

Cite this: DOI: 10.1039/c0xx00000x

www.rsc.org/xxxxxx

Tuning the depth of bowl-shaped phosphine hosts: capsule and pseudo-cage architectures in host-guest complexes with C₆₀ fullerene

Masaki Yamamura,^{a*} Kimiya Sukegawa,^a Tatsuya Nabeshima^{a*}

Received (in XXX, XXX) Xth XXXXXXXXXX 20XX, Accepted Xth XXXXXXXXXX 20XX

DOI: 10.1039/b000000x

Bowl-shaped phosphine molecules, whose bowl geometry can be controlled by a variation of the axial substituent, were synthesized, and used as host molecules to encapsulate C₆₀. Host molecules with relatively shallow bowls formed a chiral capsule, while hosts with a deeper bowls formed an achiral pseudo-cage.

Bowl-shaped π -conjugated molecules, such as corannulene¹ and sumanene² have recently attracted considerable attention as molecular hosts, due to their ability to recognize and encapsulate guest molecules on their concave surface.³ In this context, the recognition of curved carbon materials such as fullerenes and single-walled carbon nanotubes by bowl-shaped hosts is an especially active area of research, not only due to the diverse applications of these carbon materials but also owing to the unique architectures of the host-guest complexes resulting from such convex/concave interactions.⁴ As a consequence of these efforts, the last two decades have seen significant progress in the development of bowl-shaped host molecules for such carbon materials.⁵

The depth and the surface area of bowl-shaped host molecules represent important structural parameters for the recognition of guest molecules, and the correlation between surface area and affinity towards guest molecules has been intensively investigated.⁶ Conversely, the effect of the bowl depth on the recognition still remains unclear, mostly because it is non-trivial to modify the bowl depth while keeping the bowl surface constant.⁷

Recently, we have reported the successful recognition of fullerenes⁸ by using phosphorous-containing chiral host molecule **1** with a unique bowl-shaped structure.⁹ We were able to demonstrate that the incorporation of phenylacetylene groups into the bowl-shaped compound resulted in chiral induction as well as in a higher affinity towards a fullerene derivative. Subsequently, we envisioned that a modulation of the hybridization state of the central phosphorus atom should induce a modification of the bowl geometry (Fig. 1). This assumption is supported by the Walsh diagram for tertiary phosphines, wherein the molecular phosphine orbital that contains the lone pair of electrons, is stabilized upon bending to form a more pyramidal shape.¹⁰ Accordingly, the depth of the bowl should increase with increasing contributions from the 3s orbital of the phosphorous atom. Herein, we would like to report the synthesis of bowl-shaped phosphine host molecules, containing different axial

substituents on the phosphorus atom. Varying the axial substituent should affect the bowl structure of the host molecules, as the P–X bond should influence the hybridization of the phosphorous atom. A modification of the bowl geometry should thus lead to different assembly architectures in host-guest complexes with C₆₀.

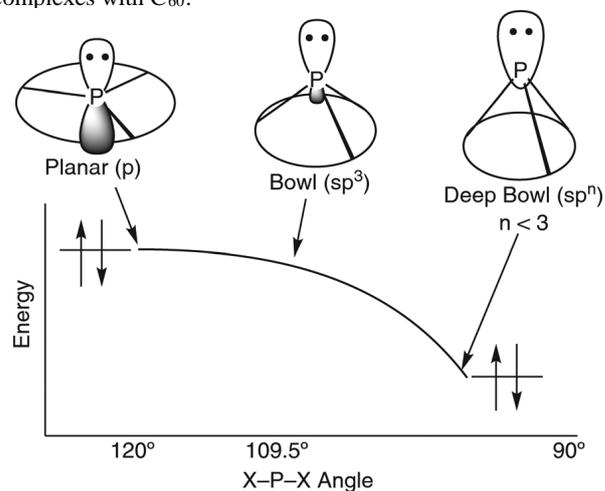
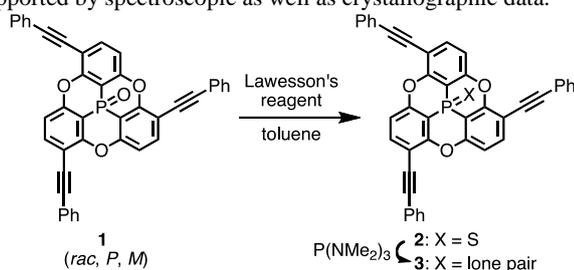


