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Communication

Unwinding Spherical Helices Increases Entropy and Stability of Frank−Kasper and Body-Centered-Cubic Periodic Arrays To Facilitate Discrimination between Self-Organization Mechanisms

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ABSTRACT: Spherical supramolecular dendrimers including helical, self-organize soft Frank−Kasper, other cubic such as body-centered cubic, and quasicrystal periodic and quasiperiodic arrays. When any of these periodic or quasiperiodic arrays forms immediately above a columnar phase, a supramolecular orientational memory effect was found to discriminate between mechanisms of self-organization of supramolecular spheres and generate unprecedented periodic arrays of helical columns which cannot be constructed by any other methodology. Here, we demonstrate that unwinding spherical helices, via their precursor nonhelical columns, increases the entropy and stability of their periodic and quasiperiodic spherical arrays and places the Frank−Kasper and other cubic phases immediately above the columnar phase. This process is not available in biology where spherical viruses self-organize body-centered cubic lattices. However, this concept reengineers, on increasing temperature, the originally expected position of the periodic and quasiperiodic array versus that of the columnar lattice. This process facilitates discrimination between different self-organization mechanisms of supramolecular spheres and also mediates the emergence of unprecedentedly complex and technologically important periodic arrays of nonhelical columns.

Our laboratory discovered the Frank−Kasper[1a,b] A15 phase in supramolecular dendrimers and in self-organizable dendronized polymers.[1c−j] Frank−Kasper phases and quasicrystals exhibited by supramolecular dendrimers were named soft Frank−Kasper phases and soft quasicrystals by one of us (V.P.).[1k] Soon after, the Frank−Kasper σ periodic[2a] and the liquid quasicrystal quasiperiodic arrays[2b,c] were discovered in spherical supramolecular dendrimers. Several years later, the same Frank−Kasper phases and quasicrystals were detected in block copolymers,[3] giant surfactants,[4] lipids,[5] surfactants,[6] nanocrystals,[7] and DNA particles.[8] Together with substantial theoretical work,[9] research on soft Frank−Kasper phases and quasicrystals facilitated the development of an independent field of research.[3−9] Chiral spherical helices have been shown by our laboratory to generate Frank−Kasper and body-centered-cubic (BCC) phases, as well as quasicrystals.[10] They were predicted and demonstrated to occur both by our and other laboratories, as the temperature increases, in the following order: columnar hexagonal → Frank−Kasper A15 → Frank−Kasper σ → BCC (see Figures 1a and 1b).[1i,g,2a] This order corresponds to the decrease of the number of soft spheres from the unit cell which have close contacts: 6 out of 8 spheres (75%) in the Frank−Kasper A15 phase have close contacts, 8 out of 30 spheres (27%) have close contacts in Frank−Kasper σ phase, and there are no close contacts in the BCC phase (Figure 1a). This order corresponds to the decreasing fraction of close spherical contacts and the progressive loss of columnar character.[1i,g,2a] In the most simplistic way, we can advance the hypothesis that soft supramolecular spherical dendrimers are similar to transition metals containing soft d atomic orbitals and therefore, they can

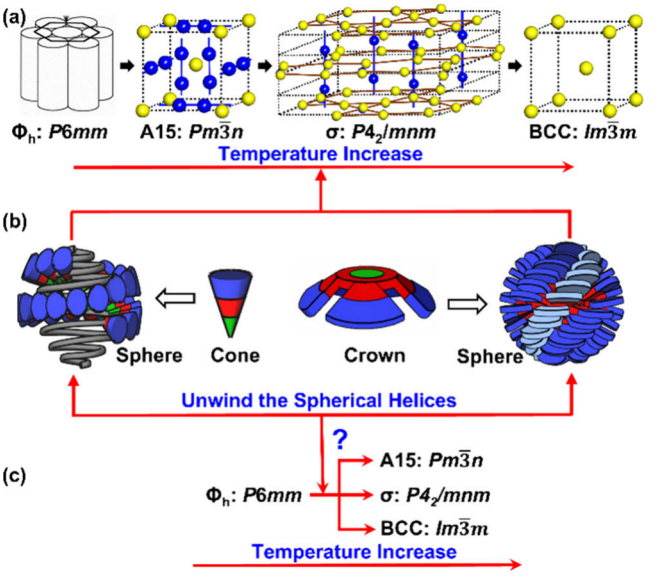

Figure 1. (a, b) Self-organization of spherical helices from conical and crown-like dendrimers and formation of their periodic arrays as a function of increased temperature; (c) unwinding of spherical helices and the potential order of their periodic arrays, as a function of increased temperature.

