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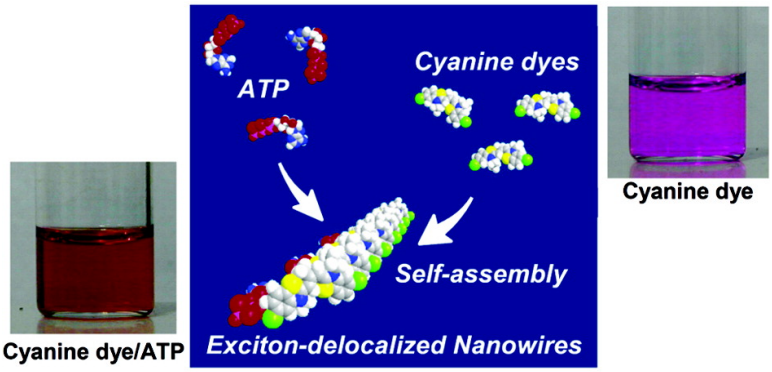

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ATP as Building Blocks for the Self-Assembly of Excitonic Nanowires

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We describe herein self-assembly of adenosine 5′-triphosphate (ATP) and dichloro-substituted thiacarbocyanine dyes into thermochromic supramolecular nanowires. Excitonic interactions among chromophores aligned in the nanowires and their reversible dissociation/reassembly characteristics render them a new family of biomolecules-based nanowire systems.

Integration of biologically important small molecules and functional organic molecules provides access to supramolecular nano-architectures that are capable of converting biomolecular structural information to physicochemical signals. However, to date, studies on self-assembly of biological molecules have been focused on large biopolymers such as proteins,[1] oligopeptides,[2] and nucleic acids.[3] Smaller biomolecules have been important targets for bio- and chemosensors, but they have not been considered as building blocks for creating functional supramolecular systems. For example, ATP, a universal energy currency in all of the biological systems, has been recognized by synthetic host−guest receptors,[4] peptides,[5] and RNA aptamers.[6] Though the binding of ATP molecules is crucial for some ATP-dependent protein assemblies,[7] development of ATP-directed artificial self-assembly has been unexplored.

We have searched for cationic chromophores which display color changes in the presence of ATP, and we came across a thiacarbocyanine dye **1**. It gives a monomeric absorption peak in methanol at 549 nm. On the other hand, a blue-shifted peak appeared at 506 nm in water, in addition to the monomer peak at 546 nm (Figure 1a). The intensity of the 506-nm peak relative to that of the 546-nm peak is increased at higher dye concentrations, indicating that the 506-nm peak is attributed to card-packed dimers which are in equilibrium with monomeric species.[8,9]

When ATP was added to aqueous solution of **1** (concentration 11 μM) at varied molar ratios, immediate color change occurred from pink to orange. Figure 1a also shows visible absorption spectra of **1** obtained at ATP concentrations of 2 and 45 μM. Addition of ATP caused a decrease in absorption intensities at 546 and 506 nm, and a new absorption peak appeared at 463 nm. In circular dichroism (CD, Figure 1b), intense peaks are observed at 423 (with positive sign) and 475 nm (with negative sign). As these signals are observed for the absorption band of achiral chromospheres, they are induced circular dichroism (ICD). The observed complex ICD pattern is indicative of excitonic interactions among multiple chromophores,[10] and the spectral blue shift to 463 nm is ascribed to the formation of parallel-oriented chromophores (H-aggregates) in chiral **1**/ATP assemblies.[11] These assemblies grow rapidly in water, as they are separated from the dispersions as fibrous microstructures (concentration of ATP, below ca. 50 μM) within 1 h. Interestingly, formation of H-aggregates is facilitated most in the presence of ATP and not by the other nucleotides (ADP or AMP). Figure 1c shows the dependence of A_{463}/A_{546}, the relative absorbance at 463 (H-aggregates) and 546 nm (monomers), on the concentration of nucleotides. More than 10-fold ADP molecules are required to attain absorption intensity of H-aggregates that are formed in aqueous ATP (see Supporting Information). It is also noteworthy that such supramolecular assemblies are not formed from AMP even at high concentrations. It is obvious that the chemical structure of nucleotides (number of anionic charges) plays a crucial role in promoting the H-aggregate formation.

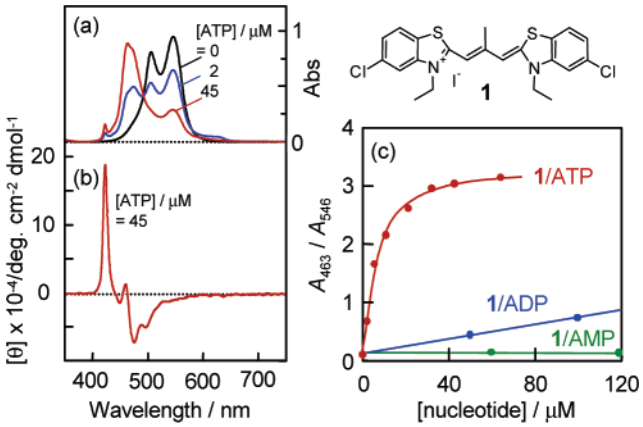

Figure 1. (a) Visible absorption and (b) CD spectra. **1** is mixed with ATP in water ([**1**] = 11 μM, pH 9, methanol content; 8 vol %). (c) Dependence of relative absorbance intensity (A_{463}/A_{546}) on nucleotide concentrations.

