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Configurational Isomers of a Stilbene-Linked Bis(porphyrin) Tweezer: Synthesis and Fullerene-Binding Studies

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A new stilbene-tethered bis(porphyrin) tweezer **5** has been synthesized through a Sonogashira cross-coupling reaction. The tweezer exists as two configurational isomers [(Z) + (E)], which have distinct cavity sizes. Fullerene-binding studies show that the (Z) isomer of the tweezer has a significantly higher affinity toward both C_{60} and C_{70} compared to the (E) congener. In addition, the (Z) → (E) photoisomerization of tweezer **5** is also discussed.

Introduction

The attractive association between the curved and flat π-surfaces of fullerenes and porphyrins, respectively, has heralded a new molecular recognition motif that can be used to sequester fullerenes.[1] In particular, it has been shown that molecular receptors consisting of a central scaffold (such as organometallic complexes, calixarenes, rotaxanes, and phenylacetylene-tethered dendrimers) can be used to pre-organize two molecules of porphyrins to access bidentate interactions with fullerenes leading to high-affinity complexation ($K_a = 10^4$–10^8 M^{-1}).[2] In addition to the nature of the scaffold, the center-to-center distance between the two porphyrin units plays an important role in the magnitude of the host–fullerene interaction.[3] Thus, the study of interconvertible isomers of bis(porphyrin) "tweezers" that possess distinct bite sizes could lead to switchable hosts for fullerenes, with applications in molecular switches, logic gates, as well as in the development of responsive materials for fullerene-separation processes.[4]

In accord with our interests in the self-assembly of fullerene and porphyrin components and in the development of switchable molecules,[5] we were particularly keen in investigating the differential fullerene-binding capacity of potentially switchable isomers of bis(porphyrin)-based tweezers. With this communication, we disclose the synthesis and contrasting fullerene-binding (C_{60} and C_{70}) ability of the (*Z* or *cis*)- and (*E* or *trans*)-configurational isomers of a stilbene-tethered porphyrin tweezer **5**. Also discussed is the photoinduced isomerization of the high-affinity (*Z*) isomer to the low-affinity (*E*) configuration.

Results and Discussion

The design of tweezer **5** includes a core stilbene module flanked by two zinc–porphyrin units by alkyne spacers. These linkers were specifically chosen, because they allow for rotation of the porphyrin units and are also sufficiently rigid to maximize interactions with the fullerene guests. Illustrations of the two configurational isomers of **5** in the *syn* conformation (i.e., the porphyrin arms are directed in a tweezer-like position) are shown in Figure 1. It was hypothesized that the (*Z*) configuration of **5** – as a result of accessing a skewed stilbene core – should present the two porphyrin arms with a short center-to-center distance (12 Å, estimated by a computer-assisted molecular model, see Supporting Information, Figure S13). In contrast, the (*E*) configuration of **5** should exhibit a more planar stilbene scaffold that projects the porphyrin arms with a larger separation of 16 Å. Since the van der Waals diameters of C_{60} and C_{70} (ca. 1 nm) match the bite size for the (*Z*) configuration, it was expected that the (*Z*) isomer of tweezer **5** would exhibit a substantially higher affinity for both fullerenes.[6]

The (*Z*) and (*E*) isomers of tweezer **5** were synthesized simultaneously as outlined in Scheme 1. Briefly, monofunctionalized free-base porphyrin **1** was prepared according to the dipyrromethane approach. That is, the acid-catalyzed condensation of phenyldipyrromethane (2 equiv.) with benzaldehyde (1 equiv.) and 3-(trimethylsilyl)-2-propynal (1 equiv.). Subsequent column chromatography on silica gel afforded porphyrin **1** in 13% yield. Reaction of porphyrin **1** with zinc acetate yielded zinc–porphyrin compound **2** quantitatively. Deprotection of the TMS group on **2** was achieved by reaction with tetrabutylammonium fluoride (TBAF) to give zinc–porphyrin compound **3** in excellent yield.[7] A diastereomeric mixture of (*E*)- and (*Z*)-3,3′-dibromostilbene (**4**) was synthesized by the reaction of 3-bromobenzaldehyde and 3-bromobenzyl bromide under Wittig conditions.[8] This mixture was directly treated with porphy-

