Cooperative interaction between organic and inorganic moieties in hybrid Silica Nanohelices for enantioselective interaction

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SUPPORTING INFORMATION

SI-1- Detailed sol-gel synthesis of the hybrid gemini/silica helices

Materials and Instruments.
L(+)-Tartaric Acid (ee 99%), D(-)-Tartaric Acid (ee 99%), Tetraethyl orthosilicate (≥99.0%), KCl (99% purity) were procured from Sigma-Aldrich and used without purification. Milli-Q water of resistivity 18.2 MΩ.cm at 25°C has been used for all the experiments.
All the circular dichroism (CD) and UV-Vis spectra were measured on a J-815(JASCO) Circular dichroism Spectrometer at 4°C. 10 mm quartz cell was used for all the CD and UV-Vis measurements. TEM CM120 (Philips) was used for visualizing the hybrid helices. IR spectra were recorded with a Thermo-Nicolet Nexus 670 FTIR spectrometer, at a resolution of 4 cm^{-1}, by coadding 50 scans.

1. Synthesis of 16-2-16 gemini tartrate and their supramolecular assembly

The synthesis of 16-2-16 gemini tartrate was performed as previously reported[i] starting from N, N, N', N'-tetramethylethylenediamine and 1-bromohexadecane then exchanging the bromide counterion to acetate using silver acetate then to enantiopure tartrate using tartaric acid. The powder of 16-2-16 gemini tartrate was dissolved into ultra-pure water at 70°C (1 mM) then aged for 4 days at 20°C. Typical used quantities are 20 mg of powder for 28 ml of ultrapure water. The powder containing L-tartrate enantiomer forms a suspension of right-handed nanohelices, whereas the one with D-tartrate forms a suspension of left-handed structures. The good formation of the structures is confirmed using TEM.

2. Synthesis of the hybrid gemini/silica nanohelices

A silica shell is formed around the organic helices through polycondensation of tetraethyl orthosilicate (TEOS). To do so, TEOS need first to be hydrolyzed in an acidic medium. 1.5 mL of TEOS were typically dispersed in 30 ml of 10 mM L or D tartaric acid solution for 7 h. Then, TEOS solution was added in the suspension of organic helices. After overnight reaction, hybrid helices are washed by water at 4°C using centrifugation (12 min/3893 g). The organic part from the hybrid helices were removed by washing with methanol at 60°C for 3-4 times followed by additional washing with 1:1 ethanol: isopropanol mixture.

3. Ion exchange inside the silica walls

(a) Ion exchange of L/D-hyb by KCl.

The suspensions of L/D-hyb (0.20 mg ml^{-1}) were washed 8–10 times by 100 mM solution of KCl using centrifugation (12 min/3893 g) at 4°C followed by 3 to 4 times washing with water using centrifugation (12 min/3893 g) at 4°C to remove excess KCl. The successful removal of the tartrate was confirmed by CD spectral measurement.

(b) Ion exchange of L/D-hyb-Cl by L/D-Tartaric Acid.

2.5 mL of L/D-hyb-Cl (1 mg/mL) solution in water was centrifuged (5 min/3893g) and mixed with 5 mM of L/D-tartaric acid and kept at 4°C for overnight. The tartrate exchanged L/D-hyb-Cl was washed with water to remove excess L/D-tartaric acid. CD and UV-Vis spectroscopy experiments were carried out to check the exchange of chloride by tartrate inside L/D-hyb-Cl.

(c) Ion exchange of L/D-hyb-Cl by DL-Tartaric Acid

Similar to the pure L or D-tartaric acid, the racemic mixture of the tartaric acid was exchanged with the L/D-hybrid-helix-Cl (1mg/mL). Concentration of the LD-tartaric acid solution is 10mM. CD measurements of the exchanged hybrid helix and the supernatant after washing were carried out to check the enantioseparation.

4. FTIR studies

2 mg/mL of L/D-hybrid-helix-Tartrate, L/D-hybrid-helix-Cl was washed with D_2O by centrifugation (10000 RPM, 5 min) at 4°C to minimize the H_2O absorption peaks in 1500-1800 and 3000-4000 cm^{-1} region. Final concentrations of the samples were adjusted to 20 mg/mL for FTIR measurements. [ii]

5. TEM Imaging

Before sample drop-casting, the 200-mesh Cu-grid was plasma treated for 30 seconds. 0.2 mg/mL solution of nanohelices of ~7 µL were drop-casted on to the grid. Excess sample were removed by filter paper followed by vacuum drying before imaging. The accelerating voltage of the TEM instrument, Philips CM200 was 80 kV during imaging.

