Supramolecular chirality control by solvent changes. Solvodichroic effect on chiral porphyrin aggregation†

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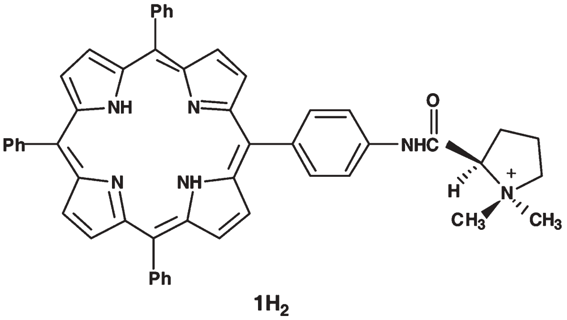
The mode of aggregation of amphiphilised porphyrin derivatives bearing a chiral functionality is strongly affected by solvent composition; this results in the tuning of the supramolecular chirality of the porphyrin aggregates.

The control and tuning of chirality at the molecular or supramolecular level is a field of ever growing interest.[1] In particular, the control of chirality in porphyrin-based self-assembling architectures[2] constitutes a mandatory step for the construction of systems mimicking biological functions, such as, for example, cytochrome P-450 activity[3] or antenna systems of phosynthetic bacteria.[4] During the course of our studies on micelle-included porphyrin derivatives as cytochrome P-450 mimics,[5] we found that the chiroptical properties of the whole systems were influenced by the structural properties of both the tetrapyrrolic macrocycles and the biomembrane models.[5d,e] We recently reported that aggregates of amphiphilic cationic porphyrin derivatives spontaneously layer onto hydrophobic surfaces, forming ordered mesostructures.[6] By analogy, we surmised that the presence of a cationic, chiral, functionality on the porphyrin periphery would result in the achievement of solid-state systems expressing elements of supramolecular chirality. This would be of important application in the field of sensors[7] and molecular materials.[8]

Herein we show that the solvent composition may deeply affect the supramolecular chirality of an amphiphilic porphyrin derivative possessing a chiral cationic functionality, namely an (L)-prolinium moiety (**$1H_2$**, Scheme 1).[9]

Porphyrin **$1H_2$** was obtained by a straightforward procedure, entailing EDC–HOBT coupling of a *p*-aminophenyl porphyrin derivative with *N*-methyl-(L)-proline.† Aggregation experiments ([**$1H_2$**] = $1.5 \div 9.0 \times 10^{-5}$ M) were carried out in mixed water–ethanol solvent mixtures. In the composition range of 100% to 50% ethanol (v:v) the macrocycle is in monomeric form, as clearly evidenced by the sharpness of the Soret band, with λ_{max} at 416 nm. Further increase of the water proportion promotes the self-aggregation process, as witnessed by the broadening and bathochromic shift of the Soret band (*vide infra*).‡[10] Circular dichroism spectroscopy reveals that the aggregation promotes the formation of large chiral suprastructures, steered by the presence of the appended chiral functionality (Fig. 1A).§ Remarkably, the organisation, and the resulting chirality of the aggregates are strongly controlled by the composition of solvent (*i.e.* water–ethanol proportion), as indicated in Fig. 1. The aggregation promoted in 75% H_2O, for example, results in the formation of porphyrin suprastructures featuring signals of 1–2 orders of magnitude larger than those obtained at a higher water proportion (90% H_2O). Concomitant UV-visible spectroscopic studies gave more insights into the observed phenomenon. In water–ethanol 90:10 (v:v), for example, the aggregation is complete within the time of mixing, and results in the formation of aggregates featuring the expected hypochromic effect but only a small red-shifted maxima (λ_{max} 421 nm. Fig. 1B). This should indicate the formation of aggregates with poorly defined structure. On the contrary, at higher ethanol proportions (*i.e.* 75% H_2O), a slower aggregation process is onset, resulting in the formation of probably J-type structures,[11] as indicated by the red shifted Soret band with λ_{max} at 460 nm (Fig. 1B). Kinetic experiments of **$1H_2$** aggregation in H_2O–EtOH 75:25 (v:v), carried out by UV-visible spectroscopy (see ESI†), gave interesting insights into the mode of aggregation. The extinction *vs* time profiles show an autocatalytic-like behaviour that can be excellently fit by a non-conventional equation earlier proposed by Pasternack [eqn. (1)].[2b] A typical kinetic profile is reported in Fig. 2, and the relative kinetic parameters, in terms of rate constants *k* and the "aggregate growth rate" parameter *n*, are summarised in Table 1.¶ Values of *k* increase linearly with increasing initial porphyrin concentration. However, values of *n* are close to 1, and were nearly independent of the initial bulk concentration of **$1H_2$**. Parallel CD spectroscopy studies reveal the onset of like kinetic behaviour, as exemplified in Fig. 3. Moreover, addition of salts (NaCl, 0.01 to 0.1 M) to **$1H_2$** (H_2O–EtOH 75:25) solutions results in a dramatic increase in the rate of porphyrin aggregation, but the spectral features of the resulting aggregates (UV-vis and CD) are very similar to those obtained in H_2O–EtOH 90:10.