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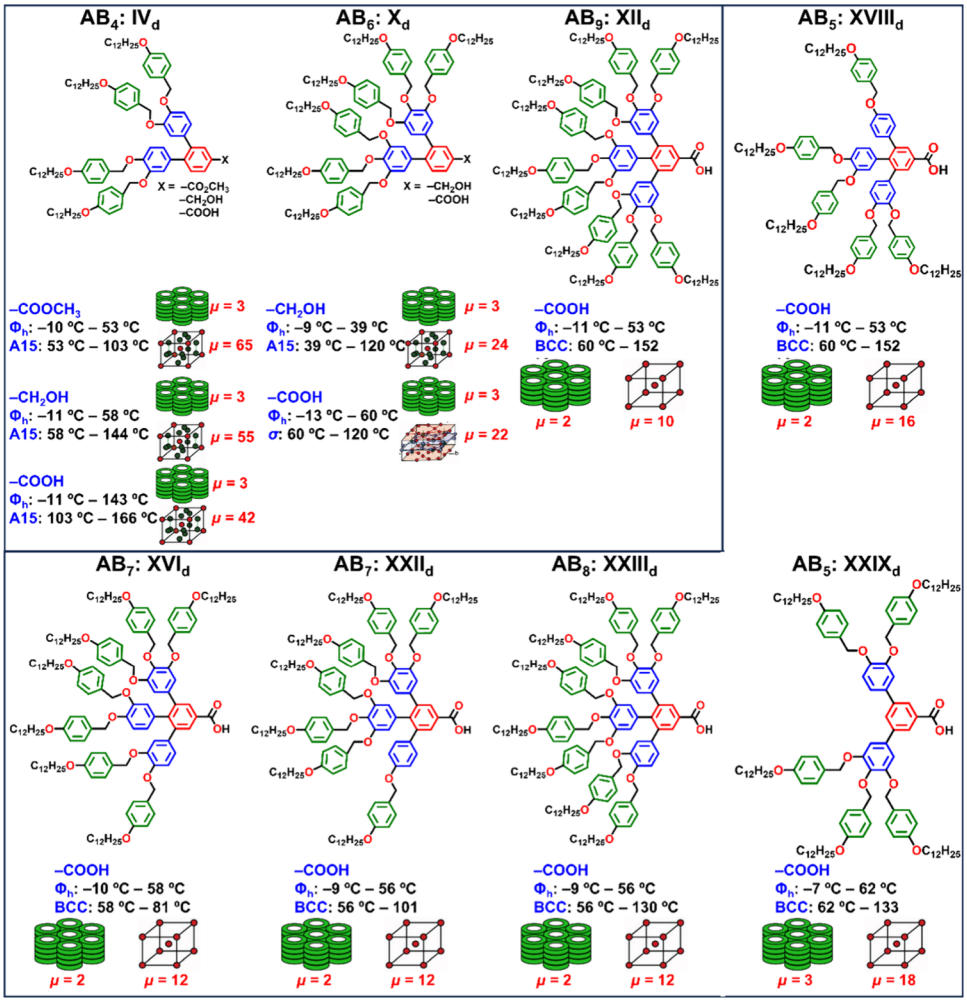

Figure 2. Structures of AB_n dendrons self-organizing columnar hexagonal, Frank–Kasper A15 ($Pm\bar{3}n$), Frank–Kasper σ ($P4_2/mnm$), and body-centered cubic (BCC) periodic arrays. Temperature ranges and the number of molecules in a unit cell are indicated.

be considered giant soft transition-metal atom-like supramolecular structures. As a consequence, both transition metals and soft spherical dendrimers exhibit Frank–Kasper phases.[1] Although exceptions from this rule of periodic array-temperature dependence exist, they have not yet been explained.[11]

