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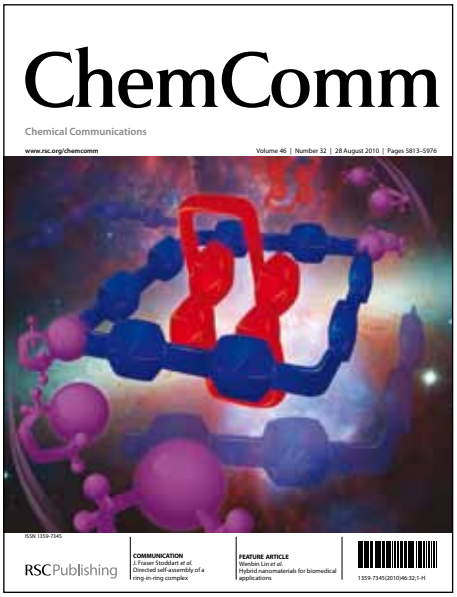

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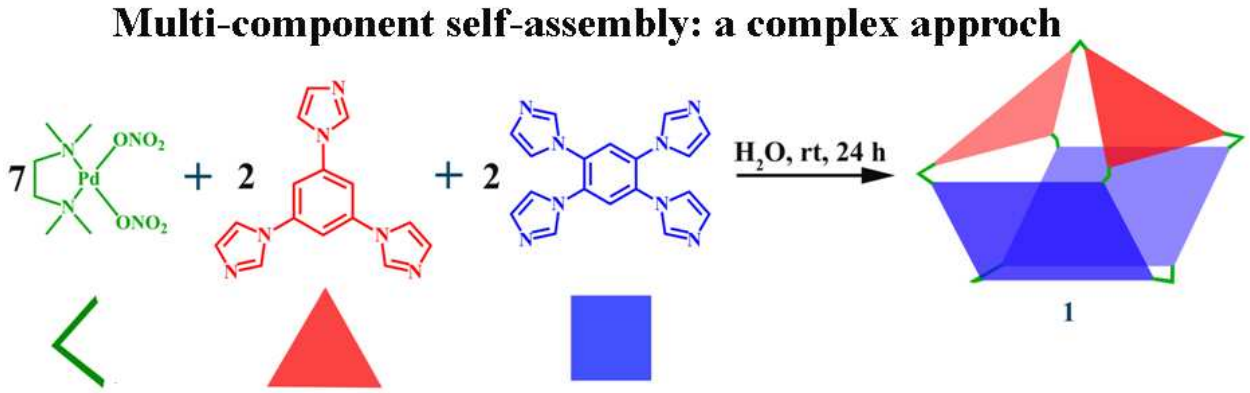
TOC

Multicomponent self-sorting of a Pd_7 molecular boat and its use in catalytic Knoevenagel condensation

Dipak Samanta and Partha Sarathi Mukherjee*



A unique three–component self-assembly of a *cis*-blocked 90° Pd(II) acceptor with a mixture of tri- and tetra-imidazole donors led to the self-sorting of a Pd_7 molecular boat, which was found to catalyse Knoevenagel condensations in aqueous medium.

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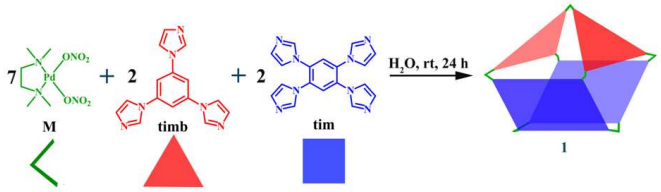
Unique three–component self-assembly of a *cis*-blocked 90° Pd(II) acceptor with a mixture of tri- and tetra-imidazole donors led to the self-sorting of a Pd_7 molecular boat with internal nanocavity, which catalyses the Knoevenagel condensation of a series of aromatic aldehydes with 1,3-dimethylbarbituric acid and Meldrum's acid in aqueous media.

Construction of supramolecular nanocages containing porosity/ channels is highly appealing for their potential applications in catalysis, gas adsorption, sensing, separation *etc*.[1] Recent past has witnessed that architectures having predetermined structures and functions can be obtained by engineering of complementary building units via self-assembly.[2] In this context, metal–ligand coordination driven self-assembly[3] has been proven to be a potential protocol for the construction of nanoscopic metallacages due to predictable directionality and high bond-enthalpy. Pd(II)/ Pt(II) in combination with polypyridyl donors have been widely used to construct several discrete architectures.[4] Two-component self-assembly has been widely used and easy to control. Recently, multi-component self-assembly[5] has come up as an effective and alternative approach to accomplish complex architectures using more than two components in a single step. Though the selective formation of a single discrete product from multicomponents is entropically unfavorable, a few strategies have been formulated to sweep over the entropic penalty using driving forces such as steric hindrance, host-guest interaction, *etc*.(higher enthalpic contribution).[6] Imidazole is better donor compared to pyridyl donor and more importantly, imidazole can have at least two different conformations (in plane) due to free rotation of C-N bond that connects them to the backbone of the ligand. This makes polyimidazole linkers to gain special attention. Until now, a very few 3D architectures are known that are obtained from a mixture of ditopic and tri- or tetratopic donors with metal acceptors (multicomponent approach), with or without employing templates.[5-6] To the best of our knowledge, a self-assembled multicomponent discrete architecture composed of both tri- and tetra-topic donors is yet to be reported due to difficulty in prediction of the final structure from the mixture of ligands having multiple donor sites.

