Dual molecular tweezers extending from a nanohoop

Journal:	*ChemComm*
Manuscript ID	CC-COM-06-2024-003196.R2
Article Type:	Communication

COMMUNICATION

Dual molecular tweezers extending from a nanohoop

M. Saeed Mirzaei,[a†] Saber Mirzaei,[a,b†] Victor M. Espinoza Castro,[a] Charlotte Lawrence,[a] and Raúl Hernández Sánchez[a,b,c*]

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

The field of nanohoops is mature enough that synthetic protocols exists to tune their size, composition (incorporation of heteroaromatic building blocks), connectivity (*para* versus *meta* linkages), and solubility in different media (hydrophobic versus hydrophilic). Here, we report an additional dimension incorporating the concept of fullerene tweezers into a nanohoop. The resulting hybrid nanohoop is highly strained at 77 kcal/mol, possesses a quantum yield of 0.12, emits at 584 nm, and displays a positive cooperative binding for C_{60} ($4K_2 >> K_1$).

Realization of well-defined molecular compounds with radial π conjugation can be traced back to the late 90's in reports of anthracene dimers[1] and [*n*]cyclo-*para*-phenylacetylenes.[2] Later, the synthesis of nanohoops, or [*n*]cyclo-*para*-phenylenes ([*n*]CPPs), was described.[3, 4] Their modular bottom up synthesis has led to a wide range of applications.[5] Since then, the field of conjugated aromatic macrocycles has expanded in many directions, including their use as novel building blocks for nanomaterials,[6] optoelectronic materials,[7] fluorophores,[8] polymers,[9] and in supramolecular recognition and sensing.[10] The curved nature of CPPs leads to weak intermolecular π-π stacking in solution; however, its cyclic nature creates an internal site suitable for hosting molecules that exhibit radial connectivity, e.g., fullerenes, or another CPP.[11] Multiple literature reports describe CPPs binding fullerenes in a belt-like fashion.[12-21] Alternatively, an entire field exists centred around developing molecular tweezers–a molecular, bivalent, tweezer-like receptor containing two recognition subunits linked covalently–to bind fullerenes.[22] However, to the best of our knowledge, a nanohoop serving as a scaffold to create molecular tweezers has not been accomplished before.

Herein, we present **1** comprising a structure built with dibenzo[*a,c*]phenazine (DBP) repeating units which form the backbone of a strained conjugated aromatic macrocycle, or nanohoop, and also act as dual molecular tweezers for binding of C_{60}. The backbone of [8]CPP can be inscribed within the nanohoop portion of **1** (Fig. 1). It has been demonstrated that [8]CPP is too small to form a belt-like host:guest adduct with C_{60}, which only becomes possible with nanohoops containing at least ten *para*-phenylenes.[12, 19, 23] Thus, fullerene binding is proposed to take place in between the DBP units (*vide infra*), effectively creating dual molecular tweezers.

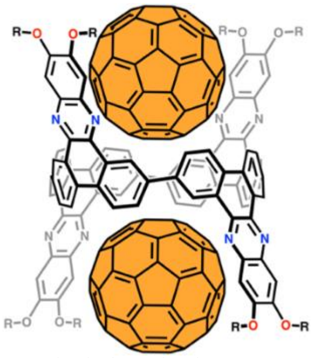

Fig. 1 Nanohoop-supported dual molecular tweezers **1** binding two equivalents of C_{60}. R = 3,5-di-*tert*-butylphenyl.

Dibenzo[*a*,*c*]phenazine, an electron acceptor with a half-wave reduction potential ($E_{1/2}$) of –1.35 V vs Ag/Ag^+ in DMF,[24] was introduced into a nanohoop by using the known building block **S1** (Supplementary Information).[25] A high-yielding and straightforward S_NAr reaction using 3,5-di-*tert*-butylphenol with K_2CO_3 in DMF led to **3a** (2.7 g, 93% yield). Miyaura borylation of **3a** catalyzed by $Pd(dppf)Cl_2$ led to **2** in 64% yield (Fig. 2a). Compound **1** was achieved by subjecting **2** to $Pt(COD)Cl_2$ and CsF in refluxing THF for 72 hours to form a square-shaped Pt metallacycle that was not isolated. Next,

---

[a] Department of Chemistry, Rice University, 6100 Main St., Houston, Texas 77005
[b] Rice Advanced Materials Institute, Rice University, Houston, Texas 77005
[c] Department of Chemistry, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
E-mail: raulhs@rice.edu

[†] These authors contributed equally to this work.

Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

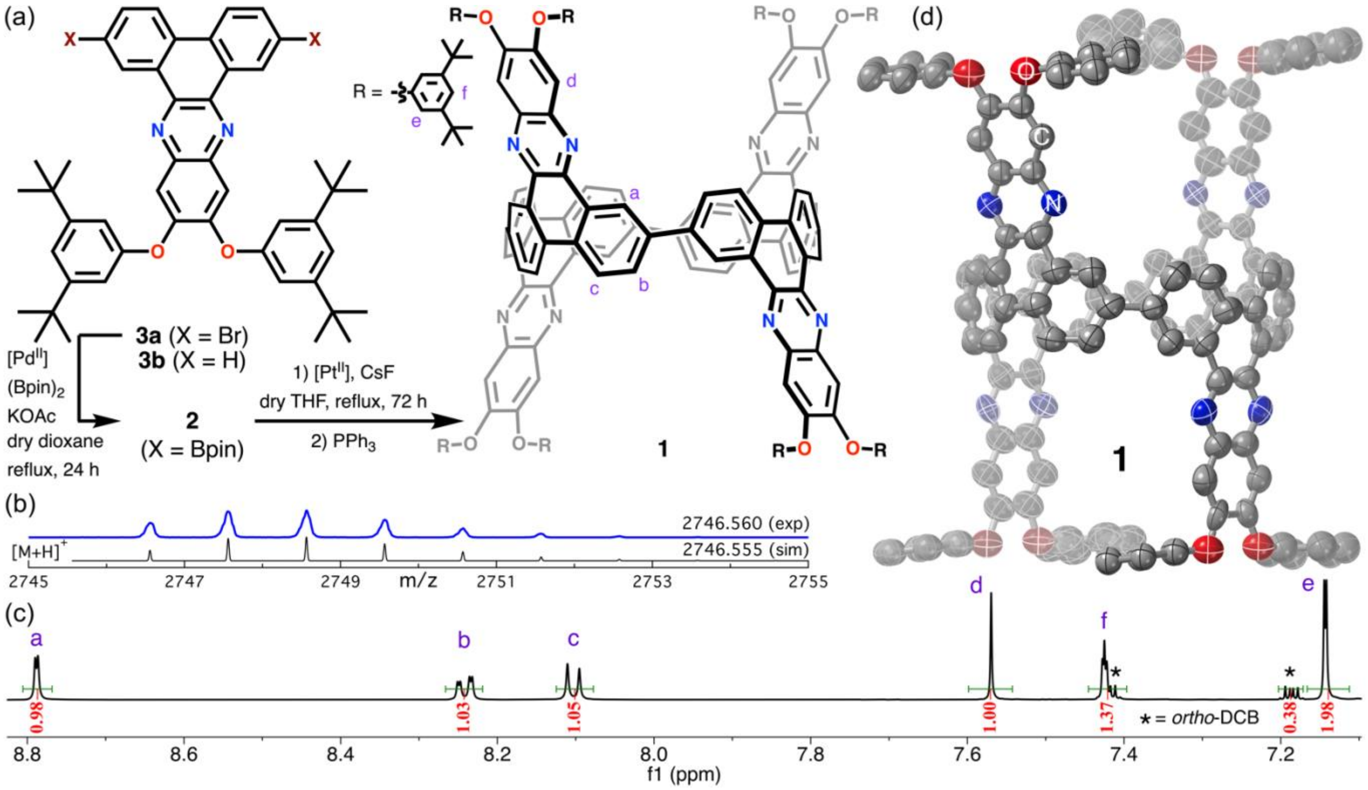

Fig. 2 Synthesis and characterization of **1**. (a) Two step synthetic protocol to get **1** from **3a**. (b) Experimental MALDI MS molecular ion peaks of **1** (blue trace). Black trace represents simulation of $[M+H]^+$ isotopic distribution. (c) Aromatic region of ^1H NMR of **1** collected in CD_2Cl_2 at 20 °C. (d) Molecular crystal structure of **1**. Thermal ellipsoids are set at 50% probability level. The H atoms and *tert*-butyl groups on the R group are removed for clarity.