For numerous applications, it would be of high interest if we could re-engineer this order and generate all Frank–Kasper, quasicrystal, and BCC arrays to occur, upon increasing the temperature, immediately above the columnar phase. The supramolecular spheres self-organizing Frank–Kasper, BCC, and quasicrystals can be approximated by short fragments of supramolecular columns when they are self-organized from crown-shaped dendrimers (see the right-hand side of Figure 1b).[10] When supramolecular spheres are produced from conical dendrons (left side of Figure 1b), they must undergo an additional cone to taper shape change at the sphere-to-column transition.[11] Therefore, in order to investigate the internal structure of the supramolecular spheres responsible for the self-organization of the Frank–Kasper phases and quasicrystals, we decided to design the internal structure of the columnar self-organizations, which are precursors to their spherical assemblies. The rational for this unprecedented conceptual approach is to design columnar self-organizations that can be characterized by oriented fiber small-angle X-ray scattering (SAXS), intermediate-angle X-ray scattering (IAXS) combined with wide-angle X-ray scattering (WAXS) experiments by the reconstruction of the X-ray diffractograms with molecular models employing methods elaborated and used in our laboratory.[10,11] Since columnar assemblies are anisotropic, they provide access to the determination of their internal structure by this combination of X-ray methodologies. SAXS and IAXS are used to determine their periodic or quasiperiodic lattice symmetry while WAXS is employed to identify their internal structure. However, Frank–Kasper, as well as other cubic and quasicrystals, are isotropic; therefore, SAXS and IAXS are used to determine only their periodic and quasiperiodic lattice symmetries, while WAXS does not provide any information on their internal structure. Therefore, we advanced the hypothesis that determination of the internal structure of supramolecular columns provides access to the internal architecture of supramolecular spheres, which are approximated by short columns (Figure 1b). As shown in recent publications,[12] this new approach was demonstrated to be successful. These concepts were employed to design the internal structure of columnar self-organizations ranging from highly ordered helical crystalline self-organizations to highly disordered nonhelical columnar liquid crystal structures. It is well-accepted that helicity minimizes the free energy of supramolecular columns, spheres and covalent macromolecules.[13,14] It is also known that increasing entropy by

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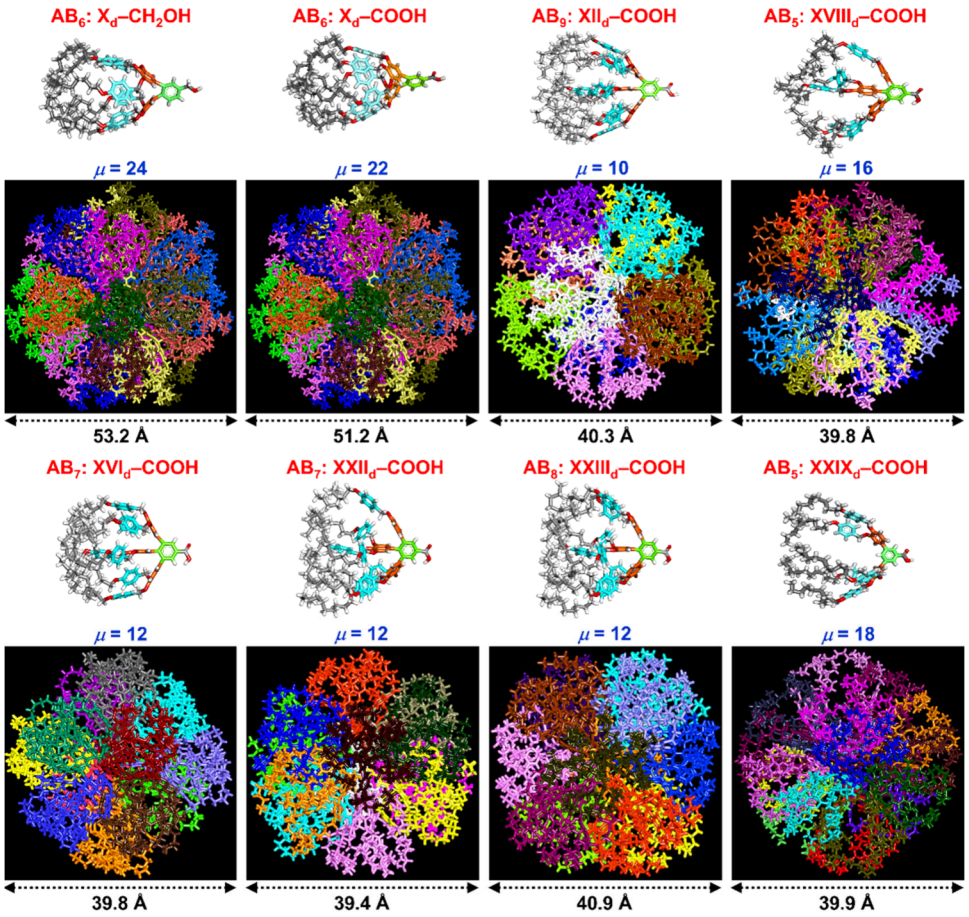