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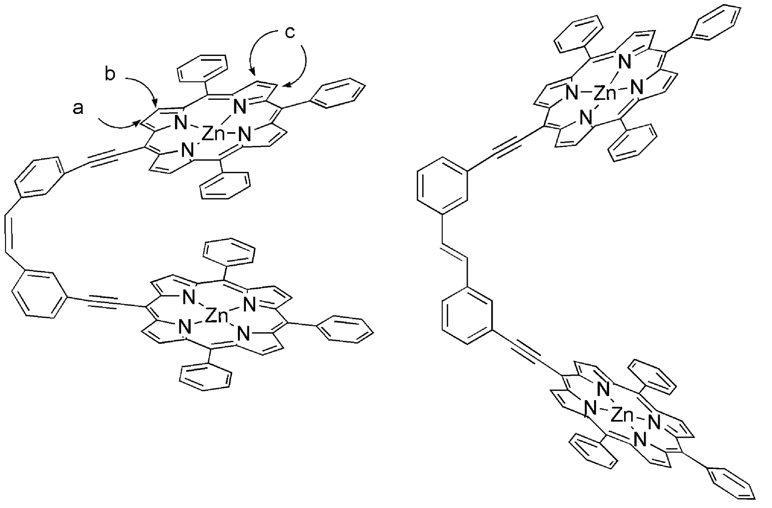
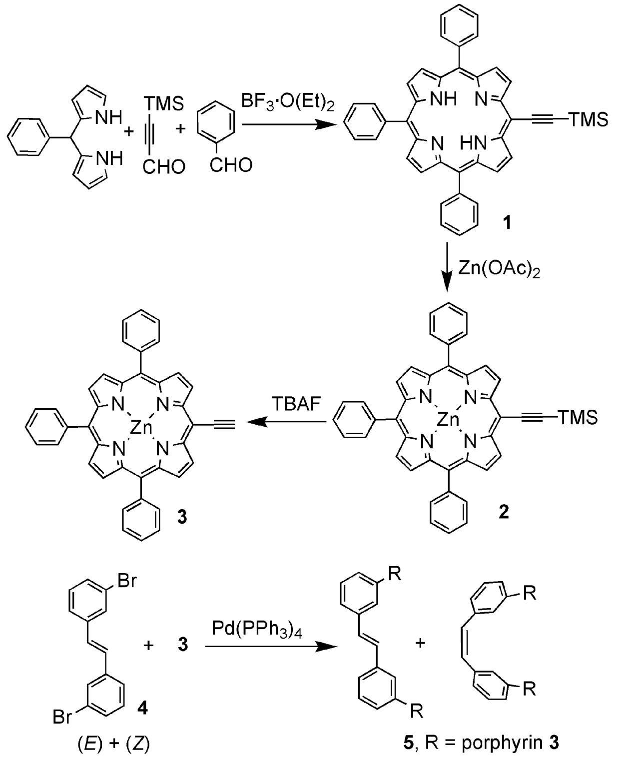


Figure 1. Proposed *syn* conformations of the (*Z*) (left) and (*E*) (right) configurations of bis(porphyrin) tweezer **5**. The letters a–c designate the various β-pyrrole protons.

rin **3** by utilizing copper-free Sonogashira reaction conditions to give tweezer **5** in good yield.[9] Isolation of the (*Z*) and (*E*) configurational isomers of tweezer **5** was successfully achieved by using preparative thin-layer chromatography (TLC) with $CHCl_3$ as the eluent [R_f of the (*Z*) and (*E*) isomers are 0.78 and 0.59, respectively].



Scheme 1. Synthesis of the (*Z*) and (*E*) configurational isomers of bis(porphyrin) tweezer **5**.

