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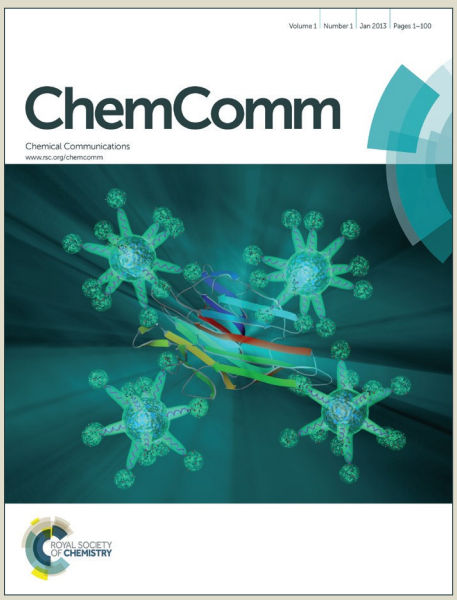

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COMMUNICATION

Coordination-driven self-assembly of iridium-cornered prismatic cage and encapsulation of three hetero guests in its large cavity†

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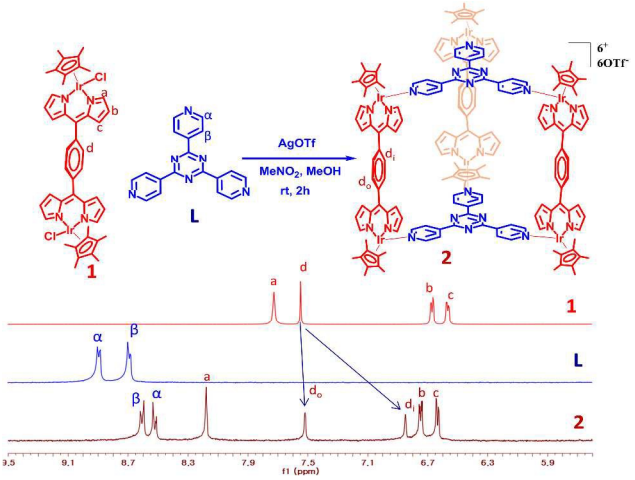
A hollow iridium-cornered prismatic cage was self-assembled without the assistance of any template. The cage was found capable of encapsulating hetero guest's triplet in its perfect sized cavity, producing the first such demonstration by an octahedral metal cornered prismatic cage.

Supramolecular container molecules with internal cavity, capable of accommodating large molecular guests, have received widespread attention owing to their numerous potential abilities such as molecular flasks for chemical reactions,[1] containers for labile chemical species,[2] transport vehicles for drug molecules,[3] hosts for aromatic stacks[4] and sensors.[5] For the synthesis of such molecules of finite shapes and sizes, coordination-driven self-assembly is one of the most efficient tools.[6] The two most common strategies applied for the synthesis of heteroleptic coordination cages[7] are: 1) self-assembly of more than two components involving square planar metal centers[8] and 2) self-assembly of two components using pre-designed acceptor clips and donor ligands.[9] Multi-component self-assembly with square-planar Pd(II) and Pt(II) has been extensively used to generate polyhedra, spheres, cubes, and prisms.[6] Fujita's group constructed a large number of trigonal prisms using square planar Pd(II) acceptors, a tritopic donor, and a linear donor of varying height with the assistance of aromatic templates.[4, 10] These prismatic cages have been used as hosts for triple to nonuple stacking of aromatics.[11] They also demonstrated numerous other applications of such assemblies and reported many unique properties of the encapsulated molecules. The characteristics of the encapsulated molecules were found to be totally different from their free state.[12] In contrast, two-component self-assembled cages using pseudo-octahedral geometries of Ru(II),[13] Rh(III),[14] and Ir(III)[15] have also been prepared and used for many encapsulation-based applications. In particular, Ru(II)-based coordination cages have demonstrated very exciting applications in target drug delivery system[3a] and photodynamic treatment by encapsulating drug molecules.[3b] However, most of these organometallic cages have relatively smaller cavity that permits just one guest inside and synthesis of a larger prismatic cage from two components self-assembly is still very challenging. Recently, an octahedral Ru(II)-cornered prismatic cage capable of encapsulating two molecules of coronene has also been reported[16] but acceptor clip based two component self-assembled architectures capable of encapsulating more than two guests have not been explored so far.