Figure 3. Self-organization of supramolecular spheres from conical AB_n dendrons. The average number of dendrons in the unit cell for $Pm\bar{3}n$ and BCC phase $\mu_{cell} = N_A\rho a^3/M_{wt}$, for σ phase $\mu_{cell} = N_A\rho abc/M_{wt}$, where N_A is Avogadro's number ($N_A = 6.022 \times 10^{23}$ mol^{-1}) and ρ is the experimental density at 23 °C. a, b, c are the experimental lattice parameters. M_{wt} is the molecular weight of the dendron. Number of molecules in the supramolecular sphere are as follows: for $Pm\bar{3}n$, $\mu = \mu_{cell}/8$; for BCC, $\mu = \mu_{cell}/2$; and, for σ, $\mu = \mu_{cell}/30$. Sphere diameters: for $Pm\bar{3}n$, $D_{sphere} = 2(3a^3/32\pi)^{1/3}$; for the BCC phase, $D_{sphere} = \sqrt{3}a/2$; and, for σ, $D_{sphere} = 2(abc/40\pi)^{1/3}$.

minimizing area is responsible for the self-organization of the periodic and quasiperiodic arrays generated from nonhelical supramolecular spheres.[9b] Unwinding the helical structure of a spherical helix is therefore, expected to increase entropy and stability of self-organizations created from supramolecular spheres. This is mediated by an entropy increase that must counterbalance the decrease in enthalpy. This concept was inspired from the "maximizing entropy by minimizing area principle of self-organization" advanced by Kamien,[9b] although it is completely different. Previously, our laboratory demonstrated that helical chirality of the columnar assemblies is transplanted from columns to spheres and therefore, both supramolecular spheres assembled from conical dendrons and from crowns form supramolecular spherical helices when generated by a first-order transition from supramolecular helical columns (see Figures 1a and 1b).[10] Therefore, we constructed nonhelical spheres from nonhelical columns[12b,c] and investigated their stability. Figure 2 summarizes our results. Unwinding of spherical helices increases the stability of the BCC and Frank–Kasper σ phases to such an extent that they both form directly from the columnar hexagonal phase.

SAXS and IAXS experiments (see Figures 1a and 1b, Figure 3, Figure 4, and Figure S1, as well as Table S1), together with experimental density, indicated that most of these supramolecular spheres can be generated either from conical dendrons or from crown-like supramolecular dendrimers. Discrimination between these two mechanisms of self-organization is not possible by X-ray diffraction experiments.

However, our laboratory demonstrated that the supramolecular orientational memory effect (SOM) elaborated in our laboratory[15] can discriminate between supramolecular spheres assembled from conical or from crown-like dendrons. In order to provide this discrimination, the Frank–Kasper phase must form immediately above the columnar hexagonal array.

The sequence of phases shown in Figure 1a cannot be used for these SOM experiments except for the case of the A15 Frank–Kasper phase. SOM was employed to demonstrate that both the A15 and σ Frank–Kasper phases from Figure 2 generated supramolecular spheres produced from crown-like supramolecular dendrimers, since they exhibit a SOM effect (see Figures S2 and S3, as well as Table S1).[15] The experiments reported here demonstrate the capability of the concept advanced in the introductory part of this manuscript and illustrate that, indeed, the internal structure of supramolecular spheres can be designed with the same helical or nonhelical order as that of their supramolecular columnar precursors. This new strategy allows SOM to discriminate between mechanisms of self-organization and, in addition, to develop unprecedented morphologies that are not accessible by any other methodology. In this particular case, we demonstrated, for the first time, the generation of orthogonal,