Both configurational isomers of **5** were characterized inter alia by UV/Vis (Figure 2) and ^{1}H NMR spectroscopy (Figure S14). The (*Z*) isomer of tweezer **5** exhibits an electronic absorption band at shorter wavelength (centered at 276 nm), whereas the (*E*) isomer shows a broad band at 316 nm. Interestingly, the Soret band for the (*Z*) isomer is blueshifted (4 nm), whereas the Q-bands are redshifted (6 nm) compared to the (*E*) configuration. In addition, ^{1}H NMR studies show that the signal of the β-protons of the (*Z*) isomer is shifted upfield from that of the (*E*) isomer. These characteristic shifts in the UV/Vis and ^{1}H NMR spectra lead us to suggest that the two porphyrin moieties on the (*Z*) form are spatially closer to each other than those of the (*E*) isomer.[10]

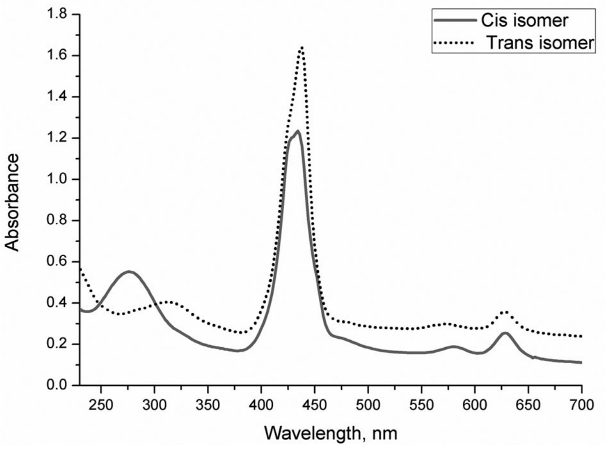


Figure 2. UV/Vis absorption spectra of the (*Z*) (solid line) and (*E*) (dotted line) isomers of **5** (5×10^{-5} M) in acetonitrile.

With the (*Z*) and (*E*) isomers characterized, the binding ability of these two configurations with C_{60} and C_{70} were investigated. Preliminary binding studies were conducted by UV/Vis titrations with a toluene/acetonitrile solvent mixture.[11] Titration of either fullerene into a solution containing the (*Z*) isomer of **5**, yielded a clear hypochromic shift in the Soret band in conjunction with the appearance of an isosbestic point at 452 nm (Figure 3). In marked contrast, similar titrations with the (*E*) isomer displayed no appreciable changes in the electronic absorption spectrum. These preliminary experiments clearly indicate that the (*Z*) isomer interacts to a higher extent with fullerenes.

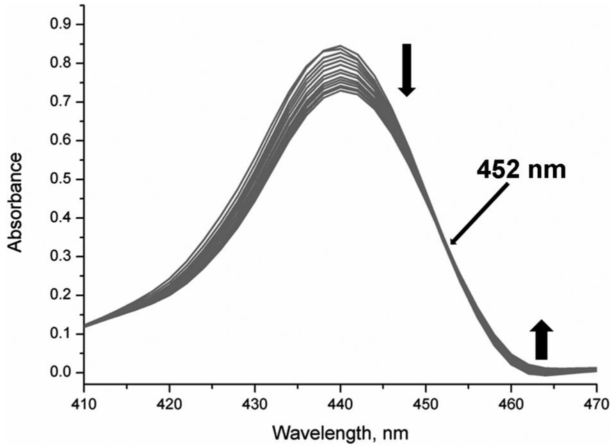


Figure 3. UV/Vis spectrum of tweezer **5** [(*Z*) isomer] upon addition of C_{60} (0–20 equiv.) in toluene/acetonitrile (1:1).

Further evidence for a strong interaction of the (*Z*) isomer with fullerenes was gathered from MALDI-TOF studies. A sample containing C_{60} (10 equiv.) and the (*Z*) isomer exhibited a peak at 2148.4 Da corresponding to a 1:1 complex (theoretical: 2148.3 Da). Similarly, a sample of the (*Z*) isomer of **5** in the presence of C_{70} (10 equiv.) shows a peak at 2269.0 Da (theoretical: 2268.3 Da) ascribed to the 1:1 complex. In contrast, these adducts were not observed with the (*E*) isomer of **5** in the presence of either C_{60} or C_{70}.