reductive elimination prompted by PPh_3 led to **1** in 9% yield. MALDI-MS analysis of **1** (Fig. 2b) matches its expected molecular ion $[M+H]^+$. Moreover, ^1H NMR characterization displays a symmetric spectrum that to a first approximation could result from the D_{2d} or C_{4v} symmetric species (Fig. 2c). However, the assignment as D_{2d} was initially supported by DFT conformational analysis, where the D_{2d} isomer (1,3-alternate) is lowest in energy relative to the C_{4v} (cone), C_s (partial-cone), and C_{2h} (1,2-alternate) conformational isomers (Fig. S12). All conformers fall within a relative energy window of 13 kcal/mol. Rotation of the DBP fragment in **1’** (R = Me) is highly disfavored, where DFT calculations indicate a rotational barrier of ~30 kcal/mol (Fig. S13). Thus, isomer interconversion is energetically prohibited at room temperature. Moreover, DFT calculations at the B3LYP/6-31G(d) level of theory concluded that contortion in **1’** results in 77 kcal/mol of strain energy (Fig. S14). Interestingly, this value is only slightly higher than that reported for [8]CPP at 72.2 kcal/mol,[26] even though **1** only has four single bonds along the nanohoop fragment with DBP units likely bending away from planarity. Finally, definitive structural assignment was obtained from single-crystal X-ray diffraction. Crystals of **1** were grown from vapor diffusion of MeCN into a solution of **1** in *ortho*-dichlorobenzene/DCM (1:1). The molecular crystal structure of **1** (Fig. 2d) displays a cylindrical shape whose diameter measured at the nanohoop fragment is 11.12(7) Å.

Species **1** is a bright yellow powder with its lowest energy absorption peak located at λ_{max} of 412 nm (Fig. 3). It also displays several absorption bands at higher energies with discernable peaks at 393, 354, and 283 nm. Time-dependent DFT (TD-DFT) analysis supported the assignment of these absorption bands. Our calculations show that the absorption at 412 nm corresponds to the HOMO-1 or HOMO-2→LUMO transition (Table S2). In fact, comparing with compound **3b** indicates that most of the observed transitions result from the dibenzo[*a,c*]phenazine fragment (Fig. 3). However, the transition at 354 nm is unique to **1** and based on our calculations it seems to arise from HOMO-6→LUMO. Additionally, the HOMO→LUMO transition in **1’** is symmetry forbidden (f = 0.0), consistent with [*n*]CPPs.[27] Our DFT results show both the HOMO and LUMO delocalized symmetrically across **1’**, the former is localized exclusively across the nanohoop fragment, while the latter presents orbital density on the entire molecule (Fig. S15).

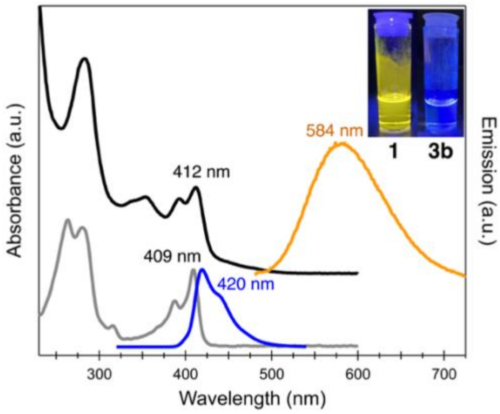

Fig. 3 Absorption and emission profile of **1** (black and orange traces) and **3b** (grey and blue traces) in CH_2Cl_2 at room temperature. Emission data were collected by light excitation at 350 nm. Inset: photographic image of a solution of **1** and **3b** in CH_2Cl_2 irradiated with UV light.

Nanohoops with emission past 550 nm are rare.[28-31] We noticed a bright orange solution when **1** is dissolved in dichloromethane and exposed to UV light. Unlike other bright nanohoop fluorophores,[29] compound **1** displays a mild fluorescence solvatochromism (Fig. S16). The visual comparison between emission from **1** and **3b** is markedly different (Fig. 3 inset). In **1**, the emission envelope is characterized by a broad band with peak at λ_{em} of 584 nm. In stark contrast, **3b** emits with λ_{em} at 420 nm. Intrigued by the emissive properties of **1**, we determined its quantum yield (ϕ, Supplementary Information). Compound **1** has a ϕ of 0.12, which is slightly higher than that of [8]CPP (0.084),[32] but lower than nanohoops with the highest quantum yields reported to date, e.g., [10-12]CPP (ϕ = 0.46 to 0.81),[33, 34] BT[10]CPP (ϕ = 0.59),[35] and TB[12]CPP (ϕ = 0.59 to 0.98).[36] Last, the red-shifted emission in **1** relative to **3b** likely results from extended π delocalization across all four DBP units.