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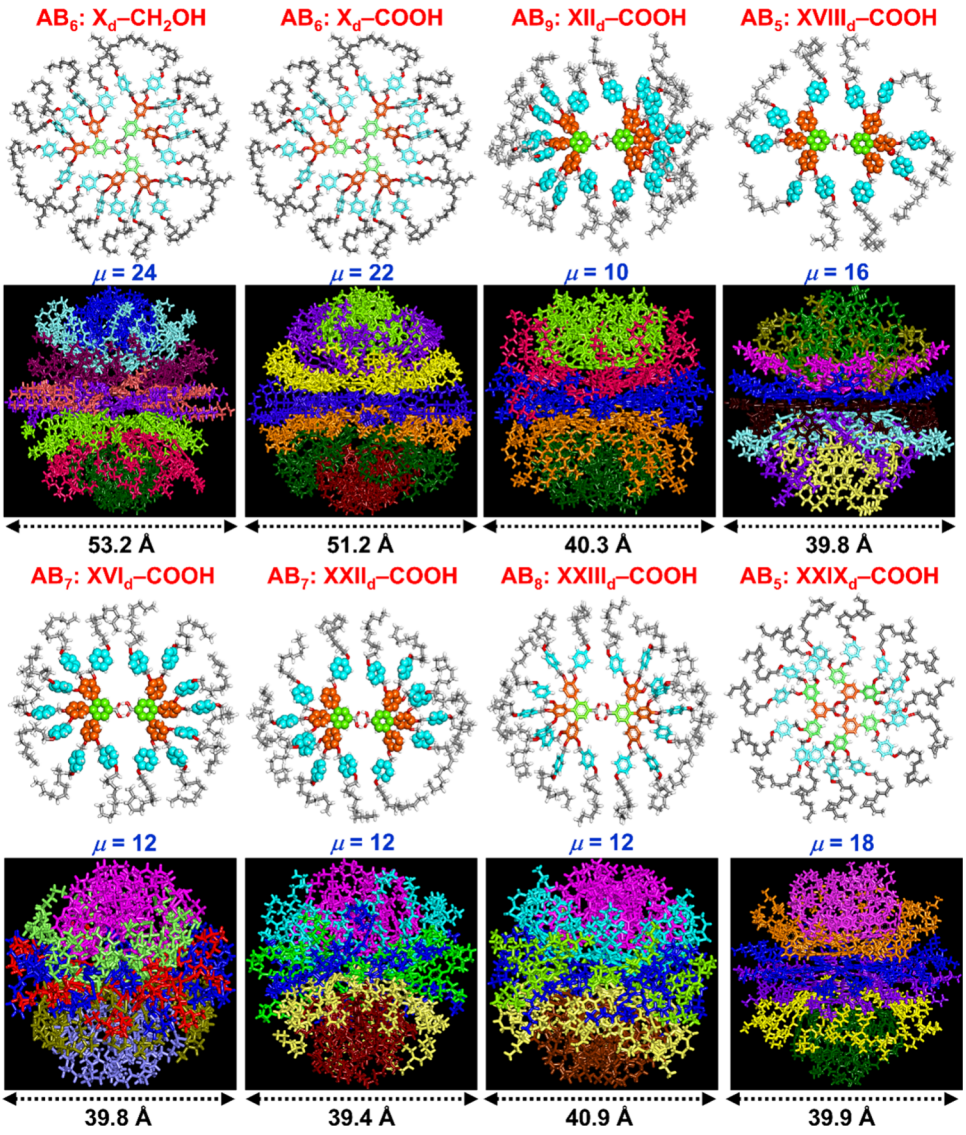

Figure 4. Self-organization of supramolecular spheres from supramolecular crown-like AB_n dendrimers. Average number of dendrons in the unit cell: for $Pm\bar{3}n$ and BCC phases, $\mu_{cell} = N_A\rho a^3/M_{wt}$; for the σ phase, $\mu_{cell} = N_A\rho abc/M_{wt}$, where N_A is Avogadro's number ($N_A = 6.022 \times 10^{23}$ mol^{-1}) and ρ is the experimental density at 23 °C. a, b, c are the experimental lattice parameters. M_{wt} is the molecular weight of the dendron. Number of molecules in the supramolecular sphere: for $Pm\bar{3}n$, $\mu = \mu_{cell}/8$; for BCC, $\mu = \mu_{cell}/2$; and, for σ, $\mu = \mu_{cell}/30$. Sphere diameters: for $Pm\bar{3}n$, $D_{sphere} = 2(3a^3/32\pi)^{1/3}$; for the BCC phase, $D_{sphere} = \sqrt{3}a/2$; and, for σ, $D_{sphere} = 2(abc/40\pi)^{1/3}$.

tetrahedral, and rhombitruncated cubooctahedral arrangements of nonhelical columns (Figure S3) with potential technological applications different from those of the helical columns including water channels[12b] and unprecedented peiodic arrays with unpredictable functions.[15] Previous examples of SOM reported from our laboratory generated similar morphologies produced from helical columns.[15] It is well-known that all spherical viruses self-organize in BCC phases.[14] However, no similar unwinding mechanism is available in biology,[14] and, at this time, it is not known if spherical dendrimersomes employed as one-component mRNA delivery systems[16] can be equipped with a related unwinding process to facilitate the delivery of the nucleic acid in the cell.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.4c13688.

Materials, methods, techniques, differential scanning calorimetry analysis, density measurements, unit cells, XRD analysis, and supramolecular orientational memory effects (PDF)

Movie showing self-assembly of spheres from conical-like dendrons (MP4)

Movie showing self-assembly of spheres from crown-like dendrons (MP4)

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

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Notes

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