Fig. 1. Walsh diagram-based correlation between the bowl geometry of phosphorus-containing host molecules (planar, bowl, and deep bowl) and the hybridization of the molecular orbital on phosphorous that contains the lone pair of electrons

Racemic (*rac*)-**1**, as well as enantiopure (*P*)- and (*M*)-**1** were prepared according to literature procedures.⁸ Treatment of phosphine oxide (*rac*)-**1** with Lawesson's reagent readily afforded the corresponding sulfide (*rac*)-**2** (Scheme 1). Crystals of (*rac*)-**2**, belonging to the centrosymmetric space group $P2_1/n$, were obtained after recrystallization from chloroform/hexane. The enantiopure sulfides (*P*)-**2** and (*M*)-**2** were obtained, under retention of the configuration,¹¹ from the corresponding enantiomers of **1**. The absolute configuration of (*M*)-**2** was determined by single crystal X-ray diffraction analysis.¹² Circular dichroism (CD) spectra of (*M*)-**2** exhibited a positive Cotton effect in the lowest excitation state (Figure S7). Polarimetry measurements established a positive specific rotation of (*M*)-**2**. A comparison of the chiroptical properties of (*M*)-**2** with the positive Cotton effect and the specific rotation of (*M*)-**1**, suggested that both compounds share an identical configuration. TD-DFT calculations at the M06-2X/6-31G(d,p) level of theory

on the rotatory strength supported a positive CD signal for (*M*)-**2** (Table S3). Accordingly, the absolute structure of (*M*)-**2** was supported by spectroscopic as well as crystallographic data.



Scheme 1. Synthesis of bowl-shaped phosphine hosts **2** and **3**.

The desulfurized phosphine **3** was obtained, under retention of the configuration, from the reaction of **2** with P(NMe₂)₃ (Scheme 1). The absolute structure of enantiopure **3** was determined in a manner similar to **2**. Single crystals of (*rac*)-**3** belong to the space group *P*-3, contain a crystallographic *C*₃-axis, and exhibit a one-dimensional π -stacked structure (Fig. 2a). In these crystals, molecules of enantiopure (*M*)-**3** or (*P*)-**3** are stacked in a convex/concave way to form columns, in which all the molecules are related by translational symmetry along the *c*-axis (4.12 Å). The concave/convex interactions render these columns anisotropic, and the directional alignment of each (*M*)-**3** or (*P*)-**3** column is diametrically opposed to its neighboring column, which contains molecules of the other enantiomer. The distance between the centroids of the phenyl planes in the stacks of **3** (3.42 Å) is consistent with commonly encountered π - π stacking distances.¹³ We also carried out a single-crystal X-ray diffraction analysis on enantiopure (*M*)-**3**, which provided a unit cell (*c* = 4.08 Å) similar to that of (*rac*)-**3**. Molecules of (*M*)-**3** are also aligned in convex/concave columnar stacks (Fig. 2b), but the packing structure of the (*M*)-**3** columns is different from that of (*rac*)-**3**: every column is surrounded by four columns orientated in opposite direction as well as by one column orientated in similar direction.

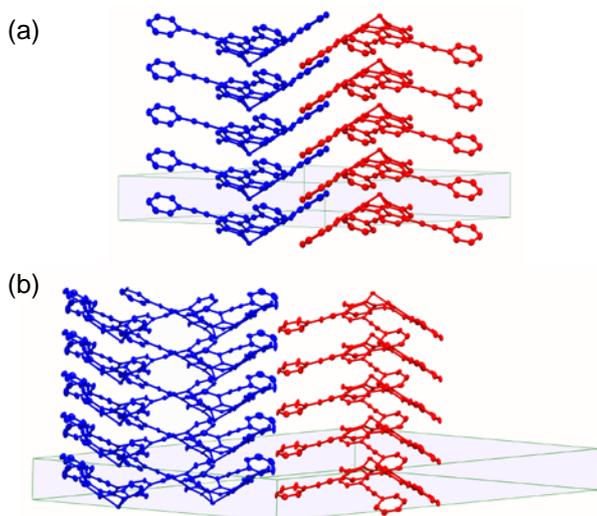


Fig. 2. ORTEP drawing of columnar π - π stacks of (*rac*)-**3** (a) and (*M*)-**3** (b); thermal ellipsoids were set at 50% probability and all hydrogen atoms omitted for clarity.

