monomeric porphyrin (434 nm) decreases with time, with a concomitant increase of the band at 412 nm due to the formation of $CuTPPS_4$ (Figure 1).[12] The corresponding kinetic traces (Figure 1, inset) can be fitted to monoexponential profiles and, as might be expected, the rate law is first-order in

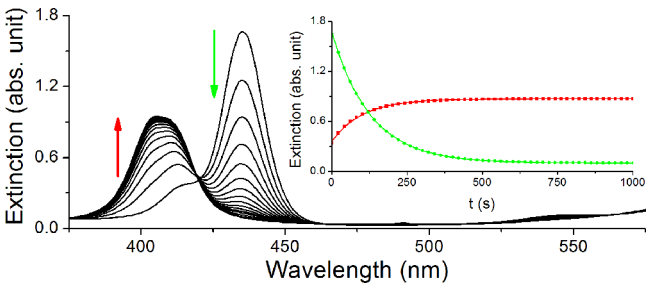

Figure 1. UV/vis spectral changes and kinetic traces (inset; green, 434 nm; red, 412 nm) for Cu(II) insertion in H_4TPPS_4, adding the porphyrin as the "first reagent". Experimental conditions: $[CuSO_4]$ = 0.3 M. k_{obs} = (7.81 ± 0.01) × 10^{-3} s^{-1}, leading to a second-order rate constant k_2 = (2.6 ± 0.1) × 10^{-2} M^{-1} s^{-1}.

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both porphyrin and Cu(II) concentrations.[11] Values obtained for the rate constants are in agreement at the two wavelengths [k_2 = (2.6 ± 0.1) × 10^{-2} M^{-1} s^{-1}], and they are consistently lower than those reported in the literature for metalation of the H_2TPPS_4 *free base* because of the pH being lower.[11]

However, when the porphyrin is added as the final reagent to a premixed solution containing both acid and Cu(II), a much more complicated pattern of behavior is observed. Figure 2

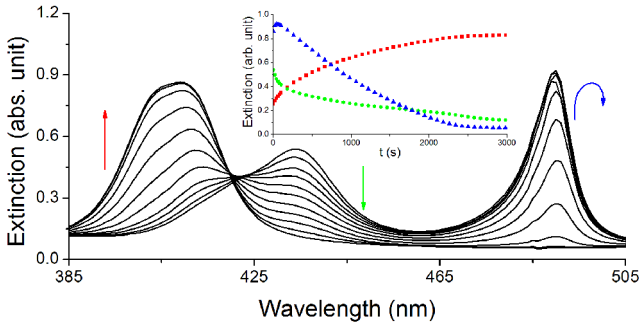


Figure 2. UV/vis spectral changes and kinetic traces (inset) for Cu(II) insertion in H_4TPPS_4, adding the porphyrin as the "last reagent". The arrows mark the decreasing H_4TPPS_4 (green), the increasing $CuTPPS_4$ (red), and the evolution of the transient J-agg (blue). Inset: λ = 434 nm (green), 412 nm (red), and 490 nm (blue). Experimental conditions: [$CuSO_4$] = 0.3 M.

shows that the B band of the diacid species (434 nm) decreases at the beginning of the process, accompanied by an increase of a new band at 490 nm that is attributable to J-agg formation.[13] After this fast initial step, the J-agg band decreases, accompanied by a further intensity reduction of the band at 434 nm and a progressive increase of absorption at 412 nm ($CuTPPS_4$ Soret absorption maximum). Cu(II) plays a dual role in this process: it screens the electrostatic repulsion among porphyrins, favoring their aggregation, and it serves as a metallating reagent, complexing the porphyrin core and causing the disassembly of the nanostructure. The complex time evolution of this system is shown in Figure 2, inset, with a near-linear profile for the extinction decay at 490 nm corresponding to pseudo-zero-order kinetics for the disappearance of the J-agg.