The literature reviewed here clearly indicates that the environment within the cage cavity is governed by local steric and electronic environments of the metal and organic ligands, enabling the incoming guests to establish new intermolecular interactions. Therefore, assemblies of new prismatic cages by varying the metal geometry and organic ligands provide a huge potential for numerous applications.

Herein, we report the two components self-assembly of a large prismatic cage without the assistance of any template, encapsulating three planar hetero guests through π–π stacking. For this purpose, we designed a new acceptor clip **1**[17] with metal-metal distance of 12.623(4) Å which is approximately four times of the π–π stacking distance.[18] The height of the acceptor generated clear idea that the resulting cage after combining it with a tripodal donor can accommodate three large planar molecules in its cavity.



Scheme 1. Self-assembly of prismatic cage 2 and comparison of ^{1}H-NMR of **1**, **L**, and **2** in CD_3OD/CD_2Cl_2 (1:1)

As shown in Scheme 1, prismatic cage 2 was quantitatively obtained by the self assembly of acceptor clip **1** with commonly used ligand 2,4,6-tris(pyridin-4-yl)-1,3,5-triazine(L) in the presence of silver triflate. Interestingly, no template was required for the self-assembly of hollow prism **2**. The bonding between ligand **L** and metal was indicated by the ^{1}H-NMR of cage **2**, as α and β pyridyl protons (PyH) were shifted upfield. Moreover, the singlet peak at 7.48 ppm for four phenyl protons of acceptor **1** split into two singlet peaks at 7.54 and 6.84 ppm, indicating the hindered rotation of phenyl ring which was also supported by ^{1}H-^{1}H ROESY NMR shown coupling between phenyl and neighbouring pyrrole protons assigned as d and c (Scheme 1). All the peaks were assigned following the ^{1}H-^{1}H ROESY and ^{13}C NMR provided in SI (Fig. 9-10S).

Using cage **2**, the inclusion complex **[2⊃(G$_1$)$_2$]** was quantitatively obtained by a very simple procedure (Scheme 2). To a CD_3OD/CD_3NO_2 (1:1, 1 mL) solution of cage **2** (18 mg, 0.004 mmol) in a reaction vial, electron-rich planar guest coronene (**G$_1$**, 3 mol eq.) was added, and the reaction mixture was

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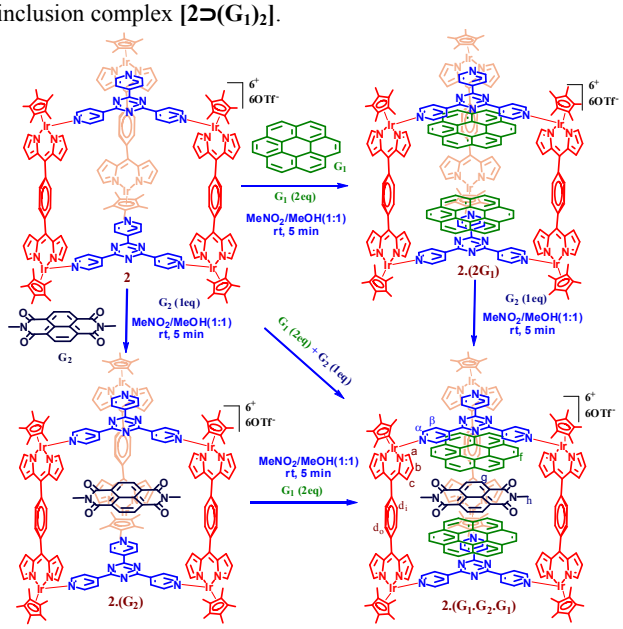
stirred at room temperature for 5 min. The excess of insoluble guest $\mathbf{G_1}$ was separated using centrifugation, and the ^{1}H NMR of the clear solution revealed the quantitative formation of the inclusion complex **[2⊃(G$_1$)$_2$]**.



Scheme 2. Systematic representation of the encapsulation of $\mathbf{G_1}$ and $\mathbf{G_2}$, one after another and all together into the cavity of prismatic cage **2**

Similarly, inclusion complex **[2⊃(G$_2$)]** was obtained by the encapsulation of guest, N,N'-dimethyl-1,4,5,8-naphthalenetetracarboxylic diimide ($\mathbf{G_2}$). The quintuple-stacking structure **[2⊃(G$_1$•G$_2$•G$_1$)]** was formed by the encapsulation of two molecules of $\mathbf{G_1}$ and one molecule of $\mathbf{G_2}$ into cage **2**. The driving forces for the quintuple-stacking were the perfect sized cavity and donor-acceptor nature of $\mathbf{G_1}$ and $\mathbf{G_2}$.