Compared to the C–P–C bond angles in triphenylphosphine (102°), those in **3** (93.8°) are extraordinarily narrow.¹⁴ Phosphine **3** may accordingly be categorized as a highly restricted phosphine, such as *e.g.* phosphabarrelene¹⁵ or phosphatriptycene¹⁶, and the highly restricted structures of these phosphines is reflected in a high *s*-character of their lone pairs of electrons. In order to shed more light on the bowl-structures and the character of the P–X bond in **1–3**, theoretical structure optimizations were carried out using DFT calculations at the M062X/6-31G(d,p) level of theory. The thus obtained theoretically calculated structures in the gas phase are almost identical to the experimentally obtained crystal structures, except for the orientation of the terminal phenyl groups (Table S2). Due to the high levels of compliance, these DFT-optimized structures were subsequently used in order to avoid minor deviations arising from experimental values (Fig. 3). Two structural parameters were employed to examine the bowl structures of **1–3**: the bowl depth (*d*) and the cone angle (θ). The former is defined as the distance between the phosphorous atom and the centroid of the three terminal carbon atoms, while the latter is determined by the angle between the P–C and the P–centroid axes (Table 1). A summary of these and other DFT-derived parameters for **1–3** is presented in Table 1. The *d* values decrease in the order of **3** (2.463 Å) > **2** (2.232 Å) > **1** (2.215 Å), while the θ values increase in the same order. The observed cone angle difference between **1** (121.09°) and **3** (114.78°) reflects a significant substituent effect on the bowl structure of these phosphines.¹⁷

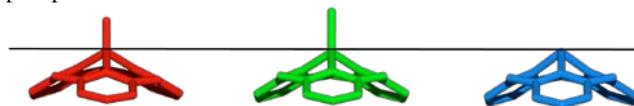


Fig. 3. DFT-optimized molecular structures for **1** (red), **2** (green), and **3** (blue); 4-phenylethynyl substituents as well as hydrogen atoms were omitted for clarity.

Table 1. Theoretically calculated structural and NBO parameters for **1–3**.

The diagram shows a phosphorus atom (P) bonded to three carbon atoms (C) forming a bowl shape. The bowl depth *d* is the distance from P to the centroid of the C-C-C triangle. The cone angle θ is the angle between a P-C bond and the P-centroid axis.

	<i>d</i> /Å ^[a]	θ /deg ^[b]	NBO charge ^[c]	Hybrid orbital ^{[c], [d]}
1 : X = O	2.215	121.09	+2.09	s(31.2%) p(67.9%)
2 : X = S	2.232	120.65	+1.45	s(32.1%) p(67.2%)
3 : X = LP	2.463	114.78	+1.01	s(55.8%) p(44.2%)

[a]: The bowl depth "*d*" is defined as the distance between the phosphorus atom and the centroid of the plane consisting of the three terminal carbon atoms; [b]: The cone angle " θ " is defined as $2 \times (\text{C–P–Y})$ (Y: the centroid of the plane consisting of the three terminal carbon atoms); [c]: Calculated at the M06-2X/6-31G(d,p) level of theory; [d]: Percentage contribution of the 3s and 3p orbitals of phosphorous to the P–X bond.