SI-2- UV spectra of the figures 1 and 2

UV spectra corresponding to the CD of figure 1:
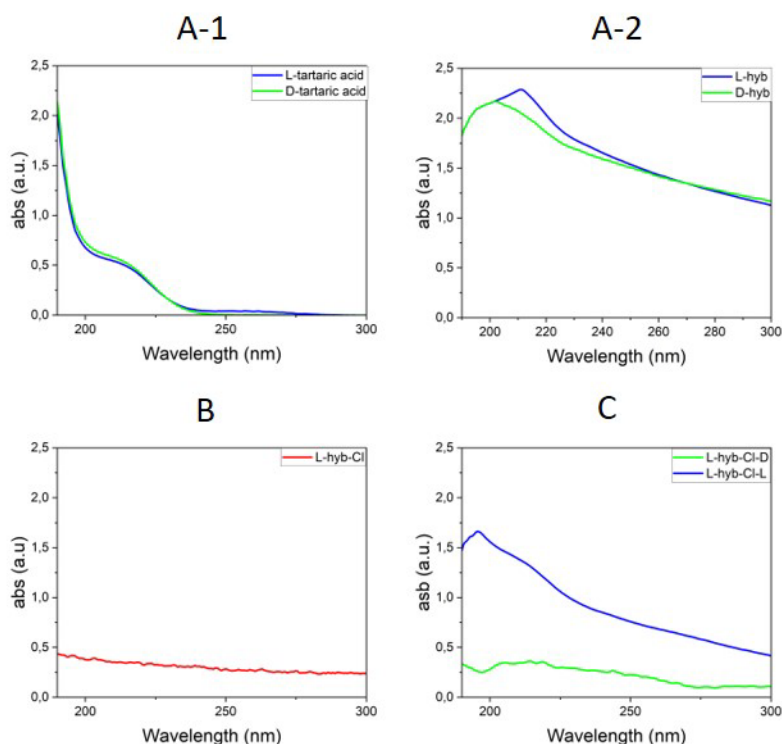
UV spectra corresponding to the CD of figure 2:
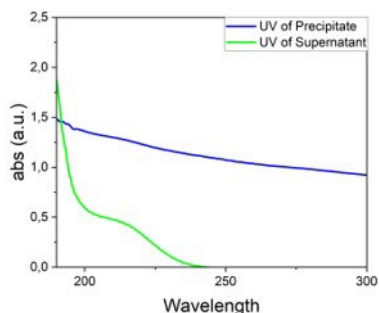
SI-3- Definition of the g-factor

Electronic circular dichroism is defined as the difference

$$\Delta A = A^l - A^r \tag{1}$$

where A^l and A^r are the absorptions of left and right circularly polarized light. For historical reasons, the output of CD instruments is usually measured as ellipticity ϑ (in mdeg), related to CD through $\Delta\vartheta$ (mdeg) = 32982 ΔA.[iii] In analogy to Beer-Lambert law, one can define a molar quantity,

$$\Delta\varepsilon = \varepsilon^l - \varepsilon^r = \frac{\Delta A}{c \cdot b} \tag{2}$$

which is dependent of concentration c, expressed in mol/L, and of pathlength b, expressed in cm.

The definition of equation (1) immediately tells us that *CD* can be measured only in correspondence to absorption bands. It is worth observing that *CD* is a signed quantity, because, ε^l may be smaller or larger than ε^r (and consequently A^l and A^r); it is easy to show that for each absorption band, the *CD* of two enantiomers are always exactly opposite.

      To discard the problem of the dependence on the sample concentration on the measured CD, optical activity of chiral system is often measured through the dimensionless g factor[iv]:

$$g = \frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon^l - \varepsilon^r}{\varepsilon} = \frac{A^l - A^r}{A} = \frac{\Delta\theta}{32982A} \tag{3}$$

where, ε^l and ε^r are the molar absorption coefficients for left and right polarized light, $\Delta\varepsilon$ and ε are the molar circular dichroism and molar absorptivity, A is conventional absorbance of non-polarized light (equivalent with the average of A^l and A^r). Thanks to the g-factor, chiroptical properties can be estimated and compared independently of the concentration and the path-length.