In order to determine quantitative association constants (K_a), fluorescence titrations were performed. Here the quenching of the porphyrin fluorescence by the fullerenes, probably as a result of photoinduced electron transfer,[12] was monitored. In a typical experiment, aliquots of C_{60} or C_{70} in toluene (stock concentration: 1×10^{-3} M or 1×10^{-4} M, respectively) were added to a solution of tweezer **5** (2.67×10^{-6} M) in toluene/acetonitrile (1:1). Figure 4 shows a representative fluorescence spectrum for the (*Z*) isomer of **5** upon addition of C_{70}. As expected, the fluorescence maximum at 630 nm (excitation at 442 nm) decreases with increasing aliquots of C_{70} suggesting putative complexation of C_{70} by **5**.

The fluorescence titration data were fit to a 1:1 binding model (confirmed by Job's plots), and nonlinear regression analysis was used to estimate K_a.[13] The results from these experiments are illustrated in Figure 5. As shown in columns 1 and 2, the binding constant between the (*Z*) isomer of **5** and C_{60} ($2.9 \pm 0.4 \times 10^4$ M^{-1}) is four times larger than that of the (*E*) isomer ($7.1 \pm 0.2 \times 10^3$ M^{-1}). Similarly, the binding constant of the (*Z*) form of **5** with C_{70} ($8.2 \pm 0.8 \times 10^4$ M^{-1}) is five times larger than that of the (*E*) form with C_{70} ($1.7 \pm 0.1 \times 10^4$ M^{-1}). These results indicate that not only is the (*Z*) isomer more effective at complexing fullerenes, but C_{70} is a better guest for both isomers of tweezer **5**.[14]

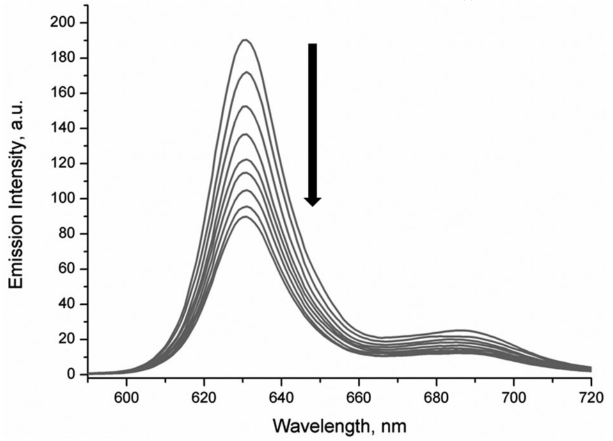


Figure 4. Fluorescence spectrum of tweezer **5** [(*Z*) isomer] in toluene/acetonitrile (1:1) upon sequential addition of C_{70} (0–15 equiv.).

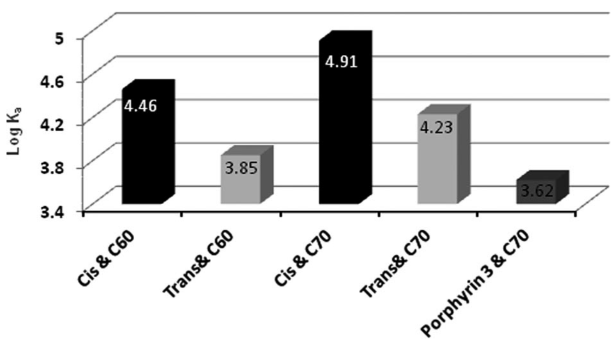


Figure 5. Binding constants for tweezer **5** and porphyrin **3** with fullerenes. All titrations include addition of fullerene (in toluene) into a solution of the porphyrin host in toluene/acetonitrile (1:1).