In order to elucidate the relationship between the bowl geometry and the axial substituent on the phosphorus atom, a

natural bond orbital (NBO) analysis was carried out, which furnished a rough correlation between θ and the NBO charge. This result implied that bonding with an electron-withdrawing substituent such as S or O decreases the electron density on the phosphorus atom, which induces a more planar structure. The proportional contributions of the phosphorus 3s and 3p orbitals to the P–X bond were calculated by a natural hybrid orbital analysis, which revealed that the s-character of the P–O bond in **1** (31.2%) is slightly lower, but comparable to that of the P–S bond in **2** (32.1%). However, the s-character of the molecular orbital containing the lone pair in **3** is substantially higher (55.8%), even surpassing that of triphenylphosphine (48.9%). This result should most likely be ascribed to the constrained structure of **1**. The s-character of the P–X bond (*i.e.* the lone pair in **3**) is accordingly strongly correlated to the cone angle, θ . This can be feasibly interpreted on the basis of the diagram shown in Figure 1, which suggests an increased s-character for the lone pair upon deviation of the molecular structure from planarity. As **3** exhibits a narrow cone angle (114.78°), the s-character of the lone pair is correspondingly high. The formation of P–X (X = O, S) bonds induces a hybridization of the phosphorus atom under concomitantly higher contributions from the 3p orbital, which results in a widening of the cone angle.

It was thus possible to modulate the bowl geometry of these phosphorus-containing host molecules by a judicious choice of the axial substituent. Subsequently, we investigated the formation of host-guest complexes between these phosphines and C₆₀ fullerene as the convex guest. Previously, we reported the formation of co-crystals of [(P)-**1**]₄⊂C₆₀, in which C₆₀ is encapsulated in the chiral cavity formed by four enantiopure molecules of (P)-**1**. A similar co-crystallization was attempted by slow evaporation of a toluene/chloroform solution of C₆₀ and (P)-**2**, and the X-ray crystallographic analysis of the obtained single crystals revealed the formation of a comparable 4:1 host-guest complex, [(P)-**2**]₄⊂C₆₀ (Fig. 4a). Structurally, [(P)-**2**]₄⊂C₆₀ is very similar to [(P)-**1**]₄⊂C₆₀, and both host-guest complexes can be categorized as capsules.¹⁸

Co-crystals of C₆₀ with (*rac*)-**1** or (*rac*)-**2** were obtained in a similar fashion and exhibited almost identical lattice parameters to those of enantiopure [(P)-**1**]₄⊂C₆₀ and [(P)-**2**]₄⊂C₆₀. This result strongly suggested a racemic twinning of homochiral single crystals, as crystallization of C₆₀ with (*rac*)-**3** from a toluene solution resulted, in contrast, in the formation of the 2:1 host-guest complex [(M)-**3**][(P)-**3**]₂⊂C₆₀ (Fig. 4b), in which the two molecules (M)-**3** and (P)-**3** form an achiral cavity. This complex may accordingly be categorized as a pseudo-cage with a large aperture.¹⁹

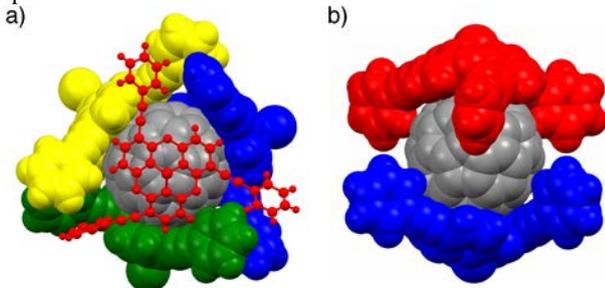


Fig. 4. Space-filling model of the crystal structures of (a) [(P)-

2]₄⊂C₆₀ and (b) [(M)-**3**][(P)-**3**]₂⊂C₆₀ ((P)-**2**, (P)-**3**, and (M)-**3**: colored; C₆₀: grey). One of the four molecules of (P)-**2** is drawn in a ball-and-stick representation to show the encapsulated C₆₀.

Within the cavities of [(P)-**1**]₄, [(P)-**2**]₄, and [(M)-**3**][(P)-**3**], no disorder was observed for C₆₀ (Figure S15 and S16), which suggested that the interactions between C₆₀ and the cavity are sufficiently strong in order to consolidate a particular orientation of the guest. The host-guest complexes could also be detected by MALDI-TOF mass spectrometry measurements, which supports efficient host-guest interactions.²⁰ The C₃-axes of the C₆₀ guests are almost identical with the pseudo-C₃-axes of the host molecules. However, the four (P)-**2** molecules in [(P)-**2**]₄⊂C₆₀ are crystallographically independent, and accordingly, the C₃-axes of the host and guest were slightly misaligned. Conversely, the C₃-axes of the host and guest in [(M)-**3**][(P)-**3**]₂⊂C₆₀ are aligned precisely with the crystallographic rotation axis of the R-3 space group. Accordingly, [(M)-**3**][(P)-**3**]₂⊂C₆₀ belongs to an S₆ point group.

