Supporting Information

Continuous Curvature Change into Controllable and Responsive Onion-Like Vesicles by Rigid Sphere-Rod Amphiphiles

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Coarse-grained simulations (CG). Coarse-grained MD simulations using the Kremer-Grest bead-spring model¹ were performed in the present work. Our recent versatile coarse-grained (CG) model for macroions^{2, 3} was modified and applied for this particular project. This model neglects atomic details on the molecules and focuses on the important interactions such as van der Waals (VDW) and counterion-mediated electrostatic interactions to represent the molecular properties. In the model, the Keggin cluster is represented by a 1 nm diameter sphere which contains charged beads (yellow) and uncharged beads (blue) on the surface (see Figure S1). The linker and rod are represented by uncharged green and red beads, respectively, with hydrophobic properties. The linker beads have bond and angle restrictions between them and the beads at both end of the linker are bonded with the Keggin and the rod, respectively. Both the Keggin and the rod are treated as rigid bodies. Except the link beads having a size of 3 Å, all the other beads have a size of 5 Å. In the model, the uncharged beads have van der Waals interactions only while the charged beads have electrostatic interactions only. The counterions are charged beads with the VDW potentials and have opposite charges to the macroion beads. The solvent is modeled by using VDW interaction potential as uncharged beads.



Figure S1. The coarse-grained (CG) model used in this paper. The Keggin cluster is represented by a 1 nm diameter sphere where the 10 beads in blue represents uncharged beads with the VDW interactions only and the four yellow beads represents the charged beads with the electrostatic interactions only. The linker is represented by three green uncharged beads having hydrophobic properties with bond and angle restriction between them and the rod is presented by the red uncharged beads with hydrophobic properties as well. The counterions and solvents are represented by a single bead and are not shown in this figure.

The VDW interactions between different kinds of species are described by the Lennard-Jones (LJ) 12-6 potential energy function:

$$U_{LJ}(r) = \begin{cases} 4\varepsilon \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6} \right] = \varepsilon \left[\left(\frac{r_{m}}{r}\right)^{12} - 2\left(\frac{r_{m}}{r}\right)^{6} \right], \ r \le r_{c} \\ 0, \qquad r > r_{c} \end{cases}$$

 $U_{LJ}(r)$ is the VDW interaction potential as a function of the distance between beads, r; r_c is the cut-off distance; ϵ is the depth of the potential well; σ is the finite distance at which the inter-particle potential is zero and rm is the distance at which the potential reaches its minimum. The distances are related as $r_m = 2^{1/6}\sigma \approx 1.122\sigma$. In the current CG model, the parameters are in reduced units where lengths are given in units of the bead diameter σ and energies are in units of K_BT. To convert units,^{2, 3} the $\epsilon = 1.0$ energy is set to 4.5 kJ/mol, and the r=1.0 distance is set to 5 Å. The ϵ of all pair interactions between all kinds of species is 1.0. The cut-off distance r_c between rod beads and the rest is of r_m in order to capture the unfavorable hydrophobic-hydrophilic interactions between them. For all the rest LJ interactions, the r_c is set at 2.5.

The electrostatic interaction between the charged beads were described by the Coulomb pair-potential:

$$U_{Coul} = k_q \frac{q_\alpha q_\beta}{r}$$

Where q_{α} and q_{β} are the charges on each bead; and $k_q = 1/4\pi\epsilon_0$, where ϵ_0 is the permittivity of vacuum. Long range Coulombic interactions were calculated using the particle-particle/particle-mesh (PPPM) Ewald algorithm.⁴ The time step is 0.005 in reduced CG unit, equivalent to 10 fs. The macromolecules, counterions and solvent were randomly distributed at the beginning of the simulations. All the simulations were performed using LAMMPS⁵ under isothermal-isobaric (NPT) ensemble at a temperature of 1.0 and a pressure of 0.1 in reduced unit.



Figure S2. Schematic illustration of synthetic procedures for Keggin-TOF_n hybrids.

Keggin-TOF₂. Keggin-alkyne (100 mg, 0.026 mmol, 1.2 equiv) and TOF_2 -N₃ (19 mg, 0.022 mmol, 1.0 equiv) were dissolved in 10 mL DMF. The solution was degassed by three freeze-pump-thaw cycles. Then $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (1 mg, 0.2 equiv) and ascorbic acid (4 mg, 1 equiv) were added into degassed solution. After another cycle of freeze-pump-thaw, the mixtures were stirred at 40 °C for 24 h. The completion of reaction was confirmed by FTIR through the disappearance of azide peak at 2100 cm⁻¹. Then the solution was passed through an ion-exchange column (TBA⁺ form) to remove Cu²⁺. DMF was reduced *in vacuo*, and the crude product was obtained by precipitating the concentrated solution into water. After that, the crude product was absorbed by Celite and loaded onto C18 reversed phase column. The column was first eluted with water/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to remove excess Keggin-