Herein, we report an example of multicomponent self-sorted Pd_7 nanocage $[\{(tmen)Pd\}_7(timb)_2(tim)_2](NO_3)_{14}(H_2O)_{20}$ (**1**), [tmen = N,N,N',N'-tetramethylethylenediamine, timb = 1,3,5-tris(1-imidazolyl)benzene, tim = 1,2,4,5-tetrakis(1-imidazolyl)benzene][7] composed of both tri- and tetra-topic linkers (Scheme 1). The cavity of this cage was utilized as nanoreactor for catalytic Knoevenagel condensations[8] of a series of aromatic aldehydes with 1,3-dimethylbarbituric acid (**e**) and Meldrum's acid (**f**) in aqueous medium.



Scheme 1. Three-component self-assembly of a Pd_7 cage (**1**) from *cis*-blocked Pd(II) 90° acceptor (M), tri-imidazole (timb) and tetra-imidazole (tim) donors.

In all the previous multicomponent coordination-driven assembly, a ditopic donor was assembled with metal acceptor in combination with a tri-/ or tetra-topic donor. To take multicomponent directional self-assembly to next level of complexity, we performed self-assembly of a 90° Pd(II) acceptor with a mixture of tritopic (timb) and tetratopic (tim) donors. One can anticipate trifacial barrel[9] and semi cylindrical molecular barrel[10] from the combination of the acceptor with individual donor separately and a molecular boat composed of all the three components (Scheme 2). In the recent past, we have established the formation of semi-cylindrical barrel *via* two-component self-assembly of Pd(II) acceptor with triimidazole donor (timb).[10] However, exclusive self-sorting of a Pd_7 molecular boat, incorporating both tri- and tetra-imidazole donors with 90° acceptor, was rather surprising due to absence of such kind of report in literature.

A yellow aqueous solution of *cis*-$(tmen)Pd(NO_3)_2$ was added into solid mixture of tri- and tetra-topic donors (timb and tim) in 7:2:2 ratio and allowed to stir for 24 h at room temperature. An immediate sharp visual color change from yellow to colorless and slow consumption of suspended solid donor indicated the progress of the reaction. Pure complex **1** as off-white precipitate was isolated by triturating the concentrated solution with acetone.

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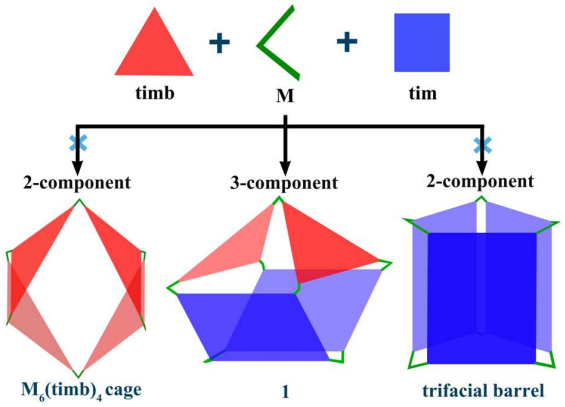
† Electronic Supplementary Information (ESI) available: Synthesis, spectroscopic characterization of the cage **1**, the product of the catalytic Knoevenagel condensations and crystallographic analysis for **1**. For cryatallographic data in CIF, ESI see DOI: 10.1039/b000000x/



Scheme 2. Possible molecular architectures from the individual linkers (tim or timb) with the acceptor (M) and three-component assembled cage (**1**).

Though ^{1}H NMR analysis was quite complicated with four sets of each four protons of tim and three sets of four protons of timb (Fig. 1), identical diffusion coefficients (2.6×10^{-10} m^2/s) for all the proton signals in diffusion-ordered (DOSY) NMR spectroscopic analysis (ESI†), ruled out the formation of mixture of products. Similarly, expected downfield shifts of the tim as well as timb were noticed in the proton signals (Fig. 1), resulting from loss of electron density of the donors upon coordination to Pd(II). Several salient peaks at m/z 1159.7, 852.9, 546.5 and 343.5 correspond to $[\mathbf{1} - 3NO_3^-]^{3+}$, $[\mathbf{1} - 4NO_3^-]^{4+}$, $[\mathbf{1} - 6NO_3^-]^{6+}$ and $[\mathbf{1} - 9NO_3^-]^{9+}$, respectively in the ESI-MS spectrum further support the formation of [7 + 2 + 2] self-assembled product. Other possible combination of Pd acceptor, tri- and tetraimidazole donors in 5:2:1 ratio also yielded **1** along with $Pd_6(timb)_4$ cage.