Since the architecture of **1** combines design principles related to conjugated aromatic macrocycles and molecular tweezers, we hypothesized that **1** could serve as an ideal host for C_{60}. To demonstrate the fullerene hosting properties of **1**, we performed ^{1}H NMR titration experiments by adding C_{60} to a solution of **1** in 1,1,2,2-tetrachloroethane–a solvent that enhances the solubility of C_{60}.[37] The data shown in Fig. 4a displays a downfield shift of resonance “a” with increasing equivalents of C_{60}. Note that resonances “b” and “c” show a mild upfield shift when C_{60} is added into **1** (Fig. S18). The data in Fig. 4a does not fit to a 1:1 host:guest (H:G) model when analyzed using Bindfit, but instead fits well to a 1:2 system with K_1 = 149 M^{-1} and K_2 = 1021 M^{-1} (Fig. S19).[38] The resulting mole fraction obtained from the fit is shown in Fig. 4b, and clearly indicates a positive cooperative effect[39, 40] where the intermediate 1:1 H:G is almost absent.[41] Moreover, fluorescence quenching experiments were conducted to further examine C_{60} binding into **1**. Analysis of the data in Fig. 4c using a 1:2 H:G model provides values of K_1 = 1956 M^{-1} and K_2 = 4311 M^{-1} (Fig. S20). While the magnitude of K_1 and K_2 between the two methods do not match, the overall trend in the association constants reflect the same positive cooperativity, that is $4K_2 >> K_1$, and confirms our initial hypothesis that **1** functions as dual molecular tweezers hosting two molecules of C_{60}. It is important to highlight that a single molecular host accommodating two fullerene species is rare.[42-45] Finally, to visualize the 1:2 host:guest adduct, a DFT model was optimized and is shown in Fig. 4d. As observed from the structure, the DBP units are pushed out to accommodate the C_{60} guests. The distortion of **1** upon C_{60} binding may explain the positive cooperative effect. Last, non-covalent interactions mainly take place between the DBP units and C_{60} with little contribution from the nanohoop as visualized in the contact surface obtained from the independent gradient model based on Hirshfeld partition of molecular density (IGMH, Figure S22).[46]

In summary, we report an orange emitting dual molecular tweezers–nanohoop which is capable of simultaneously hosting two C_{60} molecules with moderate affinity. We anticipate that the present work will pave the way towards extended nanohoop-tweezers to develop applications in optoelectronic devices and supramolecular materials.

The authors thank support by the National Science Foundation NSF CAREER CHE-2302628. This research was supported with startup funds from Rice University. This research was funded in part by a grant from The Welch Foundation (C-2142-20230405). This research was supported by the Shared Instrumentation Authority at Rice University. C.L. acknowledges summer research support from the George Holmes Memorial Fellowship at Rice University.