The high fullerene-binding affinities of the (*Z*) isomer of tweezer **5**, in conjunction with its 1:1 binding stoichiometry, lead us to propose that this configuration binds to fullerenes through a *syn* conformation (where the two porphyrin arms are placed ca. 12 Å apart and act to sandwich a fullerene molecule, see Figure 6A). In regard to the (*E*) isomer, two potential conformations are possible. Figure 6B shows the (*E*) form in the *syn* conformation with a porphyrin–porphyrin distance of 16 Å. This conformation should afford a higher affinity towards fullerenes compared to the *anti* isomer (Figure 6C). Moreover, if the (*E*) configuration binds to fullerenes through the *anti* conformation one would expect K_a to be similar to that of control **3** (i.e., interacting through only monodentate interactions). Unfortunately, we could not obtain reliable binding data for control **3** with C_{60} since the interaction was too weak. However, control **3** bound to C_{70} with $K_a = 4.2 \pm 0.9 \times 10^3$ M^{-1}, which is significantly lower than K_a for the (*E*) isomer of tweezer **5** with C_{70}. Thus, the (*E*) configuration of **5** is also thought to bind through the *syn* conformation (Figure 6B). However, since the cavity formed by the (*E*) isomer is much larger than the van der Waals diameter of the fullerenes, the binding constant is not as pronounced as compared to the (*Z*) congener.

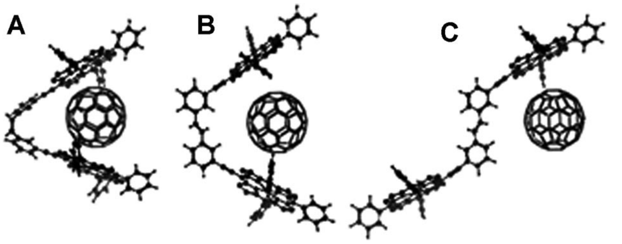


Figure 6. Schematic illustration of the proposed binding modes of tweezer **5** and fullerene C_{60}; (A) *syn* conformation of the (*Z*) isomer, (B) *syn* conformation of the (*E*) isomer, and (C) *anti* conformation of the (*E*) isomer.

The afore-mentioned experiments have demonstrated that the two configurational isomers of tweezer **5** bind C_{60} and C_{70} with different affinities. Since the parent stilbene can undergo photoswitching between the (*Z*) and (*E*) configurations,[15] and the two configurational isomers of tweezer **5** have distinct absorption profiles, we investigated the potential of using light to induce isomerization of tweezer **5**.[16] First, a solution of the (*Z*) isomer of **5** in [D_6]-benzene was irradiated with a hand-held UV lamp [254 nm, where the (*Z*) isomer has a higher absorption profile] in a pyrex NMR tube at 25 °C, and the reaction was monitored by ^{1}H NMR spectroscopy. As shown in Figure 7, conversion of the (*Z*) isomer to the (*E*) form is observed, albeit not completely, over a period of 7 h. The ratio of the two isomers at 7 h was determined by the integral intensities of the pyrrole β-proton signals. The (*E*)/(*Z*) ratio was found to be 35:65 at the photostationary state.[17]

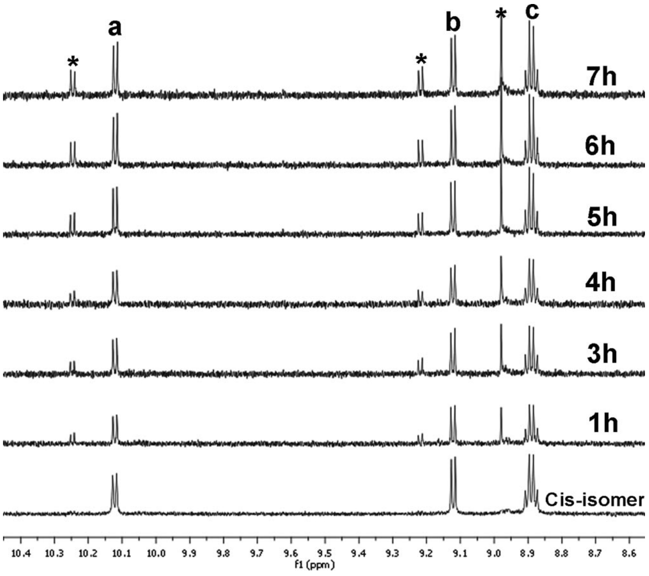


Figure 7. Stacked NMR spectra (pyrrole β-proton region) of tweezer **5** showing the photoswitching of the (*Z*) isomer upon irradiation with 254 nm light (from 1 to 7 h in [D_6]benzene). The (*Z*) isomer protons (a–c) are assigned according to Figure 1, and the peaks marked by asterisks correspond to the (*E*) isomer.