To investigate the effect of the Cu(II) concentration on the rate of this assembly−disassembly process, we have performed a series of kinetic experiments starting from [$CuSO_4$] = 0.05 M, which ensures the formation of a detectable amount of J-agg in the reaction mixture. When the concentration is increased up to [$CuSO_4$] = 0.3 M, both the rates of H_4TPPS_4 self-assembly and subsequent metalation *increase*. Above this concentration, a further increase up to [$CuSO_4$] = 0.8 M causes a *decrease* in the overall rate for metalation (Figure SI2 in the Supporting Information) The bell-shaped dependence of the metalation rates on the copper(II) ion concentration is a consequence of competitive phenomena: on the one hand, stabilization of the J-agg with increasing IS; on the other hand, a parallel increase in the metalation rate. To disentangle these two factors, we measured the metalation rates on preformed J-agg versus the Cu(II) ion concentration at an IS maintained at 2 M by complementing $CuSO_4$ with the appropriate amount of Na_2SO_4 (Figure 3). Under these conditions, we observe that (i) J-agg are stabilized and the metalation process is slower with respect to the experiments conducted with variable salt concentration at lower IS and (ii) there is a linear dependence

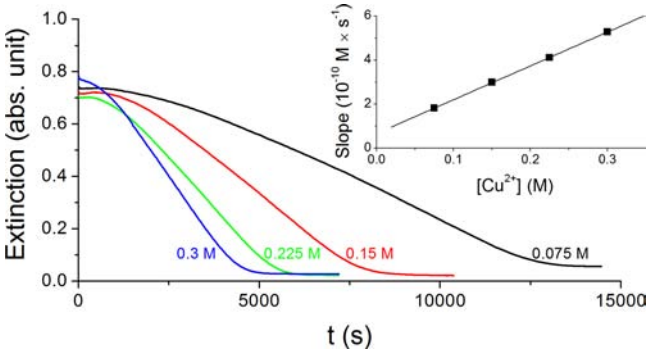
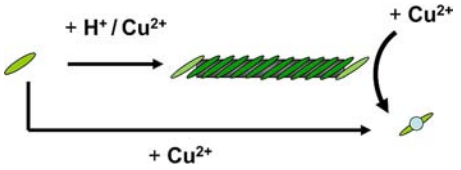


Figure 3. Extinction changes at 490 nm for the Cu(II) insertion in preformed J-agg according to protocol (iii) as a function of the added $CuSO_4$. Inset: values of the slopes obtained from a linear fit of the extinction changes at 490 nm versus Cu(II) ion concentration. Black line: slope = (1.53 ± 0.01) × 10^{-9} s^{-1}; intercept = (6.72 ± 0.2) × 10^{-11} M s^{-1}. Experimental conditions: labels indicate [$CuSO_4$]; IS = 2 M by the addition of Na_2SO_4.

of the metalation rates on Cu(II) concentration. Furthermore, we note a small nonzero intercept at [Cu^{2+}] = 0 M, suggesting a pathway for metalation that is independent of Cu(II) concentration. This effect is currently under investigation, but we speculate that it might be ascribed to end molecules dissociating from the aggregate and being rapidly scavenged by Cu(II) ions.

The experimental kinetic evidence suggests a mechanism for the assembly and disassembly processes under investigation, as shown in Scheme 1. The diacid porphyrin units self-organize as

Scheme 1. Simplified Mechanistic Sketch for the Assembly and Subsequent Disassembly Processes of H_4TPPS_4 Mediated by Cu(II) Ions in Acidic Aqueous Solutions



nanoarrays ("seeds"), and this process is fostered under acidic conditions and/or by an increase of the IS, in our case by the addition of $CuSO_4$. However, the initial mixing protocol determines the actual transition pathway and the role of J-agg.

When the acidified porphyrin is *prediluted* in an acidic solution, the addition of Cu(II) salt as the "last reagent" does not promote aggregation but leads directly to formation of the metalloporphyrin. On the other hand, when a H_2TPPS_4 stock solution is added to a mixture of acid and salt, the higher local concentration of the porphyrin triggers the nucleation process and J-agg are formed.[5] The extent of aggregation increases with the $CuSO_4$ concentration because the resulting aggregates are stabilized by the higher IS. Copper(II) insertion into the macrocycle can occur through direct metalation of the monomeric H_4TPPS_4 or through attack on the J-agg, the two predominant porphyrin species in solution. Given the putative structure of the nanoaggregates,[4] it is not unreasonable to assume a lowered reactivity or even nonreactivity of the porphyrins embedded in the inner part of the structure, similar to other nanoassemblies.[10c] The central core of the inner porphyrin units is both protonated and involved in hydrogen