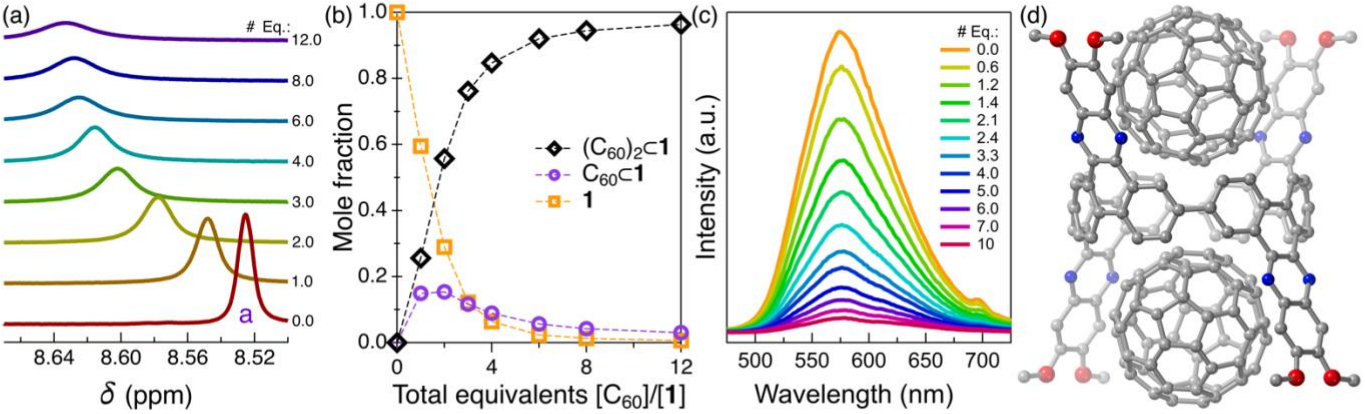

Fig. 4 (a) ^{1}H NMR titration of C_{60} into **1** in 1,1,2,2-tetrachloroethane-d_2 at 20 °C. Shift of resonance “a” is shown as labelled in Fig. 2a. (b) Mole fraction of **1**, $C_{60}\subset$**1**, and $(C_{60})_2\subset$**1** obtained from fitting NMR data in (a) to a 1:2 host:guest model using Bindfit. (c) Fluorescence quenching titration of **1** with C_{60} in 1,1,2,2-tetrachloroethane. (d) DFT optimized structure of $(C_{60})_2\subset$**1** at the B3LYP-D3BJ/6-31G*+PCM(CH_2Cl_2) level of theory.

Data availability

Data supporting this article have been included in the ESI.

Conflicts of interest

There are no conflicts to declare.