alkyne. The column was further eluted with CH₂Cl₂/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/10) to give the solutions containing the final product. After evaporating solvents, the solid was washed with water three times and dried *in vacuo* to give the Keggin-TOF₂. Yield: 78%. ¹H NMR (CD₃CN, 500 MHz, ppm): 7.92-7.58 (m, 9H), 7.48-7.32 (m, 6H), 7.15 (d, 2H), 7.01 (t, 1H), 4.46 (t, 2H), 4.40 (d, 2H), 4.02 (t, 2H), 3.86 (s, 3H), 3.16 (t, 32H), 2.55 (t, 2H), 2.27 (t, 2H), 2.31-2.10 (m, 8H), 1.69-1.60 (m, 32H), 1.46-1.27 (m, 34H), 1.16-0.87 (m, 72H), 0.81-0.55 (m, 20H). MS (MALSI-TOF): Calculated for [M+TBA]⁺ (C₁₄₆H₂₆₅O₄₂N₉PW₁₁Sn): 4990.61, found 4990.38.



Figure S3. NMR spectra of Keggin-TOF₂ in CD₃CN.

Keggin-TOF₄. Keggin-alkyne (100 mg, 0.026 mmol, 1.2 equiv) and TOF₄-N₃ (33 mg, 0.022 mmol, 1.0 equiv) were dissolved in 10 mL DMF. The solution was degassed by three freeze-pump-thaw cycles. Then CuSO₄·5H₂O (1 mg, 0.2 equiv) and ascorbic acid (4 mg, 1 equiv) were added into degassed solution. After another cycle of freeze-pump-thaw, the mixtures were stirred at 40 °C for 24 h. The completion of reaction was confirmed by FTIR through the disappearance of azide peak at 2100 cm⁻¹. Then the solution was passed through an ion-exchange column (TBA⁺ form) to remove Cu²⁺. DMF was reduced *in vacuo*, and the crude product was obtained by precipitating the concentrated solution into water. After that, the crude product was absorbed by Celite and loaded onto C18 reversed phase column. The column was first eluted with water/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to remove excess Keggin-alkyne. The column was further eluted with CH₂Cl₂/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to give the solutions containing the final product. After evaporating solvents, the solid was washed with water three times and dried *in vacuo* to give the Keggin-TOF₄. Yield: 73%. ¹H NMR (CD₃CN, 500 MHz, ppm): 7.99-7.64 (m, 20H), 7.48-7.33 (m, 6H), 7.15 (d, 2H), 7.01 (t, 1H), 4.48 (t, 2H), 4.41 (d, 2H), 4.05 (t, 2H), 3.88 (s, 3H), 3.16 (t, 32H), 2.55 (t, 2H), 2.29 (t, 2H), 2.31-2.10 (m, 16H), 1.69-1.60 (m, 32H), 1.46-1.27 (m, 34H), 1.16-0.87 (m, 96H), 0.81-0.55 (m, 40H). MS (MALSI-TOF): Calculated for [M+TBA]⁺ (C₁₉₆H₃₂₉O₄₂N₉PW₁₁Sn): 5655.66, found 5655.01.



Figure S4. NMR spectra of Keggin-TOF₄ in CD₃CN.

Keggin-TOF₆. Keggin-alkyne (100 mg, 0.026 mmol, 1.2 equiv) and TOF₄-N₃ (48 mg, 0.022 mmol, 1.0 equiv) were dissolved in 20 mL DMF/THF (v/v=4/1). The solution was degassed by three freeze-pump-thaw cycles. Then CuSO₄·5H₂O (1 mg, 0.2 equiv) and ascorbic acid (4 mg, 1 equiv) were added into degassed solution. After another cycle of freeze-pump-thaw, the mixtures were stirred at 40 °C for 24 h. The completion of reaction was confirmed by FTIR through the disappearance of azide peak at 2100 cm⁻¹. Then the solution was passed through an ion-exchange column (TBA⁺ form) to remove Cu²⁺. Solvent was reduced *in vacuo*, and the crude product was obtained by precipitating the concentrated solution into water. After that, the crude product was absorbed by Celite and loaded onto C18 reversed phase column. The column was first eluted with water/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to remove excess Keggin-alkyne. The column was further eluted with CH₂Cl₂/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/2) to give the solutions containing the final product. After evaporating solvents, the solid was washed with water three times and dried *in vacuo* to give the Keggin-TOF₆. Yield: 70%. ¹H NMR (CD₃CN, 500 MHz, ppm): 8.01-7.67 (m, 32H), 7.48-7.33 (m, 6H), 7.15 (d, 2H), 7.01 (t, 1H), 4.50 (t, 2H), 4.41 (d, 2H), 4.05 (t, 2H), 3.88 (s, 3H), 3.16 (t, 32H), 2.57 (t, 2H), 2.31 (t, 2H), 2.28-2.06 (m, 24H), 1.69-1.60 (m, 32H), 1.46-1.27 (m, 34H), 1.16-0.87 (m, 120H), 0.81-0.55 (m, 60H). MS (MALSI-TOF): Calculated for [M+TBA]⁺ (C₂₄₆H₃₉₃O₄₂N₉PW₁₁Sn): 6320.70, found 6320.54.