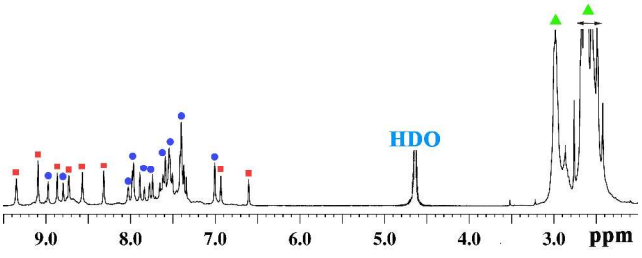


Fig. 1 ^{1}H NMR spectrum of complex **1** recorded in D_2O (colour codes: blue circles = timb, red squares = tim, green triangles = tmen).

Finally, single-crystal X-ray analysis (ESI†) unambiguously established the formation of a Pd_7 molecular boat (Fig. 2) comprising of both tim and timb linkers. Single crystals suitable for X-ray diffraction were obtained by slow vapor diffusion of acetone into aqueous solution of the complex **1** at room temperature for two weeks. Though there are severe disorders in nitrate anions and solvent molecules due to poor diffraction of the crystal, low temperature X-ray diffraction data disclosed the formation of a Pd_7 molecular boat without any doubt. Complex **1,** that crystallized in triclinic system with space group P-1 has three different Pd(II) centers. Pd1- Pd4 are linked to one timb-N and one tim-N. Pd5 and Pd6 are coordinated to two tim-N, and Pd7 is connected to two timb-N to attain square planar geometry with Pd-N average bond distances in the range of 2.03 – 2.04 Å. The average diagonal distance between the orthogonal Pd-metal centers is 17.05 Å. BET surface area was very low of the order of 0.49 m^2/g with pore diameter calculated using Harvath-Kawazoe method was 1.0 nm. Three different imidazole rings in timb are in different magnetic environments in complex **1**. Likewise, one half of tim is different from the other half due to different connectivity which is reflected in the NMR spectrum (Fig.1). More interestingly, two tim and two timb units are converged inward to adopt a boat like architecture. Notably, two NO_3^- are located in the internal cavity of complex **1** and the persisting counter-anions placed outside the cage.

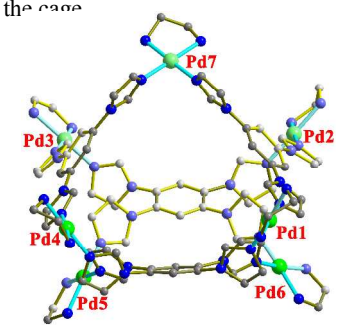
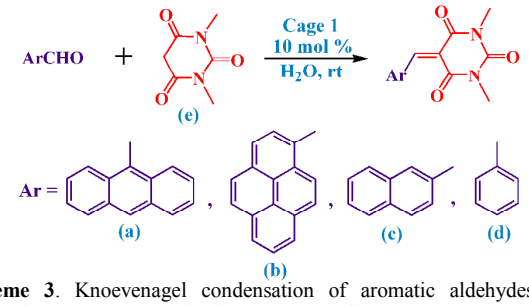


Fig. 2 Molecular structure of complex **1**. Colour codes: light green = Pd; blue = N, grey = C. For clarity, all hydrogen atoms, methyl groups, counter anions and solvent molecules are removed.

In biological systems, the reactivity of one molecule can be tuned by sequestering it from the bulk to achieve high catalytic activity, selectivity of enzyme to the substrate, and storage or transport of proteins.[11] The interior cavity of the cage (Fig. 2) is surrounded by the aromatic walls of the tri- and tetra-imidazole donors. Such cavity provides a suitable environment to encapsulate large planar aromatic guest such as 9-anthracenealdehyde (**a**) through π-π stacking interaction with the walls of the cage.[10] When an excess of **a** was suspended in an aqueous solution of **1**, the colorless solution turned yellow in 1 h upon stirring at room temperature. Though NMR spectrum of the encapsulated complex was very complicated, UV-Vis spectroscopic analysis (ESI†) and sharp color change indicated encapsulation of **a** within the hydrophobic cavity of **1**. This prompted us to explore complex **1** as a catalyst for Knoevenagel condensation of a number of aromatic aldehydes with **e** (dimethylbarbituric acid) and **f** (Meldrum's acid) at ambient condition especially in green aqueous medium (Scheme 3).