The stoichiometry for **1**/ATP and **1**/ADP assemblies is determined by using the continuous variation method. The absorption at 463 nm increased with the molar fraction of dyes (X_{dye}) and gave peaks in the vicinity of $X_{dye} = 0.75$ (for **1**/ADP) and $X_{dye} = 0.85$ (for **1**/ATP), respectively. These values correspond to average binding ratios of 3:1 for **1**/ADP and 6:1 for **1**/ATP. These compositions deviate somewhat from those simply expected from electrostatic interactions. The excess binding of **1** to ATP gives positive net charges to the nanowires, and accumulation of multiple secondary forces such as van der Waals interactions, hydrophobic interactions, and aromatic stacking would be responsible for the observed complexation ratio.

The morphology of the supramolecular assemblies is observed by transmission electron microscopy (TEM, JEOL JEM-2010, acceleration voltage, 120 kV). Interestingly, aqueous **1**/ATP ([**1**] = 11 μM, [ATP] = 45 μM) gives developed nanowires with a minimum width of ca. 10 nm and lengths of several micrometers (Figure 2a). The observed width of nanowires is larger than the molecular size of **1** (ca. 1.6 × 0.7 nm) and ATP (ca. 1.4 × 1.0 nm), indicating that they consist of bundled **1**/ATP complexes. Similar nanowires are also observed for aqueous **1**/ADP when they form H-aggregated pairs (concentration of ADP, 45 μM). On the

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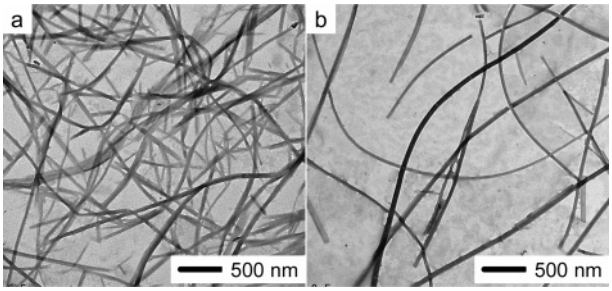

Figure 2. TEM images of **1**/ATP mixtures. (a) Aqueous dispersion of **1** and ATP mixed at 25 °C. (b) Nanowires reassembled by cooling the heat-dissociated mixture (temperature, 55 °C) to 5 °C. Aqueous samples were dropped on carbon-coated grids and were poststained with uranyl acetate. [**1**] = 11 μM, [ATP] = 45 μM; heating/cooling rate, 2 °C min^{-1}.

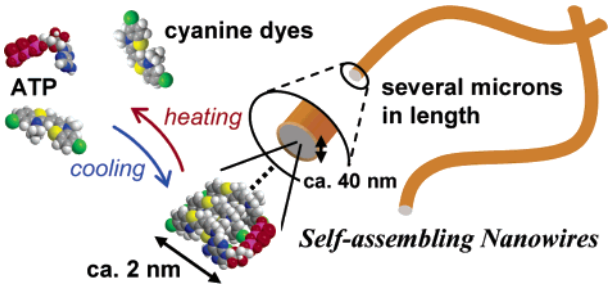

Figure 3. Schematic illustration of supramolecular nanowires self-assembled from ATP molecules and cationic cyanine dyes **1**.

other hand, monomeric dyes in aqueous **1**/AMP (at any concentrations) gave no aggregate structures. As no aggregate structures are observed for these single components alone, formation of nanowires requires integration of **1** and ATP. This feature is also common to artificial complementary hydrogen bond networks in water[12] and supramolecular hydrogels.[13] In these systems, highly developed amphiphilicity is acquired upon the formation of specific molecular pairs, and it is essential for their hierarchical self-assembly in water. In the present nucleotide/cyanine pairs, it is also expected that the water environment favored the amphiphilic organization of **1**/ATP into supramolecular nanowires.

The ATP-directed self-assembly is thermally reversible. Temperature dependence of the absorption intensity at 463 nm (H-aggregates) was examined. Upon heating, the peak intensity is gradually decreased and is replaced by the monomeric absorption peak at 546 nm (55 °C).[14] At 55 °C, nanowires were not observable in TEM, in agreement with the spectral observation. Therefore, the excitonic nanowires formed at room temperature are dissociated into nonaggregated ion pairs at elevated temperatures. On the other hand, the intensity of the 463-nm peak is restored upon cooling the dispersion below 44 °C, and nanowires with regular widths of ca. 40 nm are abundantly observed (Figure 2b). The enhanced regularity in the nanowire structure is indicative of improved molecular order in the supramolecular assemblies.

A schematic illustration of the thermally reversible self-assembly of excitonic nanowires is shown in Figure 3. Cyanine dyes **1** bind to ATP by multiple secondary interactions, and these complexes further self-assemble into the developed nanowires. In these **1**/ATP nanowires, cyanine chromophores form H-aggregates, as revealed by the exciton-coupled absorption and ICD spectra. The supramolecular nanowires display reversible thermal dissociation/reassembly characteristics, reminiscent of the lipid-packaged conjugated nanowires of one-dimensional mixed-valence complexes in organic media.[15]

In summary, self-assembling, excitation-delocalized nanowires are formed from ATP and cyanine dyes. As far as we are aware, this is the first example of ATP-based supramolecular nanoassemblies. Though adsorption of cationic cyanine dyes on DNA[16] and peptide nucleic acids (PNA)[17] has been reported, those are local dye aggregation phenomena on the pre-existing polymer scaffolds. No morphological investigations have been made for these biopolymer mixtures, and they lack the element of bottom-up assembly from small biomolecules. By employing the noncovalent combinatorial approach, biologically important small molecules turn to building blocks for the functional nanoarchitectures. Lipids or amphiphiles are no longer required as structure-directing units. Excitonic chromophore arrays as observed in this study are expected to show efficient energy migration along the nanowires,[13] and we also envisage that control of interactions between ATP-based nanowires with ATP-binding proteins may lead to biosensory applications.

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Supporting Information Available: Experimental details, spectral data, TEM and optical microscopy of nucleotide/**1** complexes, and their analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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