Figure S5. NMR spectra of Keggin-TOF₆ in CD₃CN.

Keggin-TOF₈. Keggin-alkyne (50 mg, 0.026 mmol, 1.2 equiv) and TOF₄-N₃ (31 mg, 0.022 mmol, 1.0 equiv) were dissolved in 20 mL DMF/THF (v/v=2/1). The solution was degassed by three freeze-pump-thaw cycles. Then CuSO₄·5H₂O (1 mg, 0.4 equiv) and ascorbic acid (4 mg, 2 equiv) were added into degassed solution. After another cycle of freeze-pump-thaw, the mixtures were stirred at 40 °C for 24 h. The completion of reaction was confirmed by FTIR through the disappearance of azide peak at 2100 cm⁻¹. Then the solution was passed through an ion-exchange column (TBA⁺ form) to remove Cu²⁺. Solvent was reduced *in vacuo*, and the crude product was obtained by precipitating the concentrated solution into water. After that, the crude product was absorbed by Celite and loaded onto C18 reversed phase column. The column was first eluted with water/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to remove excess Keggin-alkyne. The column was further eluted with CH₂Cl₂/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/1) to give the solutions containing the final product. After evaporating solvents, the solid was washed with water three times and dried *in vacuo* to give the Keggin-TOF₈. Yield: 71%. ¹H NMR (CD₃CN, 500 MHz, ppm): 8.02-7.68 (m, 44H), 7.48-7.34 (m, 6H), 7.18 (d, 2H), 7.02 (t, 1H), 4.50 (t, 2H), 4.41 (d, 2H), 4.05 (t, 2H), 3.88 (s, 3H), 3.16 (t, 32H), 2.57 (t, 2H), 2.32 (t, 2H), 2.28-2.06 (m, 32H), 1.69-1.60 (m, 32H), 1.46-1.27 (m, 34H), 1.16-0.87 (m, 144H), 0.84-0.55 (m, 80H). MS (MALSI-TOF): Calculated for [M+TBA]⁺ (C₂₉₆H₄₅₇O₄₂N₉PW₁₁Sn): 6985.74, found 6985.34.



Figure S6. NMR spectra of Keggin-TOF₈ in CD₃CN.



Figure S7. Mass spectra of TOF_n (n=2, 4, 6, 8) with different rod length. The mass of repeating unit is 664.



Figure S8. Mass spectra of Keggin-TOF_n (n=2, 4, 6, 8) with different rod length. The mass of repeating unit is 664.



Figure S9. Schematic illustration of synthetic procedures of Keggin-IOF₄ hybrids.

Keggin-IOF₄. Keggin-alkyne (100 mg, 0.026 mmol, 1.2 equiv) and TOF₄-N₃ (33 mg, 0.022 mmol, 1.0 equiv) were dissolved in 10 mL DMF. The solution was degassed by three freeze-pump-thaw cycles. Then CuSO₄·5H₂O (1 mg, 0.2 equiv) and ascorbic acid (4 mg, 1 equiv) were added into degassed solution. After another cycle of freeze-pump-thaw, the mixtures were stirred at 40 °C for 24 h. The completion of reaction was confirmed by FTIR through the disappearance of azide peak at 2100 cm⁻¹. Then the solution was passed through an ion-exchange column (TBA⁺ form) to remove Cu²⁺. Solvent was reduced *in vacuo*, and the crude product was obtained by precipitating the concentrated solution into water. After that, the crude product was absorbed by Celite and loaded onto C18 reversed phase column. The column was first eluted with water/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to remove excess Keggin-alkyne. The column was further eluted with CH₂Cl₂/acetonitrile (10 mM TBABr in acetonitrile, v/v=1/4) to give the solutions containing the final product. After evaporating solvents, the solid was washed with water three times and dried *in vacuo* to give the Keggin-IOF₄. Yield: 70%. ¹H NMR (CD₃CN, 500 MHz, ppm): 7.95-7.59 (m, 24H), 7.49-7.34 (m, 3H), 7.15-7.04 (m, 3H), 7.02 (t, 1H), 4.62 (t, 2H), 4.47 (d, 2H), 4.11 (t, 2H), 3.16 (t, 32H), 2.61 (t, 2H), 2.42 (t, 2H), 2.28-2.04 (m, 16H), 1.69-1.60 (m, 32H), 1.46-1.27 (m, 32H), 1.16-0.87 (m, 96H), 0.84-0.55 (m, 40H). MS (MALSI-TOF): Calculated for [M+TBA]⁺ (C₁₉₅H₃₂₇O₄₁N₉PW₁₁Sn): 5625.63, found 5625.71.