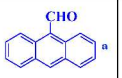
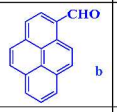
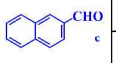
Scheme 3. Knoevenagel condensation of aromatic aldehydes using molecular cage **1** as a catalyst in aqueous medium.

Water is generally not considered as favorable solvent for Knoevenagel condensation as water is a byproduct of such reaction and may drive the backward reaction. Therefore, performing dehydration reactions like Knoevenagel condensation in environmental friendly aqueous medium is a challenging approach. Aldehyde **a** was treated with one equivalent of **e** in presence of 10 mol% of cage **1** in 1 mL of water and the mixture was allowed to stir. After 72 h, the condensation product (**2**) was extracted with $CDCl_3$ and NMR spectroscopy revealed that compound **2** was formed in ~35 % yield (with respect to aldehyde). The product was characterized by elemental analyses, ESI-MS as well as NMR (ESI†). To conclude the catalytic activity of **1**, we carried out the same reaction in absence of cage

in water, and found that the reaction proceeded poorly with very low yield (~5 %). Even in organic solvents ($CHCl_3$, acetone, dichloromethane), only ~3-4 % of aldehyde transformed to product after 72 h. We believe that, at first, the aromatic aldehyde is encapsulated within the hydrophobic cavity of the cage (**1**) via π-π stacking interaction between the aromatic walls of the cage and aromatic backbone of aldehyde to form host-guest complex. After the reaction, due to the hydrophobicity of the pocket, the loss of water takes place easily to generate dehydrated product which is too bulky for encapsulation and readily comes out of the cage.

Similarly, the condensation of 1-pyrene aldehyde (**b**) with **e**, efficiently elevated to ~33 % within 3 h whereas the reaction is scarcely occurred without cage (~2 %). We have also performed the same reaction with individual components [*cis*-(tmen)$Pd(NO_3)_2$, tim or timb] and found that reaction progressed only up to ~3 % which clearly suggested that the hydrophobic cavity is crucial for the reaction. Relatively smaller aldehyde, 2-naphthaldehyde (**c**), in general, reacts with active methylene compound even in aqueous media due to higher reactivity. However, when we performed the reaction in presence of the cage, the yield of the condensation product (**4** and **5**) significantly increased (Table 1), which demonstrates that the cavity of the cage plays a vital role in promoting the reaction. In contrast, benzaldehyde (**d**) undergoes condensation with **e** at almost equal rate corresponding to the reaction without cage (Table 1). Initially, it was thought that due to higher reactivity of **e**, cage has not influenced the yield. To verify this, we replaced **e** with **f**, where **f** is lesser reactive than **e** owing to higher p*Ka* and found that in this case also, cage doesn't regulate the yield. We also checked the reaction of aliphatic aldehyde like isobutyraldehyde with **e** for 10 h in presence of **1**, which showed no rate enhancement. Such observation demonstrates that the cavity of the cage **1** is quite selective in promoting the rate of Knoevenagel condensation of polycyclic aldehydes, which are very less reactive at ambient condition in aqueous medium without any catalyst.

Table 1. Yields of the Knoevenagel condensations of aromatic aldehydes and active methylene compounds in presence and absence of cage **1**.

ArCHO	Active methylene compounds	Time	Product (Yield %)	
			With 1	Without 1
 a	e	72 h	2 (35)	2 (5)
 b	e	3 h	3 (33)	3 (2)
 c	e	75 min	4 (77)	4 (25)
	f	8 h 30 min	5 (51)	5 (21)
 d	e	4 min	6 (69)	6 (64)
	f	6 h	7 (58)	7 (45)

In conclusion, we have demonstrated social self-sorting of an unprecedented Pd_7 molecular cage (**1**) *via* multi-component self-assembly of tri- and tetra-imidazole donors without employing any template. Such interesting social self-sorting was possible due to having required directions of the donor nitrogens of the building units. This approach may have wide application in generating further complex architectures of varied shapes and sizes using multiple donors with higher denticity. Along with the structural confirmation through ESI-MS and NMR studies, single crystal X-ray analysis showed that the cage **1** has a large internal cavity. Furthermore, the preferential affinity of the cavity towards aromatic molecules through π-π stacking has been successfully employed to catalyze the Knoevenagel condensation of a series of aromatic aldehydes with 1,3-dimethylbarbituric acid /Meldrum's acid in green aqueous medium. Construction of water soluble other polyhedral cages *via* multi-component self-assembly including their host-guest chemistry and further exploitation in catalytic reactions[12] have potential to explore.

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