The estimated π - π distance between the host and guest in [(M)-**3**][(P)-**3**]₂⊂C₆₀ (3.74 Å)²¹ is comparable to the closest π - π distance reported for curved host-fullerene complexes based on convex/concave interaction (3.68-3.87 Å).²² Similar π - π distances of 3.51-3.89 and 3.63-3.96 Å were observed for [(P)-**1**]₄⊂C₆₀ and [(P)-**2**]₄⊂C₆₀, respectively. However, the dihedral angles between the adjoined benzene rings in the host and guest in [(M)-**3**][(P)-**3**]₂⊂C₆₀ (10.4°) is lower than that in [(P)-**1**]₄⊂C₆₀ (18.8°) or [(P)-**2**]₄⊂C₆₀ (21.1°). These structural parameters suggest a stronger binding between C₆₀ and **3** compared to **1** and **2**, which most likely arises from a more efficient π - π contact.

For [(P)-**1**]₄⊂C₆₀, [(P)-**2**]₄⊂C₆₀, and [(M)-**3**][(P)-**3**]₂⊂C₆₀, distances of 7.58, 7.62, and 7.89 Å, respectively, were measured between the phosphorus atom and the centroid of the C₆₀ guest. This trend in distances is linearly correlated to the bowl depth of the corresponding host molecule (Table 1). In all complexes, these structural parameters are indicative of a nearly equivalent distance between the bottom of the central phosphangulene units and the centroid of C₆₀ (Fig. 5). However, the distance between the centroid of the terminal benzene ring in the side chains of [(M)-**3**][(P)-**3**]₂⊂C₆₀ and the centroid of C₆₀ is shorter (9.41 Å) compared to those in [(P)-**1**]₄⊂C₆₀ (9.88 Å) and [(P)-**2**]₄⊂C₆₀ (10.3 Å). A close inspection of the molecular structures led us to the conclusion that the different stoichiometry of the host-guest complexes should arise from the different spatial arrangement of the side chains, ultimately leading to differing degrees of contact or repulsion.

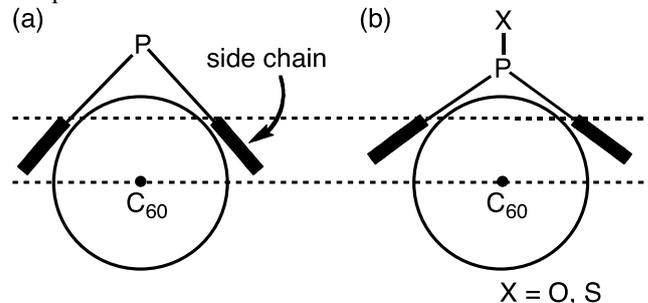


Fig. 5. Location of the C₆₀ guest molecules in co-crystals with (a) deep or (b) shallow bowl-shaped phosphine hosts.

In conclusion, we disclosed the synthesis of phosphorus-containing bowl-shaped host molecules with different axial substituents on the central phosphorus atom. X-ray crystallographic analyses revealed that the axial substituent (O, S, or LP) has a significant effect on the bowl geometry, both with respect to the depth of the bowl as well as to its cone angle. An NBO analysis performed on the basis of DFT-calculated optimized structures indicated that the bonding properties of the P–X bonds should play an important role in tuning the geometry of the bowl. Although all host molecules encapsulated C₆₀ as a guest molecule in co-crystals, the structures of the host-guest complexes are significantly different, depending on the bowl geometry of the host molecule. Hosts **1** and **2**, with relatively shallow bowls, afforded chiral cavities composed of four host molecules, while host **3**, with a deeper bowl, afforded an achiral cavity composed of two molecules. This study thus provides a strategy for the design of bowl-shaped phosphine host molecules with tunable bowl geometries. The control over the bowl geometry afforded control over the assembly architectures in co-crystals with C₆₀ fullerene, and resulted in the formation of chiral capsules or an achiral pseudo-cage. This modulation approach should hence allow the induction of specific supramolecular architectures that may be used in order to control the electrochemical and/or photochemical properties of fullerenes.