SI-4. DL-TA separation by inorganic silica helices

A control experiment has been carried out to prove the importance of the gemini bilayer inside the hybrid nanohelices: the organic moieties were removed by washing with hot methanol (60°C). The same enantioseparation than the experiments done with the hybrid nanohelices was carried out with the pure inorganic nanohelices. The flat CD spectra of the supernatants presented in the figure below suggest that no obvious separation is observed. This confirms the importance of the presence of the silica shell AND the gemini surfactant together for the separation process.
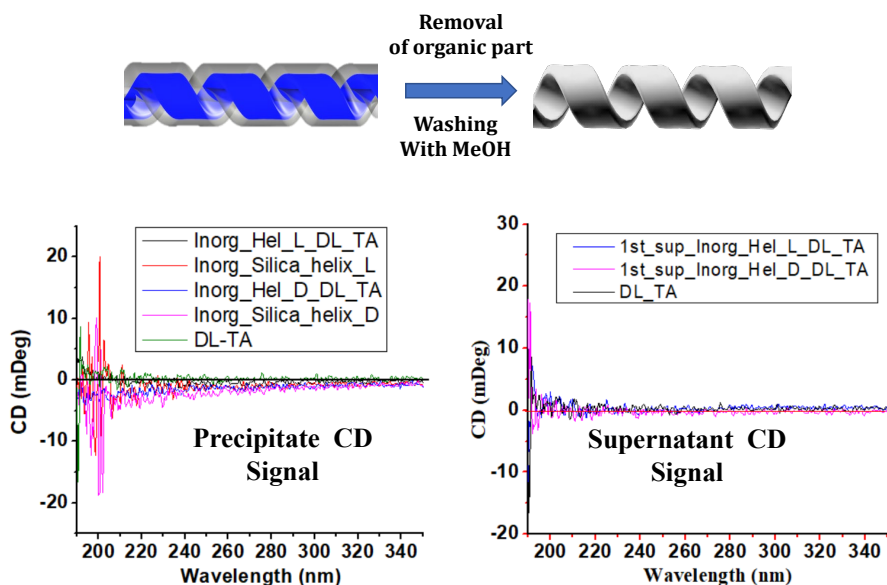
Schematic representation of removal of organic part from hybrid nanohelices and CD spectrum of precipitate and supernatant for separation of DL-TA by inorganic helices. Concentration of Inorg_Silica_Hel_L or D is 1 mg/mL in Milli-Q water.
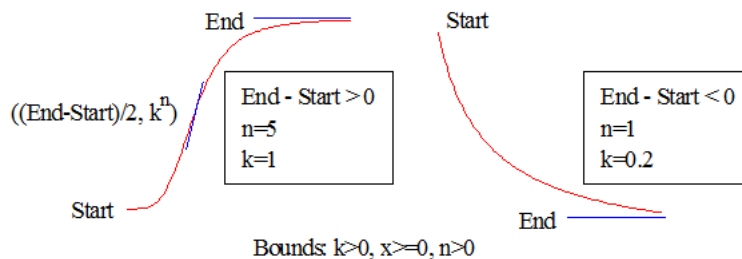
SI-5- Integral Infra-Red spectra
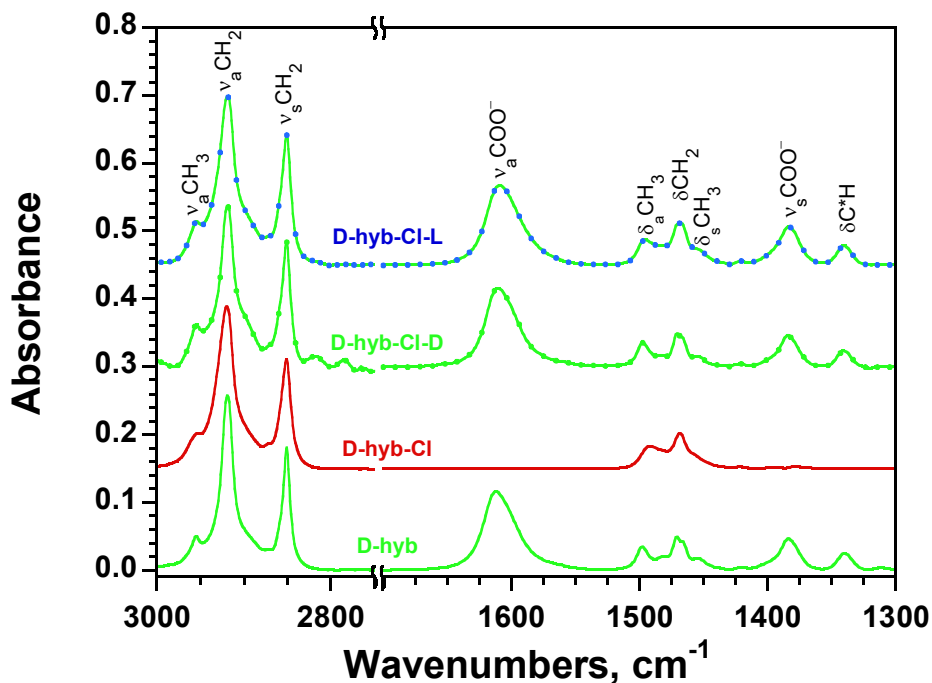
IR spectra of D-Hyb, D-Hyb-Cl, D-Hyb-Cl-D and D-Hyb-Cl-L in the 3000-2800 cm^{-1} and 1700-1300 cm^{-1} regions. Spectral measurements were carried out in D$_2$O with 20 mg/mL concentrations of the hybrid helices.