Expected changes after the encapsulation in the NMR spectra of **[2⊃(G$_1$)$_2$]**, **[2⊃(G$_2$)]**, and **[2⊃(G$_1$•G$_2$•G$_1$)]** are clearly visible (Supporting Information). In the ^{1}H-NMR of **[2⊃(G$_1$)$_2$]** in CD_3OD/CD_3NO_2(1:1), a broad singlet appeared at 6.91 ppm, and the peak area matched with two eq. of $\mathbf{G_1}$, clearly indicating the symmetrical stacking of two guests inside the cage. In the ^{1}H-NMR of empty cage **2**, α and β PyH of the ligand L appeared together as a broad singlet at 8.58 ppm, which after encapsulating $\mathbf{G_1}$ showed a high upfield shift of the β PyH at 6.96 ppm, whereas the signal for the α PyH shifted slightly downfield at 8.82 ppm. The change in the chemical shift indicated the shielding of β protons due to the stacking of π-electron rich coronene molecule. Similarly, the ^{1}H NMR spectrum of **[2⊃(G$_1$•G$_2$•G$_1$)]** also matched with all the expected peaks of both guests. The broad peak for coronene in the spectrum of **[2⊃(G$_1$)$_2$]** turned very sharp in the spectrum of **[2⊃(G$_1$•G$_2$•G$_1$)]**, indicated the tight packed stacking. Interaction of $\mathbf{G_1}$ with pyrrole, pyridyl and inner phenyl protons was also confirmed by its ROESY NMR spectrum. DOSY NMR spectra of **2** and **[2⊃(G$_1$•G$_2$•G$_1$)]** confirmed that the signals are associated to the prismatic cage and encapsulated guest molecules (Figure 11-13S).

The ^{1}H NMR spectrum of **[2⊃(G$_2$)]** fully agreed with expected peaks; however, not much change was observed from the spectrum of hollow cage **2** which indicated that guest $\mathbf{G_2}$ was settled in the middle of the cage. That is perhaps due to unfavourable (acceptor-acceptor) stacking of guest $\mathbf{G_2}$ with ligand panel **L** which directed $\mathbf{G_2}$ away in the middle of the cage. The cage was able to encapsulate electron-deficient $\mathbf{G_2}$, because of electron-rich phenyl rings of the acceptors. The identity of encapsulated cages was further confirmed when stepwise addition of $\mathbf{G_2}$ to the solution of **[2⊃(G$_1$)$_2$]** and $\mathbf{G_1}$ to the solution of **[2⊃(G$_2$)]** resulted in the quintuple stack **[2⊃(G$_1$•G$_2$•G$_1$)]**, evidently observed in ^{1}H NMR (Fig. 1).

To a CD_3OD/CD_3NO_2 (1:1) solution of inclusion complexes **[2⊃(G$_2$)]**, 0.5 eq. of $\mathbf{G_1}$ was added, and the reaction mixture was stirred for 5 min. Then, ^{1}H-NMR spectrum was recorded (Fig. 1). This process was repeated up to 3.0 eq. addition of $\mathbf{G_1}$. Upon the addition of increasing amounts of $\mathbf{G_1}$, signals corresponding to a new complex, **[2⊃(G$_1$•G$_2$•G$_1$)]**, increased in intensity, whereas the intensity of **[2⊃(G$_2$)]** signals decreased.

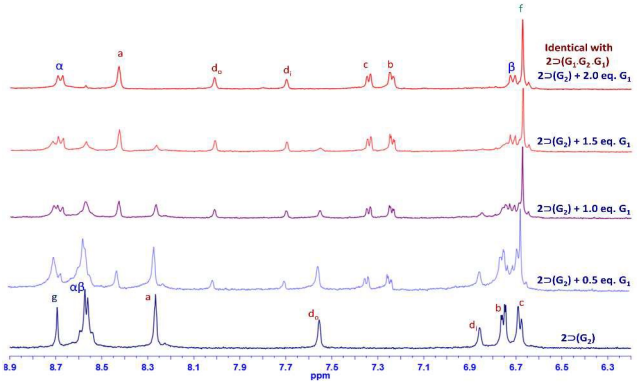


Fig. 1 Transformation of ^{1}H-NMR spectrum of **[2⊃(G$_2$)]** in the spectrum of **[2⊃(G$_1$•G$_2$•G$_1$)]** upon increasing addition of $\mathbf{G_1}$