We are grateful to Prof. Dr. Y. Uchiyama (Kitasato University) for his assistance with chiral HPLC. This work was financially supported by Grants-in-Aid for Scientific Research from MEXT, Japan. This work was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas “pi-System Figuration” (15H00985) and “Photosynergetics” (15H01079) from MEXT, Japan.

Notes and references

^a Graduate School of Pure and Applied Sciences and Tsukuba Research Center for Interdisciplinary Materials Science (TIMS), University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8571 Japan; E-mail: myama@chem.tsukuba.ac.jp, nabesima@chem.tsukuba.ac.jp

† Electronic Supplementary Information (ESI) available: Synthetic procedure, spectral data, and crystal structures. See DOI: 10.1039/b000000x/

‡ Footnotes should appear here. These might include comments relevant to but not central to the matter under discussion, limited experimental and spectral data, and crystallographic data.

- 1 a) W. E. Barth and R. G. Lawton, *J. Am. Chem. Soc.* 1966, **88**, 380; b) L. T. Scott, M. M. Hashemi and M. S. Bratcher, *J. Am. Chem. Soc.* 1992, **114**, 1920.
- 2 H. Sakurai, T. Daiko and T. Hirao, *Science* 2003, **301**, 1878.
- 3 For molecular recognition of bowl-shaped π -conjugated molecules, see: a) S. Mizyed, P. E. Georghiou, M. Bancu, B. Cuadra, A. K. Rai, P. Cheng and L. T. Scott, *J. Am. Chem. Soc.* 2001, **123**, 12770; b) P. E. Georghiou, A. H. Tran, S. Mizyed, M. Bancu and L. T. Scott, *J. Org. Chem.* 2005, **70**, 6158; c) L. N. Dawe, T. A. AlHujran, H.-A. Tran, J. I. Mercer, E. A. Jackson, L. T. Scott and P. E. Georghiou, *Chem. Commun.* 2012, **48**, 5563.
- 4 a) N. Martin, J.-F. Nierengarten, (Eds), *Supramolecular Chemistry of Fullerenes and Carbon Nanotubes* **2012**, Wiley-VCH; b) F. D'Souza, K. M. Kadish, (Eds), *Handbook of Carbon Nano Materials Volume 1. Syntheses and Supramolecular Systems* **2011**, World Scientific Publishers.
- 5 For bowl-shaped host molecules such as calixarenes, see: a) J. L. Atwood, G. A. Koutsantonis and C. L. Raston, *Nature* 1994, **368**,