Concomitant resonance light scattering experiments (RLS)[12] indicate that the solvent also strongly influences the size of the porphyrin aggregates (Fig. 4). In H_2O–EtOH 75:25 (v:v) the



$1H_2$

Scheme 1 Structure of the porphyrin studied in the work.

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† Electronic supplementary information (ESI) available: experimental and spectroscopic details. See http://www.rsc.org/suppdata/cc/b4/b419275c/
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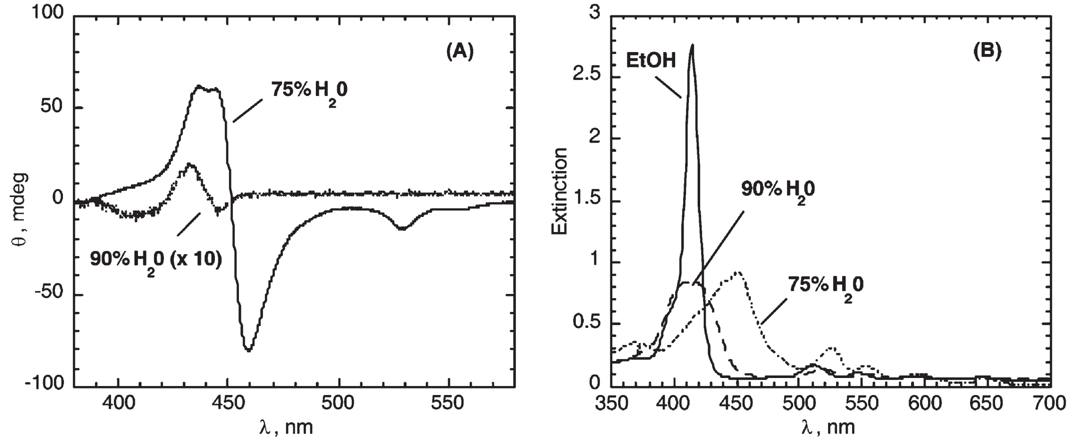

Fig. 1 A) CD spectra of $\mathbf{1H_2}$ (3.0×10^{-5} M) in different aqueous solvents. B) Extinction spectra of $\mathbf{1H_2}$ in different media: EtOH (—); H_2O–EtOH 75:25 (v:v) (······); H_2O–EtOH 90:10 (v:v) (- - - -).

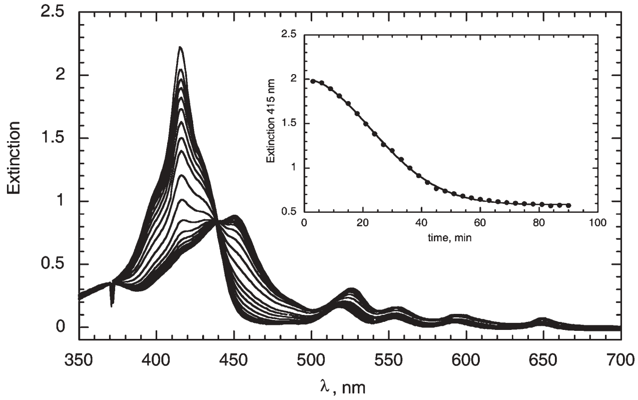

Fig. 2 UV-vis spectral changes of $\mathbf{1H_2}$ (4.5×10^{-5} M) in H_2O–EtOH (75:25 v:v) with time. In the inset is reported the fit of the experimental data points by eqn. (1) (see text¶).

Table 1 Kinetic parameters for the aggregation of $\mathbf{1H_2}$[a]

Entry	[$\mathbf{1H_2}$] (M)	k (10^{-4} s^{-1})	n
1	1.5×10^{-5}	3.1 (±0.1)	0.7 (±0.1)
2	3.0×10^{-5}	4.0 (±0.1)	1.1 (±0.1)
3[b]	3.0×10^{-5}	5.3 (±0.1)	1.2 (±0.2)
4	4.5×10^{-5}	6.0 (±0.1)	0.8 (±0.1)
5	6.0×10^{-5}	7.3 (±0.1)	0.9 (±0.1)
6	7.5×10^{-5}	10.5 (±0.3)	0.7 (±0.2)
7	9.0×10^{-5}	14.2 (±0.1)	0.8 (±0.2)

[a] Aggregation studies are carried out in H_2O–EtOH (75:25 v:v), T = 25 °C. [b] Kinetic followed by CD spectroscopy.