Figure S10. NMR spectra of Keggin-IOF₄ in CD₃CN.



Figure S11. Mass spectra of Keggin-IOF₄.



Figure S12. FTIR spectra of TOF₂-N₃ and Keggin-TOF₂.



Figure S13. FTIR spectra of TOF₄-N₃ and Keggin-TOF₄.



Figure S14. FTIR spectra of TOF₆-N₃ and Keggin-TOF₆.



Figure S15. FTIR spectra of TOF₈-N₃ and Keggin-TOF₈.



Figure S16. FTIR spectra of IOF₄-N₃ and Keggin-IOF₄.



Figure S17. UV-Vis spectra of different hybrids in CH₃CN.



Figure S18. Full 2D NOESY spectra, the Zoom-in image in Figure 3b is highlighted as blue rectangle.



Figure S19. Chemical structure of DC_{60} -TOF₄.



Figure S20. DLS results of 0.2 mg/mL DC₆₀-TOF₄ in 50% THF/water solution. The R_h is 73 nm.



Figure S21. SLS results of 0.2 mg/mL DC₆₀-TOF₄ in 50% THF/water solution. The R_g is 76.0±1.5 nm. $R_g/R_h \approx 1$ indicates hollow nature of assemblies.



Figure S22. TEM images taken from the solutions of 0.2 mg/mL DC_{60} -TOF₄ in 50% THF/water.



Figure S23. TEM images taken from the solutions of 0.2 mg/mL Keggin-TOF₄ solution (70% water/acetonitrile) with addition of 10 equiv TBABr.



Figure S24. TEM images taken from the solutions of 0.2 mg/mL Keggin-TOF₄ solution (70% water/acetonitrile) with addition of 100 equiv TBABr. Due to the large size of assemblies, the center cannot be clearly shown. However, onion-like structures still exist at the edge of assemblies.



Figure S25. TEM images taken from the solutions of 1.0 mg/mL Keggin-TOF₄ solution (70% water/acetonitrile).



Figure S26. TEM images taken from the solutions of 2.0 mg/mL Keggin-TOF₄ solution (70% water/acetonitrile).



Figure S27. Cryo-TEM images taken from Keggin-TOF₄ solution.



Figure S28. Analysis of vesicle size (radius) for multilayered vesicles with 2-3 layers. The scale bar is 20 nm.





Figure S29. Analysis of vesicle size (radius) for multilayered vesicles with 4 layers. The scale bar is 20 nm.

5 layers 5 layers 25.3 nm 26.1 nm 24.6 nm 25.7 nm26.0 nm 24.7 nm 24.2 nm 25.2 nm

Figure S30. Analysis of vesicle size (radius) for multilayered vesicles with 5 layers. The scale bar is 50 nm.

6 layers



Figure S31. Analysis of vesicle size (radius) for multilayered vesicles with 6-7 layers. The scale bar is 50 nm.

8 layers



Figure S32. Analysis of vesicle size (radius) for multilayered vesicles with 8-9 layers. The scale bar is 50 nm.

10 layers



Figure S33. Analysis of vesicle size (radius) for multilayered vesicles with 10-12 layers. The scale bar is 50 nm.



Figure S34. SAXS measurements taken from Keggin-TOF₄ solution containing onion-like vesicles. The low-q peak at 0.12Å-1 corresponds to inter-bilayer distance of 5.2 nm and the high q-peak at 0.43Å-1 corresponds to distance between the Keggin ions of 1.5 nm within each individual bilayer.



Figure S35. DLS results of 0.2 mg/mL Keggin-TOF₂ in 50% water/acetonitrile solution.



Figure S36. UV-Vis spectra of Keggin-TOF₂ in different solvent polarity.



Figure S37. DLS results of 0.2 mg/mL Keggin-TOF₆ in 50% water/acetonitrile solution.



Figure S38. Random aggregation from 0.2 mg/mL Keggin-TOF₈ solution (50% water/acetonitrile).



Figure S39. DLS results of 0.2 mg/mL Keggin-IOF₄ in 50% water/acetonitrile solution.



Figure S40. Non-crystallization feature of multilayered vesicles. 1D WAXS pattern from freeze drying solution of multilayered vesicle.



Figure S41. With the slight tuning of angle between IOF₄ rods, the distance between Keggin clusters will dramatically changes.

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