[2⊃(G$_2$)] was absolutely transformed into **[2⊃(G$_1$•G$_2$•G$_1$)]** upon addition of 2.0 eq. of $\mathbf{G_1}$. The ^{1}H NMR did not change upon the addition of excess $\mathbf{G_1}$ and started precipitating in CD_3OD/CD_3NO_2 (1:1). Similarly, **[2⊃(G$_1$)$_2$]** was converted into **[2⊃(G$_1$•G$_2$•G$_1$)]** upon increasing addition of $\mathbf{G_2}$.

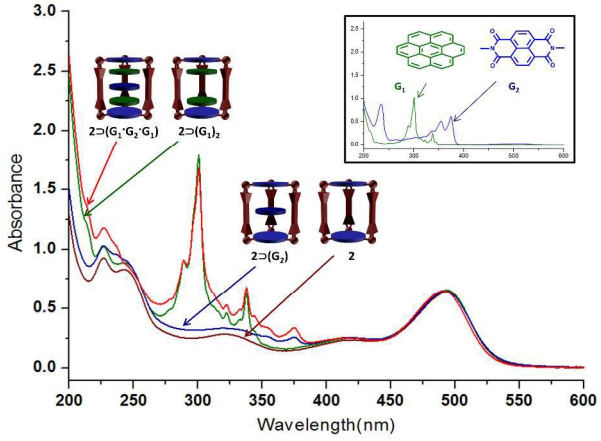


Fig. 2 UV/Vis spectra (CH_3CN, rt) of cages **2**, **[2⊃(G$_1$)$_2$]**, **[2⊃(G$_2$)]**, and **[2⊃(G$_1$.G$_2$.G$_1$)]** (inset showing spectra of $\mathbf{G_1}$ and $\mathbf{G_2}$ in identical conditions)

In addition to the clear and satisfactory NMR observations, the stacking of aromatics $\mathbf{G_1}$ and $\mathbf{G_2}$ inside the assembly was also supported by the UV/Vis spectroscopic analysis (Fig. 2). The spectra of **[2⊃(G$_1$)$_2$]** and **[2⊃(G$_1$•G$_2$•G$_1$)]** have shown new sharp bands at ~335 and 300 nm, which matched with $\mathbf{G_1}$, confirming its presence. Similarly, the presence of $\mathbf{G_2}$ was confirmed by a broad band at 375 nm in the spectrum of **[2⊃(G$_2$)]** and **[2⊃(G$_1$•G$_2$•G$_1$)]**.

The X-ray crystallographic analysis (Supporting Information) provided concrete evidence for dicoronene-encapsulated structure **[2⊃(G$_1$)$_2$]** and quintuple-stacking structure of **[2⊃(G$_1$•G$_2$•G$_1$)]** (fig. 3). The solution of coronene in THF was added to a solution of **[2⊃(G$_1$)$_2$]** and **[2⊃(G$_1$•G$_2$•G$_1$)]** in nitromethane, and diethyl

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ether was diffused to obtain suitable crystals within 24 h. The crystal structure of **[2⊃(G$_1$)$_2$]** and **[2⊃(G$_1$•G$_2$•G$_1$)]** revealed that along with two molecules of coronene inside the cage, one more coronene was stacked between the two cages, extending the π–π stcking. The inclusion cage, **[2⊃(G$_1$•G$_2$•G$_1$)]**, was almost a perfect trigonal prism, and the maximum twist was just 5°. The average interplanar distances **L··G$_1$** and **G$_1$··G$_2$** were 3.4 and 3.5 Å, respectively, indicating a very close packing of the π-donor and acceptors. The crystal structure of **[2⊃(G$_1$)$_2$]** is shown in Fig. 3 in which two coronene molecule were symmetrically stacked to the ligand panel at an average interplanar distance of 3.4 Å, and two diethyl ether molecules were trapped in between the coronene molecules. The inclusion complex **[2⊃(G$_1$)$_2$]** was also nearly a trigonal prism with a maximum tilt of 8°.