Similar conversion experiments were conducted by starting from the (*E*) isomer of tweezer **5** and irradiating with a long-wavelength lamp (365 nm). Unfortunately, these attempts were unsuccessful. Possible reasons for the lack of (*E*) → (*Z*) photoswitching include (a) overlapping of the (*E*) isomer absorption profile with that of the (*Z*) form in this region of the UV/Vis spectrum (see Figure 2) preventing selective irradiation of the (*E*) isomer, and (b) quenching of the alkene excited state through energy transfer to the porphyrin moieties of tweezer **5**. Similar findings have been reported for the photoisomerization of azobenzene scaffolds.[18]

Conclusions

We have designed and synthesized a novel porphyrin tweezer **5** that exists as two configurational isomers. The (*Z*) isomer was found to sequester fullerenes with a significantly higher association constant than the (*E*) form. This enhancement is ascribed to a bite size that matches the van der Waals diameter of the fullerenes. Preliminary photoswitching studies indicate that the (*Z*) isomer can be converted into the (*E*) congener by irradiation at 254 nm. However, the reaction does not go to completion. This work is the first attempt to develop configurational stilbene isomers as receptors with photo-regulable fullerene binding capacity. We are currently investigating the use of alternative linkers, switchable scaffolds, and substituted porphyrin arms in order to obtain more effective photoswitching.

Supporting Information (see footnote on the first page of this article): General experimental procedures and spectroscopic characterization, fitting curves for K_a determination, Job's Plots, and MALDI-TOF.

Acknowledgments

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[1] a) M. M. Olmstead, D. A. Costa, K. Maitra, B. C. Noll, S. L. Philips, P. M. Van Calcar, A. L. Balch, *J. Am. Chem. Soc.* **1999**, *121*, 7090–7097; b) P. D. W. Boyd, M. C. Hodgson, C. E. F. Rickard, A. G. Oliver, L. Chaker, P. J. Brothers, R. D. Bolskar, F. S. Tham, C. A. Reed, *J. Am. Chem. Soc.* **1999**, *121*, 10487–10495; c) P. D. W. Boyd, C. A. Reed, *Acc. Chem. Res.* **2005**, *38*, 235–242.

[2] a) D. Sun, F. S. Tham, C. A. Reed, L. Chaker, M. Burgress, P. D. W. Boyd, *J. Am. Chem. Soc.* **2000**, *122*, 10704–10705; b) A. Hosseini, S. Taylor, G. Accorsi, N. Armaroli, C. A. Reed, P. D. W. Boyd, *J. Am. Chem. Soc.* **2006**, *128*, 15903–15913; c) M. Kas, K. Lang, I. Stibor, P. Lhotak, *Tetrahedron Lett.* **2007**, *48*, 477–481; d) J.-S. Marois, K. Cantin, A. Desmarais, J.-F. Morin, *Org. Lett.* **2008**, *10*, 33–36; e) T. Nishioka, K. Tashiro, T. Aida, J.-Y. Zheng, K. Kinbara, K. Saigo, S. Sakamoto, K. Yamaguchi, *Macromolecules* **2000**, *33*, 9182–9184; f) M. Ayabe, A. Ikeda, Y. Kubo, M. Takeuchi, S. Shinkai, *Angew. Chem. Int. Ed.* **2002**, *41*, 2790–2792.

[3] a) N. Solladie, S. Bouatra, S. Merkas, R. Rein, J. Roeser, *J. Porphyrins Phthalocyanines* **2005**, *9*, 779–787; b) K. Tashiro, T. Aida, J.-Y. Zheng, K. Kinbara, K. Saigo, S. Sakamoto, K. Yamaguchi, *J. Am. Chem. Soc.* **1999**, *121*, 9477–9478; c) see also ref.[6]

[4] a) T. Haino, C. Fukunaga, Y. Fukazawa, *Org. Lett.* **2006**, *8*, 3545–3548; b) Y. Shoji, K. Tashiro, T. Aida, *J. Am. Chem. Soc.* **2004**, *126*, 6570–6571.