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bonding with sulfonate groups that sterically hinder attack above and below the porphyrin plane. In contrast, the porphyrins at the ends of the nanostructure are exposed and are, therefore, expected to be more reactive. These are the most likely sites for Cu(II) attack. Consequently, J-agg are disassembled by metalation, maintaining constant their mean concentration even while reducing their size, thus explaining the observed pseudo-zero-order kinetics; i.e., the J-agg are serving as reservoirs of porphyrin reactive units. Indeed, this hypothesis is supported by a comparison of the kinetic traces observed for the same kinetic run using UV/vis extinction and resonance light scattering (RLS; Figure 4). The steeper slope

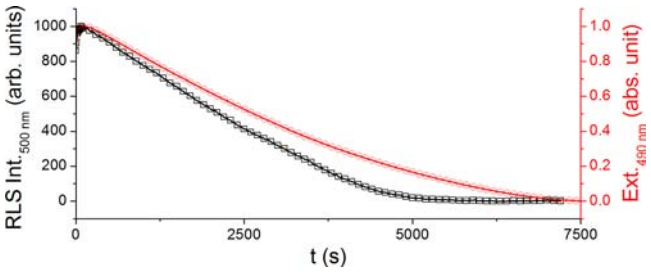

Figure 4. Normalized kinetic traces monitored by RLS at 500 nm (black) and UV/vis extinction at 490 nm (left) for Cu(II) insertion in the porphyrin H_4TPPS_4. Experimental conditions: $[CuSO_4]$ = 0.1 M; porphyrin added last.

for the RLS results reflects the greater sensitivity of this method to the aggregate size.[14] We exclude a mechanism involving a direct attack on porphyrins deeply embedded within the nanostructures because that would lead to fragmentation of the nanoassemblies, formation of additional reactive ends, and acceleration of the rates according to an autocatalytic scheme.[10c] The bell-shaped dependence of the rates on the Cu(II) ion reflects a competitive stabilization of the J-agg on increasing the IS and a concomitant increase in the metalation rate.

In spite of the large amount of data on the reactivity of monomeric porphyrins toward metalation reactions, very few studies have been reported on their aggregated species. J-aggregates are attracting increasing interest by the scientific community for many different applications, and therefore a knowledge of their kinetic behavior is very important to the design of supramolecular devices. The results reported here provide an example of the complexity of these systems, involving kinetically and thermodynamically coupled supramolecular assembly processes.

■ ASSOCIATED CONTENT

Supporting Information

Experimental methods and kinetic data for the formation of J-agg in the absence and presence of Cu(II) sulfate. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Würthner, F.; Kaiser, T. E.; Saha-Möller, C. R. *Angew. Chem., Int. Ed.* **2011**, *50*, 3376−3410. (b) Kitagawa, Y.; Segawa, H.; Ishii, K. *Angew. Chem., Int. Ed.* **2011**, *50*, 9133−9136. (c) D'Urso, A.; Randazzo, R.; Lo Taro, L.; Purrello, R. *Angew. Chem., Int. Ed.* **2010**, *49*, 108−112. (d) Collini, E.; Ferrante, C.; Bozio, R. *J. Phys. Chem. C* **2007**, *111*, 18636−18645. (e) Kobayashi, T.; Kano, H. *Nonlinear Opt., Quantum Opt.* **2004**, *31*, 115−135. (f) Ribó, J. M.; Crusats, J.; Sagues, F.; Claret, J.; Rubires, R. *Science* **2001**, *292*, 2063−2066.

(2) Kalyanasundaram, K. *Photochemistry of Polypyridine and Porphyrin Complexes*; Academic Press: London, 1992.

(3) (a) Rotomskis, R.; Augulis, R.; Snitka, V.; Valiokas, R.; Liedberg, B. *J. Phys. Chem. B* **2004**, *108*, 2833−2838. (b) Schwab, A. D.; Smith, D. E.; Rich, C. S.; Young, E. R.; Smith, W. F.; de Paula, J. C. *J. Phys. Chem. B* **2003**, *107*, 11339−11345. (c) Collings, P. J.; Gibbs, E. J.; Starr, T. E.; Vafek, O.; Yee, C.; Pomerance, L. A.; Pasternack, R. F. *J. Phys. Chem. B* **1999**, *103*, 8474−8481. (d) Ribò, J. M.; Crusats, J.; Farrera, J. A.; Valero, M. L. *J. Chem. Soc., Chem. Commun.* **1994**, 681−682. (e) Akins, D. L.; Zhu, H. R.; Guo, C. *J. Phys. Chem.* **1994**, *98*, 3612−3618.