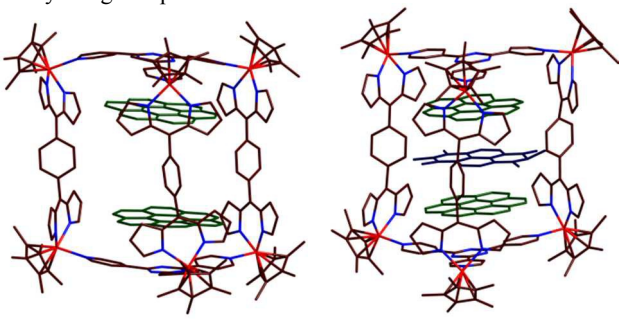

Fig. 3 X-ray crystal structure of **[2⊃(G$_1$)$_2$]** (left) and **[2⊃(G$_1$•G$_2$•G$_1$)]** (right). Counter anions, solvent molecules and hydrogen atoms were omitted for clarity.

In conclusion, we demonstrated the design and self-assembly of a nanometer-sized trigonal prismatic cage. Unlike most of the reported prismatic cages obtained by multi-component self-assembly, the quantitative self-assembled hollow cage was obtained very quickly without the assistance of any aromatic templates. The cavity of the cage was found to be perfect in size for the encapsulation of hetero guest's triplet and is the first such demonstration by any octahedral metal-cornered prismatic cage. As an advantage over the previously reported cages, π-electron donor and acceptor guests can be encapsulated one after another, or all together during or after the self-assembly of the cage. Biomedical applications by encapsulating drug molecules and study of catalytic reactions inside the cage are underway in our laboratory.

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Notes and references

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†Electronic Supplementary Information (ESI) available: [Synthesis and characterisation of compounds **1** and **2.** Crystalolgraphic data of **1**, **[2⊃(G$_1$)$_2$]** and **[2⊃(G$_1$•G$_2$•G$_1$)]**. CCDC 1036112-103614. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b000000x/

1 (a) M. J. Wiester, P. A. Ulmann and C. A. Mirkin, *Angew. Chem. Int. Ed.,* 2011, **50,** 114. (b) M. Yoshizawa, J. K. Klosterman and M. Fujita, *Angew. Chem. Int. Ed.,* 2009, **48,** 3418. (c) T. S. Koblenz, J. Wassenaar and J. N. H. Reek, *Chem. Soc. Rev.,* 2008, **37,** 247.

2 (a) M. Kawano, Y. Kobayashi, T. Ozeki and M. Fujita, *J. Am. Chem. Soc.,* 2006, **128,** 6558. (b) S. Horiuchi, T. Murase and M. Fujita, *J. Am. Chem. Soc.,* 2011, **133**, 12445.

3 (a) B. Therrien, G. Süss-Fink, P. Govindaswamy, A. K. Renfrew and P. J. Dyson, *Angew. Chem., Int. Ed.,* 2008, **47**, 3773. (b) F. Schmitt, J. Freudenreich, N. P. E. Barry, L. Juillerat-Jeanneret, G. Süss-Fink and B. Therrien, *J. Am. Chem. Soc.,* 2012, **134,** 754. (c) J. E. M. Lewis, E. L. Gavey, S. A. Cameron and J. D. Crowley, *Chem. Sci.*, 2012, **3**, 778. (d) B. Therrien, *Chem. Eur. J*., 2013, **19**, 8378.

4 (a) J. K. Klosterman, Y. Yamauchi and M. Fujita, *Chem. Soc. Rev.,* 2009, **38,** 1714. (b) T. Murase, K. Otsuka, and M. Fujita, *J. Am. Chem. Soc.,* 2010, **132**, 7864.

5 H. Takezawa, T. Murase, G. Resnati, P. Metrangolo and M. Fujita *J. Am. Chem. Soc.,* 2014, **136,** 1786.

6 (a) T. R. Cook, Y.-R. Zheng and P. J. Stang, *Chem. Rev.,* 2013, **113**, 734. (b) R. Chakrabarty, P. S. Mukherjee and P. J. Stang, *Chem. Rev.,* 2011, **111,** 6810. (c) M. Fujita, M. Tominaga, A. Hori, and B. Therrien, *Acc. Chem. Res.,* 2005, **38**, 369. (d) B. H. Northrop, Y.-R. Zheng, K.-W. Chi, and P. J. Stang, *Acc. Chem. Res*., 2009, **42,** 1554. (e) S. Mukherjee, P. S. Mukherjee, *Chem. Commun*., 2014, **50**, 2239.

7 (a) S. De, K., Mahata, and M. Schmittel, *Chem. Soc. Rev.,* 2010, **39,** 1555. (b) M. Schmittel and B. He, *Chem. Commun.,* 2008, 4723.