SI-6. Hill function model

$$y = START + (END - START)\frac{x^n}{k^{-n} + x^n}$$

| End — Start > 0 |
| n=5 |
| k=1 |

| End — Start < 0 |
| n=1 |
| k=0.2 |

Bounds: k>0, x>=0, n>0

SI-7. Enantiomeric enrichment of the solution

In order to study a possible enantiomeric enrichment of the L/D tartrate solution, the solution has been mixed successively with several L-Hyb-Cl systems and the CD specta of the supernatant were measured after each cycle (the supernatant of the cycle 1 is re-used and mixed with a new L-Hyb-Cl system to perform the cycle 2, etc…). The resulting g-factors shown in the following graph clearly show that the enantiomeric enrichment as measured by the g-factor values increases at the beginning before reaching a plateau at the 3rd cycle, from 1% to 2,5%.
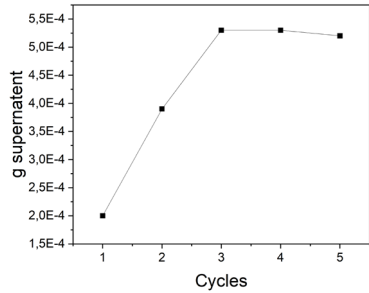
Evolution of the g-factors of the L/D tartaric acid solution in successive contact with the L-Hyb-Cl systems.

SI-8. Recyclability of the system

Using the ion-exchange method, the recyclability of the chloride exchanged hybrid system was studied. After each cycle of separation, tartrate ions were replaced by Cl⁻ ions before re-starting the separation. With this method, we were successful in demonstrating the separation of the tartaric acid racemic mixture.
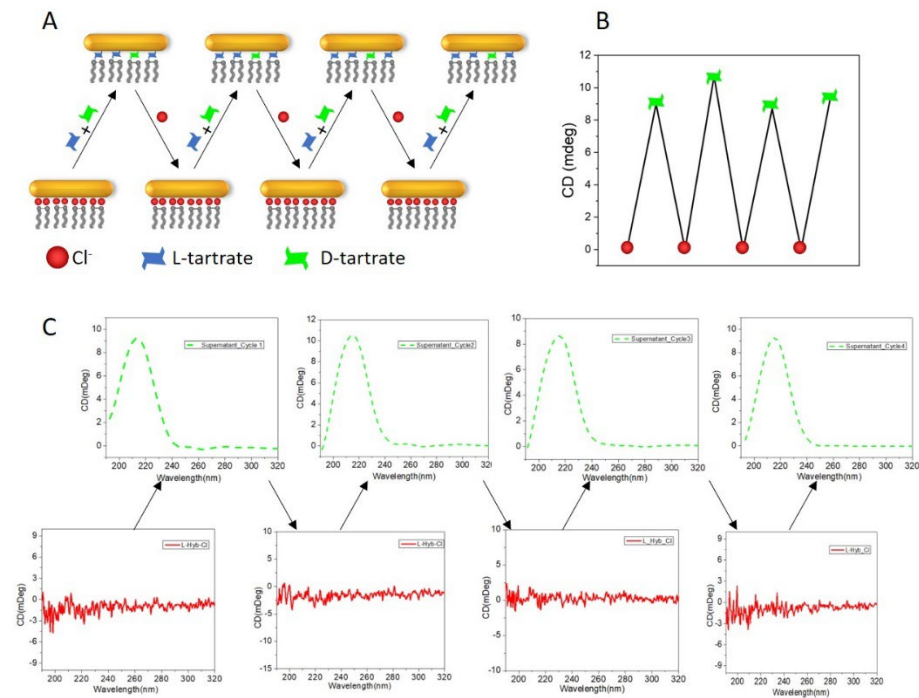

A- Schematic Representation of the ion-exchange leading to recyclability study. B- maximum of the CD signals of the L-Hyb-Cl (red) and supernatant (green) after separation of the racemic mixture of the tartrate. C- Corresponding CD spectra.