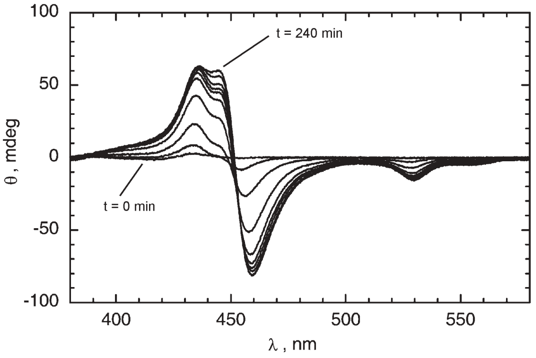

Fig. 3 CD spectral changes upon aggregation of (3.0×10^{-5} M, H_2O–EtOH 75:25 v:v).

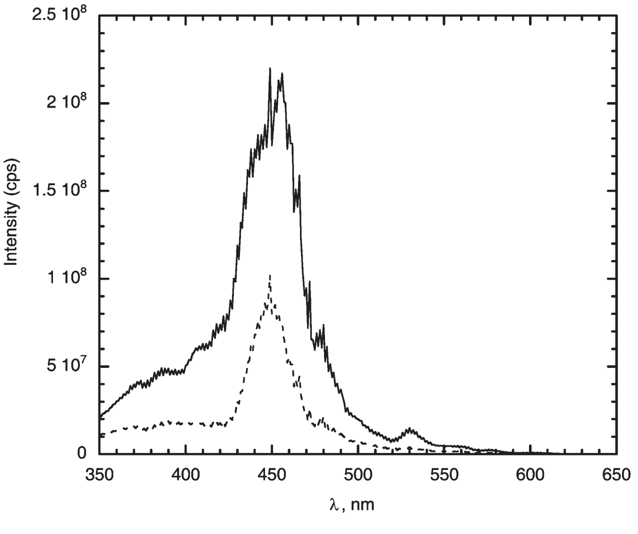

Fig. 4 RLS spectra of $\mathbf{1H_2}$ 3.0×10^{-5} M in H_2O–EtOH 75:25 (v:v) (solid line), and in H_2O–EtOH 90:10 (v:v) (dotted line) after complete aggregation.

relative scattering signals are markedly more intense (up to two-fold) than those observed in the case of aggregation in H_2O–EtOH 90:10 (v:v). This might be the consequence of the formation of a larger number of nucleation seeds resulting in the formation of smaller aggregates.‖ Opposite effects have been reported in the DNA-template assisted aggregation of water-soluble porphyrin, in which higher ellipticity was promoted by hydrophobic effects (*i.e.* high ionic strength).[2c] In our present case, the increase of ellipticity is promoted in a less polar (*i.e.* ethanol rich) solvent. Specific non-covalent interactions, such as, for example, π–cation interactions,[6,13] exerted by the cationic, chiral peripheral functionality would play a striking role in the formation of well-defined, chiral porphyrin aggregates. These forces are more effective in a less polar medium. In a more polar solvent mixture (*i.e.* 90% H_2O), in fact, the onset of less specific π–π stacking or other hydrophobic interactions becomes overwhelming, promoting the formation of less structured, smaller porphyrin aggregates in a faster process.

In conclusion, we showed the possibility of tuning the morphology, and then the supramolecular chirality, of porphyrin aggregates by simple changes of solvent composition. This opens interesting perspectives in the field of stereoselective solid-state sensors, in which the control of the morphology of the layers constitutes a crucial step. Addressed studies are actively being carried out in our laboratories. We gratefully acknowledge the financial support of MIUR-FIRB (Project nr. RBNE01KZZM). The helpful discussion of Prof. Luigi Monsù Scolaro (University of Messina, Italy) is gratefully acknowledged.

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Notes and references

‡ The term *extinction* is of more appropriate use than *absorbance*, because of the presence of RLS scattering contributions to UV-vis (and CD, *vide infra*) bands. See, for example, ref. 10.

§ It is worth noting that in non-aggregative conditions, porphyrin solutions are CD silent in the Soret band region. Moreover, aggregates of related cationic, achiral, amphiphilic porphyrin derivatives (ref. 6) are CD silent, indicating the overwhelming effect of the chirality of the macrostructures in the observed phenomenon.

¶ The equation used is of the form:

$$E = E_{\mathrm{inf}} + (E_0 - E_{\mathrm{inf}})\exp[-(kt)^{n+1}/(n+1)] \qquad (1)$$

Where E, E_0, E_{inf} are the extinction values at time t, initially, and at equilibrium, respectively, n is the "aggregate growth rate" parameter, and k is the kinetic constant. Eqn. (1) is a reduced form of a more general non-conventional equation that is widely used in fractal-type aggregation of porphyrins and other related macrocycles. The "fractal-type" equation reduces to eqn. (1) in the limiting case of $m = 1$ (m is a parameter determining the size of aggregation nuclei). Indeed, in our case, a fit with the "fractal-type" equation gave m values very close to 1 (*i.e.* 0.95–1.1) together with a poorer adherence of the calculated profiles to the experimental data points.

‖ The possibility that in more polar conditions a different mechanism is operating should be taken into consideration. This would affect the size and the morphology of the supramolecular architectures. For this reason, detailed stopped-flow kinetic experiments are under way.

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