[5] M. Fathalla, S.-C. Li, U. Diebold, A. Alb, J. Jayawickramarajah, *Chem. Commun.* **2009**, 4209–4211.

[6] 12 Å is considered an optimal cavity diameter since this is close to the distance between two porphyrin macrocycles in tetraphenylporphyrin/fullerene cocrystallates. In fact, receptors that present a cavity of ca. 12 Å display particularly strong fullerene-binding constants. See for example: a) D. Sun, F. S. Tham, C. A. Reed, L. Chaker, P. D. W. Boyd, *J. Am. Chem. Soc.* **2002**, *124*, 6604–6612; b) D. Sun, F. S. Tham, C. A. Reed, P. D. W. Boyd, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 5088–5092.

[7] D. P. Arnold, R. D. Hartnell, *Tetrahedron* **2001**, *57*, 1335–1345.

[8] R. Antnioletti, F. Bonadies, A. Ciammaichella, A. Viglianti, *Tetrahedron* **2008**, *64*, 4644–4648.

[9] During the course of the synthesis of tweezer **5**, Sonogashira cross-coupling reactions were attempted in the presence and absence of CuI. The copper-free approach gave better yields, since the copper-cocatalyzed reaction led to a high percentage of the Glaser coupling product (i.e., the homodimer of porphyrin **3**).

[10] V. V. Borovkov, J. M. Lintuluoto, Y. Inoue, *J. Phys. Chem. B* **1999**, *103*, 5151–5156.

[11] In a typical experiment, aliquots of fullerenes dissolved in toluene were added to a solution of tweezer **5** dissolved in toluene/acetonitrile (1:1). This solvent mixture (as opposed to neat toluene) can significantly increase the magnitude of host–fullerene interactions; see ref.[2b]

[12] a) T. Hasobe, A. S. D. Sandanayaka, T. Wada, Y. Araki, *Chem. Commun.* **2008**, 3372–3374; b) H. Nobukuni, Y. Shimazaki, F. Tani, Y. Naruta, *Angew. Chem. Int. Ed.* **2007**, *46*, 8975–8978; c) M. E. El-Khouly, O. Ito, P. M. Smith, F. D'Souza, *J. Photochem. Photobiol., C* **2004**, *5*, 79–104.

[13] A. K. Connors, *Binding Constants: The Measurements of Molecular Complex Stability*, John Wiley & Sons, New York, NY, **1987**.

[14] These results are in agreement with a previous report also showing that C_{70} binds with a higher K_a to bis(porphyrin) receptors. This finding is ascribed to the ovoid shape of C_{70} and a slightly larger van der Waals diameter that allow for better interactions with the receptor. See ref.[2a,2b]

[15] a) P. Kuad, A. Miyawaki, Y. Takashima, H. Yamaguchi, A. Harada, *J. Am. Chem. Soc.* **2007**, *129*, 12630–12631; b) R. Rojanathanes, T. Tuntulani, W. Bhanthumnavin, M. Sukwattanasinitt, *Org. Lett.* **2005**, *7*, 3401–3404.

[16] While this work was in progress T. Arai et al. have recently reported the photoswitching of a porphyrin–(*Z*)-stilbene–porphyrin triad, wherein the porphyrin units are linked through flexible spacers. However, these authors have not investigated the fullerene-binding capacity of their compound. See: M. Wahadoszamen, T. Yamamura, A. Momotake, Y. Nishimura, T. Arai, *Heterocycles* **2009**, *79*, 331–337.

[17] Interestingly, carrying out this switching experiment in the presence of C_{60} shows no (Z) → (E) conversion.

[18] a) M. V. Peters, R. Goddard, S. Hecht, *J. Org. Chem.* **2006**, *71*, 7846–7849; b) C. A. Hunter, L. D. Sarson, *Tetrahedron Lett.* **1996**, *37*, 699–702.

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