(4) (a) Rich, C. C.; McHale, J. L. *Phys. Chem. Chem. Phys.* **2012**, *14*, 2362−2374. (b) Hollingsworth, J. V.; Richard, A. J.; Vicente, M. G. H.; Russo, P. S. *Biomacromolecules* **2012**, *13*, 60−72. (c) Friesen, B. A.; Wiggins, B.; McHale, J. L.; Mazur, U.; Hipps, K. W. *J. Am. Chem. Soc.* **2010**, *132*, 8554−8555. (d) Vlaming, S. M.; Augulis, R.; Stuart, M. C. A.; Knoester, J.; van Loosdrecht, P. H. M. *J. Phys. Chem. B* **2009**, *113*, 2273−2283. (e) Friesen, B. A.; Nishida, K. R. A.; McHale, J. L.; Mazur, U. *J. Phys. Chem. C* **2009**, *113*, 1709−1718. (f) Gandini, S. C. M.; Gelamo, E. L.; Itri, R.; Tabak, M. *Biophys. J.* **2003**, *85*, 1259−1268.

(5) Castriciano, M. A.; Romeo, A.; Villari, V.; Micali, N.; Scolaro, L. M. *J. Phys. Chem. B* **2003**, *107*, 8765−8771.

(6) Micali, N.; Villari, V.; Castriciano, M. A.; Romeo, A.; Scolaro, L. M. *J. Phys. Chem. B* **2006**, *110*, 8289−8295.

(7) Micali, N.; Mallamace, F.; Romeo, A.; Purrello, R.; Scolaro, L. M. *J. Phys. Chem. B* **2000**, *104*, 5897−5904.

(8) The kinetic profiles are strongly dependent on the reagent mixing order: adding the porphyrin as the last reagent leads to a fast nucleation with a concomitant substantial reduction or disappearance of the lag period.[7]

(9) (a) Pasternack, R. F.; Fleming, C.; Herring, S.; Collings, P. J.; de Paula, J.; DeCastro, G.; Gibbs, E. J. *Biophys. J.* **2000**, *79*, 550−560. (b) Pasternack, R. F.; Gibbs, E. J.; Collings, P. J.; de Paula, J. C.; Turzo, L. C.; Terracina, A. *J. Am. Chem. Soc.* **1998**, *120*, 5873−5878.

(10) (a) Watanabe, K.; Kano, K. *Bioconjugate Chem.* **2010**, *21*, 2332−2338. (b) Kano, K.; Watanabe, K.; Ishida, Y. *J. Phys. Chem. B* **2008**, *112*, 14402−14408. (c) Pasternack, R. F.; Gibbs, E. J.; Bruzewicz, D.; Stewart, D.; Engstrom, K. S. *J. Am. Chem. Soc.* **2002**, *124*, 3533−3539.

(11) Schneider, V. *Struct. Bonding (Berlin)* **1975**, *23*, 123−166.

(12) The band at 412 nm corresponding to the $CuTPPS_4$ metal porphyrin is accompanied by a second band at 405 nm, which could be ascribed to a dimer of this compound. The relative amounts of the two species change as a function of the salt concentration because the equilibrium is forced toward the dimer at higher IS. See: Kemnitz, K.; Sakaguchi, T. *Chem. Phys. Lett.* **1992**, *196*, 497−503.

(13) This process can be isolated by forming J-agg through the use of sodium rather than Cu(II) sulfate, revealing this process to be much faster ($t_{1/2}$ < 3 s; see Figure SI1 in the Supporting Information) than Cu(II) metalation ($t_{1/2}$ ∼ 100 s; see Figure 1, inset).

(14) Parkash, J.; Robblee, J. H.; Agnew, J.; Gibbs, E.; Collings, P.; Pasternack, R. F.; de Paula, J. C. *Biophys. J.* **1998**, *74*, 2089−2099.