SI-9. Separation study with other analytes

We investigated to know if the system shows selective property for other chiral anions sharing similar structure such as malic acid (only one hydroxide group), glucaric acid (longer inter carboxylate distance, 4 hydroxide groups) or gluconic acid (only one carboxylate and 5 hydroxide groups).

1/ Separation of the DL malic acid:
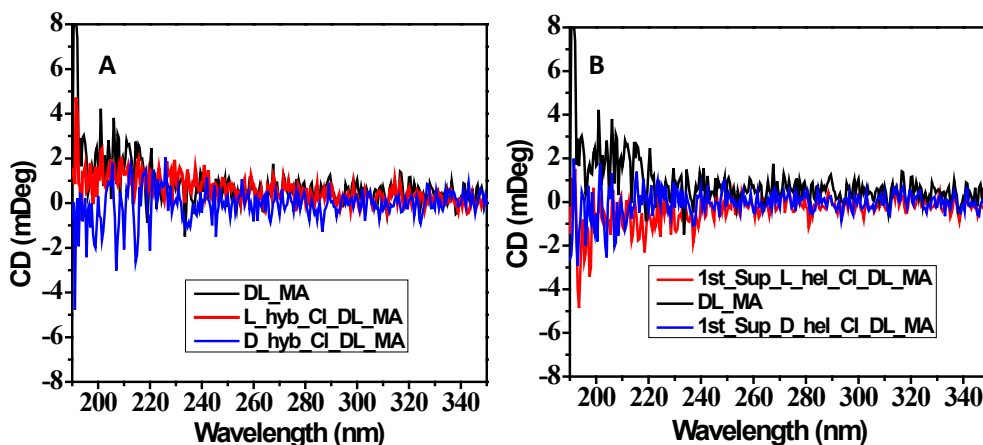
Separation study of a 10mM DL-malic acid with L-hyb-Cl and D-hyb-Cl (L-hyb-Cl/D-Hyb-Cl= 1mg/mL in Milli-Q water). A- CD spectra of the DL malic acid solution (in blak) and the precipitates after separation by L-Hyb-Cl (in red) and D-Hyb-Cl (in blue) showing no selectivity. B- CD spectra of the corresponding supernatant showing no enantiomeric excess.

2/ Selective recognition of glunonate and glucarate:
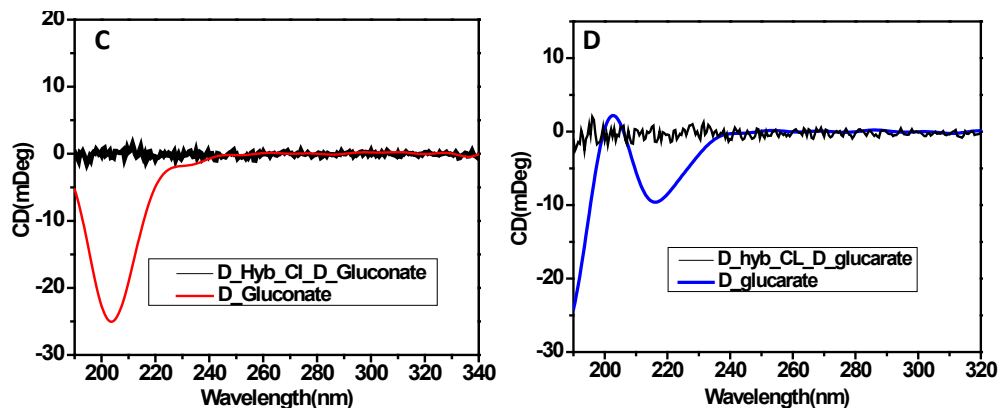
Specific recognition of D-gluconate (2 mM) and D-glucarate (2 mM) incubated with D-hyb-Cl (1mg/mL in Milli-Q water). The CD spectra of the precipitate (in black) show no interaction with the genimi surfactant for both gluconate (C) and glucarate (D).

References:

i. A. Brizard et al, Counterion, Temperature, and Time Modulation of Nanometric Chiral Ribbons from Gemini-Tartrate Amphiphiles, *J. Am. Chem. Soc.* **2007**, 129, 3754.

ii. Y. Okazaki et al, Induced circular dichroism of monoatomic anions: silica-assisted the transfer of chiral environment from molecular assembled nanohelices to halide ions, *Chem. Commun.* **2018**, 54, 10244-10247.

iii. G. Albano, G. Pescitelli, L. Di Bari, Chiroptical Properties in Thin Films of π-Conjugated Systems, *Chem. Rev.* **2020**, 120, 18, 10145–10243

iv. N. Berova, et al, Application of electronic circular dichroism in configurational and conformational analysis of organic compounds, *Chem. Soc. Rev.* **2007**, 36, 914-931.