8 (a) Y.-R. Zheng, Z. Zhao, M. Wang, K. Ghosh, J. B. Pollock, T. R. Cook, P. J. Stang, *J. Am. Chem. Soc.,* 2010, **132,** 16873. (b) M. Yoshizawa, J. Nakagawa, K. Kumazawa, M. Nagao, M. Kawano, T. Ozeki, M. Fujita, *Angew. Chem., Int. Ed.,* 2005, **44,** 1810. (c) D. Samanta and P. S. Mukherjee, *Chem. Eur. J*., 2014, **20**, 5649. (d) D. Samanta and P. S. Mukherjee, *Chem. Commun.*, 2014, **50**, 1595.

9 (a) T. R. Cook, V. Vajpayee, M. H. Lee, P. J. Stang and K.-W. Chi, *Acc. Chem. Res.,* 2013, **46,** 2464. (b) A. Granzhan, T. Riis-Johannessen, R. Scopelliti, and K. Severin, *Angew. Chem., Int. Ed.*, 2010, **49**, 5515. (c) Y.-F. Han and G.-X. Jin, *Acc. Chem. Res.,* 2014, **47**, 3571.

10 M. Yoshizawa, J. Nakagawa, K. Kumazawa, M. Nagao, M. Kawano, T. Ozeki, and M. Fujita, *Angew. Chem., Int. Ed.,* 2005, **44,** 1810.

11 (a) K. Harris, D. Fujita and M. Fujita, *Chem. Commun.,* 2013, **49,** 6703. (b) Y. Inokuma, M. Kawano and M. Fujita, *Nature Chem.,* 2011**,** **3**, 349.

12 K. Ono, M. Yoshizawa, M. Akita, T. Kato, Y. Tsunobuchi, S.-i. Ohkoshi and M. Fujita, *J. Am. Chem.Soc.,* 2009, **131***,* 2782.

13 (a) V. Vajpayee, Y. J. Yang, S. C. Kang, H. Kim, I. S. Kim, M. Wang, P. J. Stang and K.-W. Chi, *Chem. Commun.,* 2011, **47**, 5184 (b) A. Mishra, S. C. Kang and K.-W. Chi, *Eur. J. Inorg. Chem.,* 2013, 5222 (c) A. Mishra, A. Dubey J. W. Min, H. Kim, P. J. Stang and K.-W. Chi, *Chem. Commun.,* 2014, **50,** 7542. (d) B. Kilbas, S. Mirtschin, T. Riis-Johannessen, R. Scopelliti and K. Severin, *Inorg. Chem.,* 2012, **51,** 5795. (e) V. Vajpayee, S. Bivaud, S. Goeb, V. Croue, M. Allain, B. V. Popp, A. Garci, B. Therrien, M. Salle, *Organometallics,* 2014, **33,** 1651.

14 (a) Y.-F. Han, Y.-J. Lin, L.-H. Weng, H. Berke, and G.-X. Jin, *Chem. Commun.,* 2008**,** 350. (b) Z. Grote, S. Bonazzi, R. Scopelliti and K. Severin, *J. Am. Chem. Soc.,* 2006, **128,** 10382.

15 (*a*) Y. F. Han and G. X. Jin, *Chem. Soc. Rev.*, 2014, **43**, 2799. *(b)* Y.-F. Han, L. Zhang, L.-H. Weng and G.-X. Jin, *J. Am. Chem. Soc.,* 2014, **136,** 14608. (*c*) Y.-F. Han, W.-G. Jia, W.-B. Yu and G.-X. Jin, *Chem. Soc. Rev.*, 2009, **38**, 3419. (*d*) Y.-F. Han, H. Li and G.-X. Jin, *Chem. Commun.*, 2010, **46**, 6879. (*e*) Y.-Y. Zhang, Y.-J. Lin, X.-C. Shi and G.-X. Jin, *Pure Appl. Chem.,* 2014, **86**, 953.

16 S. Mirtschin, A. Slabon-Turski, R. Scopelliti, A. H. Velders, and K. Severin, *J. Am. Chem. Soc.,* 2010, **132**, 14004.

17 The acceptor clip **1** was synthesized using known precursor by a two-step reaction and fully characterized by spectroscopic and single crystal X-ray analysis (see supporting information for more details).

18 E. A. Meyer, R. K. Castellano and F. Diederich, *Angew. Chem. Int. Ed.,* 2003, **42**, 1210.

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