- 229; b) T. Suzuki, K. Nakashima and S. Shinkai, *Chem. Lett.* 1994, 699; c) T. Haino, M. Yanase and Y. Fukazawa, *Angew. Chem., Int. Ed.* 1997, **36**, 259; d) K. Tsubaki, K. Tanaka, T. Kinoshita and K. Fuji, *Chem. Commun.* 1998, 895; e) T. Haino, M. Yanase, C. Fukunaga and Y. Fukazawa, *Tetrahedron* 2006, **62**, 2025; for tribenzotriquinacenes, see: f) D. Pham, J. C. Bertran, M. M. Olmstead, M. Mascal and A. L. Balch, *Org. Lett.* 2005, **7**, 2805; g) B. Breidenkötter, S. Henne and D. Volkmer, *Chem. Eur. J.* 2007, **13**, 9931; for subphthalocyanines, see: h) C. G. Claessens and T. Torres, *Chem. Commun.* 2004, 1298; i) S. Shimizu, S. Nakano, T. Hosoya and N. Kobayashi, *Chem. Commun.* 2011, **47**, 316.
- 6 A. Sygula, F. R. Fronczek, R. Sygula, P. W. Rabideau and M. M. Olmstead, *J. Am. Chem. Soc.* 2007, **129**, 3842.
- 7 Recently, an increasing number of studies on bowl-shaped molecules, whose bowl geometry can be tuned by chemical reactions or external redox, photon, or mechanical stimuli, has been reported: a) T. Kushida and S. Yamaguchi, *Organometallics* 2013, **32**, 6654; b) T. Kushida, C. Camacho, A. Shuto, S. Irle, M. Muramatsu, T. Katayama, S. Ito, Y. Nagasawa, H. Miyasaka, E. Sakuda, N. Kitamura, Z. Zhou, A. Wakamiya and S. Yamaguchi, *Chem. Sci.* 2014, **5**, 1296; c) C. Yuan, S. Saito, C. Camacho, T. Kowalczyk, S. Irle and S. Yamaguchi, *Chem. Eur. J.* 2014, **20**, 2193.
- 8 M. Yamamura, T. Saito, T. Nabeshima, *J. Am. Chem. Soc.* 2014, **136**, 14299.
- 9 a) F. C. Krebs, P. S. Larsen, J. Larsen, C. S. Jacobsen, C. Boutton and N. Thorup, *J. Am. Chem. Soc.* 1997, **119**, 1208; b) G. K. H. Madsen, F. C. Krebs, B. Lebech and F. K. Larsen, *Chem. Eur. J.* 2000, **6**, 1797.
- 10 C. C. Levin, *J. Am. Chem. Soc.* **1975**, **97**, 5649.
- 11 T. Kawashima, S. Kojima and N. Inamoto, *Chem. Lett.* 1989, 849; b) K. Michal-Pietrusiewicz and M. Zablocka, *Chem. Rev.* 1994, **94**, 1375.
- 12 Sufficiently small Flack χ values were obtained for (*M*)-**2** and (*M*)-**3** in order to determine the absolute structure (Table S1 in the Supporting Information).
- 13 S. Tsuzuki, K. Honda, T. Uchimaru, M. Mikami and K. Tanabe, *J. Am. Chem. Soc.* 2002, **124**, 104.
- 14 A similar value (93°) has been reported by Krebs; see: reference 9.
- 15 B. Breit and E. Fuchs, *Chem. Commun.* 2004, 694.
- 16 a) C. Jongmsa, J. P. de Kleijn and F. Bickelhaupt, *Tetrahedron* 1974, **30**, 3465. b) J. Kobayashi, T. Agou and T. Kawashima, *Chem. Lett.* 2003, **32**, 1144. c) T. Agou, J. Kobayashi and T. Kawashima, *Chem. Lett.* 2004, **33**, 1028. d) H. Tsuji, T. Inoue, Y. Kaneta, S. Sase, A. Kawachi and K. Tamao, *Organometallics* 2006, **25**, 6143.
- 17 Only very few reports describe a change from planar to bowl-shaped molecular structures: a) E. Tsurumaki, S.-Y. Hayashi, F. S. Tham, C. A. Reed and A. Osuka, *J. Am. Chem. Soc.* 2011, **133**, 11956; b) K. Matsuo, S. Saito and S. Yamaguchi, *J. Am. Chem. Soc.* 2014, **136**, 12580.
- 18 For reports on the modulation of assembled architectures, e.g. capsules, cages, or tubes, see: a) K. Harano, S. Hiraoka and M. Shionoya, *J. Am. Chem. Soc.* 2007, **129**, 5300; b) N. Kishi, M. Akita and M. Yoshizawa, *Angew. Chem. Int. Ed.* 2014, **53**, 3604.
- 19 The host part in [(*M*)-**3**][(*P*)-**3**]C₆₀ is a “pseudo-cage” rather than a “cage” because the two host molecules are not connected to each other.
- 20 In our previous work, an NMR titration study of **1** with C₆₀ exhibited negligible spectral change, indicating very weak interaction in solution, see reference 8.
- 21 The π - π distance is defined as the distance between the centroids of adjoined benzene rings in the host and one of the six-membered rings of the C₆₀ guest.
- 22 J. Xia, J. W. Bacon and R. Jasti, *Chem. Sci.* 2012, **3**, 3018.