Notes and references

1. S. Kammermeier, P. G. Jones and R. Herges, *Angew. Chem. Int. Ed.*, 1996, **35**, 2669-2671.
2. T. Kawase, H. R. Darabi and M. Oda, *Angew. Chem. Int. Ed.*, 1996, **35**, 2664-2666.
3. R. Jasti, J. Bhattacharjee, J. B. Neaton and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2008, **130**, 17646-17647.
4. D. Wu, W. Cheng, X. Ban and J. Xia, *Asian J. Org. Chem.*, 2018, **7**, 2161-2181.
5. S. Mirzaei, E. Castro and R. Hernández Sánchez, *Chem. Eur. J.*, 2021, **27**, 8642-8655.
6. H. Omachi, T. Nakayama, E. Takahashi, Y. Segawa and K. Itami, *Nat. Chem.*, 2013, **5**, 572–576.
7. Y. Xu, M.-Y. Leung, L. Yan, Z. Chen, P. Li, Y.-H. Cheng, M. H.-Y. Chan and V. W.-W. Yam, *J. Am. Chem. Soc.*, 2024, **146**, 13226–13235.
8. B. M. White, Y. Zhao, T. E. Kawashima, B. P. Branchaud, M. D. Pluth and R. Jasti, *ACS Cent. Sci.*, 2018, **4**, 1173–1178.
9. G. M. Peters, G. Grover, R. L. Maust, C. E. Colwell, H. Bates, W. A. Edgell, R. Jasti, M. Kertesz and J. D. Tovar, *J. Am. Chem. Soc.*, 2020, **142**, 2293-2300.
10. D. Lu, Q. Huang, S. Wang, J. Wang, P. Huang and P. Du, *Front. Chem.*, 2019, **7**.
11. M. B. Minameyer, Y. Xu, S. Frühwald, A. Görling, M. von Delius and T. Drewello, *Chem. Eur. J.*, 2020, **26**, 8729-8741.
12. T. Iwamoto, Y. Watanabe, T. Sadahiro, T. Haino and S. Yamago, *Angew. Chem. Int. Ed.*, 2011, **50**, 8342-8344.
13. T. Iwamoto, Y. Watanabe, H. Takaya, T. Haino, N. Yasuda and S. Yamago, *Chem. Eur. J.*, 2013, **19**, 14061-14068.
14. H. Isobe, S. Hitosugi, T. Yamasakia and R. Iizukaa, *Chem. Sci.*, 2013, **4**, 1293-1297
15. Y. Nakanishi, H. Omachi, S. Matsuura, Y. Miyata, R. Kitaura, Y. Segawa, K. Itami and H. Shinohara, *Angew. Chem. Int. Ed.*, 2014, **53**, 3102-3106.
16. I. González-Veloso, E. M. Cabaleiro-Lago and J. Rodríguez-Otero, *Phys. Chem. Chem. Phys.*, 2018, **20**, 11347-11358.
17. Y. Xu, B. Wang, R. Kaur, M. B. Minameyer, M. Bothe, T. Drewello, D. M. Guldi and M. v. Delius, *Angew. Chem. Int. Ed.*, 2018, **57**, 11549-11553.
18. T. C. Lovell, S. G. Bolton, J. P. Kenison, J. Shangguan, C. E. Otteson, F. Civitci, X. Nan, M. D. Pluth and R. Jasti, *ACS Nano*, 2021, **15**, 15285-15293.
19. F. Bernt and H. A. Wegner, *Chem. Eur. J.*, 2023, **29**, e202301001.
20. Y. Xu, F. Steudel, M.-Y. Leung, B. Xia, M. v. Delius and V. W.-W. Yam, *Angew. Chem. Int. Ed.*, 2023, **62**, e202302978.
21. X. Chang, Y. Xu and M. v. Delius, *Chem. Soc. Rev.*, 2024, **53**, 47-83.
22. E. M. Pérez and N. Martín, *Pure Appl. Chem.*, 2010, **82**, 523-533.
23. Y. Nagasawa and S. Okada, *J. Phys. Soc. Jpn.*, 2017, **86**, 104702.
24. B. J. Tabner and J. R. Yandle, *J. Chem. Soc. A*, 1968, DOI: 10.1039/J19680000381, 381-388.
25. K. Wang, P. Jiang, Z.-G. Zhang, Q. Fu and Y. Li, *Macromol. Chem. Phys.*, 2013, **214**, 1772-1779.
26. Y. Segawa, H. Omachi and K. Itami, *Org. Lett.*, 2010, **12**, 2262-2265.
27. T. Iwamoto, Y. Watanabe, Y. Sakamoto, T. Suzuki and S. Yamago, *J. Am. Chem. Soc.*, 2011, **133**, 8354-8361.
28. E. R. Darzi, E. S. Hirst, C. D. Weber, L. N. Zakharov, M. C. Lonergan and R. Jasti, *ACS Cent. Sci.*, 2015, **1**, 335-342.
29. T. Kuwabara, J. Orii, Y. Segawa and K. Itami, *Angew. Chem. Int. Ed.*, 2015, **54**, 9646-9649.
30. D. Ari, E. Dureau, O. Jeannin, J. Rault-Berthelot, C. Poriel and C. Quinton, *Chem. Commun.*, 2023, **59**, 14835-14838.
31. V. Bliksted Roug Pedersen, T. W. Price, N. Kofod, L. N. Zakharov, B. W. Laursen, R. Jasti and M. Brøndsted Nielsen, *Chem. Eur. J.*, 2024, **30**, e202303490.
32. M. Fujitsuka, D. W. Cho, T. Iwamoto, S. Yamago and T. Majima, *Phys. Chem. Chem. Phys.*, 2012, **14**, 14585-14588.
33. E. R. Darzi, T. J. Sisto and R. Jasti, *J. Org. Chem.*, 2012, **77**, 6624-6628.
34. M. Fujitsuka, C. Lu, B. Zhuang, E. Kayahara, S. Yamago and T. Majima, *J. Phys. Chem. A*, 2019, **123**, 4737-4742.
35. T. C. Lovell, Z. R. Garrison and R. Jasti, *Angew. Chem. Int. Ed.*, 2020, **59**, 14363-14367.
36. Z.-L. Qiu, C. Tang, X.-R. Wang, Y.-Y. Ju, K.-S. Chu, Z.-Y. Deng, H. Hou, Y.-M. Liu and Y.-Z. Tan, *Angew. Chem. Int. Ed.*, 2020, **59**, 20868-20872.
37. R. S. Ruoff, D. S. Tse, R. Malhotra and D. C. Lorents, *J. Phys. Chem.*, 1993, **97**, 3379–3383.
38. http://supramolecular.org/
39. A. D. Hughes and E. V. Anslyn, *Proc. Natl. Acad. Sci. USA*, 2007, **104**, 6538-6543.
40. D. H. Williams and M. S. Westwell, *Chem. Soc. Rev.*, 1998, **27**, 57-64.
41. P. Thordarson, *Chem. Soc. Rev.*, 2011, **40**, 1305-1323.
42. K. Miki, T. Matsushita, Y. Inoue, Y. Senda, T. Kowada and K. Ohe, *Chem. Commun.*, 2013, **49**, 9092–9094.
43. K. Li, Z. Xu, H. Deng, Z. Zhou, Y. Dang and Z. Sun, *Angew. Chem. Int. Ed.*, 2021, **60**, 7649–7653.
44. X. Zhang, H. Shi, G. Zhuang, S. Wang, J. Wang, S. Yang, X. Shao and P. Du, *Angew. Chem. Int. Ed.*, 2021, **60**, 17368–17372.
45. L. Zhan, C. Dai, G. Zhang, J. Zhu, S. Zhang, H. Wang, Y. Zeng, C. H. Tung, L. Z. Wu and H. Cong, *Angew. Chem. Int. Ed.*, 2022, **61**, e202113334.
46. T. Lu and Q. Chen, *J. Comput. Chem.*, 2022, **43**, 539-555.

Data availability

The data supporting this article have been included as part of the ESI.