# Synthesis and *trans*-β-carotenoid inclusion properties of a new class of water soluble calixarenes †

**Mohamed Makha,[a] Ian R. McKinnon[b] and Colin L. Raston*[c]**

[a] *Department of Chemistry, University of Leeds, Leeds, UK LS2 9JT. E-mail: c.l.raston@chemistry.leeds.ac.uk; Fax: +44 0113 233 6401; Tel: +44 0113 233 6555*
[b] *School of Chemistry, Monash University, Clayton, Melbourne, Victoria 3800, Australia*
[c] *Department of Chemistry, University of Western Australia, Perth, WA 6009, Australia. E-mail: clraston@chem.uwa.edu.au*

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The paper describes the synthesis of water soluble sulfonated calixarenes derived from *p*-benzylcalix[5,6,7,8]arenes and *p*-cumylcalix[4,6]arene along with their chlorosulfonyl derivatives. Inclusion phenomena of the sulfonated *p*-benzyl and *p*-phenyl calix[5,6]arenes towards carotenoids are also reported; $^1$H NMR, UV–VIS and light scattering experiments are consistent with a model in which the carotenoid is surrounded by two calixarenes and these supermolecules form large aggregates, 100–150 nm in diameter.

## Introduction

Water soluble calix[*n*]arenes are a widely investigated class of compounds becoming increasingly important in the field of supramolecular chemistry. They offer interesting inclusion properties and a wide range of metal coordination complexes both in solution and in the solid state.[1] One type of such compound are sulfonated calixarenes which can form large molecular assemblies with various guest molecules leading to supramolecular architectures of high complexity.[2] In this context, we are interested in building water soluble sulfonated calixarenes with cavities deeper than those of traditional *p*-$SO_3^-$-calix[*n*]arenes, able to bind large guest molecules, and to explore their supramolecular interactions. Calixarenes bearing benzyl or cumyl groups at the *para*-position were the calixarenes of choice, and recently we reported the synthesis of sulfonated *p*-phenylcalixarene analogues.[3] Herein, we report the synthesis and spectroscopic characterisation of novel water soluble calixarenes derived from *p*-benzylcalix[5,6,7,8]arenes and *p*-cumylcalix[4,6]arene along with their chlorosulfonyl derivatives. Also included is the study of the aggregation behaviour of these sulfonated calixarenes in water using dynamic light scattering, and the screening of their inclusion phenomena towards the carotenoids, *trans*-β-carotene and asthaxantin.

In aqueous media, amphiphilic compounds tend to aggregate with the free energy gain originating from the hydrophobic effect,[5] which is also responsible for the complexation of lipophilic molecules inserted into the central part of the amphiphile. This concept suggests that the shape of the hydrophobic molecule and the aggregation morphology can be influenced or partly regulated by the shape of the included guest molecule. In organic media, calix[5,6]arenes in particular are known to form discrete inclusion complexes with hydrophobic molecules such as fullerene $C_{60}$.[6] The solubilization of $C_{60}$ in water has also been achieved either by using substituted cyclodextrins or a sulfonated derivative of calix[8]arene.[7] In contrast, calixarene inclusion complexes of carotenoids are not widely investigated, noting that there are only few reports of such inclusion phenomena with cyclodextrin macrocycles.[8] Furthermore and in the pursuit of encapsulating carotenoids, Baumeister and Matile have developed water soluble β-barrels, formed *via* a self-assembly process of peptide strands.[9]

The present study is directed towards using such host molecules, ultimately for separation technology, and also for use in material chemistry. This is significant in that the carotenoids are readily avaliable natural products with potential applications beyond those already established, for example in food and pharmaceutical industries.

## Results and discussion

The general synthesis of these novel water soluble calixarenes was carried out following an adaptation of the literature procedure for sulfonation of other calixarenes, Scheme 1.[3,4] The chlorosulfonyl derivatives were produced in variable yields depending on the extent of exlusion of moisture. It is noteworthy that the sulfonation reaction is regioselective, incorporating chlorosulfonyl groups only at the *para* position of the benzyl or cumyl group moieties. The sulfonic acid calixarenes were isolated either from the reaction mixure or from the hydrolysis of the chlorosulfonyl derivatives as deliquescent solids. The sodium salts of the derivatives were obtained by straightforward titration of the sulfonic acids. Unlike the parent sulfonato-calix[*n*]arenes, *p*-benzylcalix[5,6]arene sulfonates **9**, **10** and *p*-phenylcalix[5,6]arenes[3] **16**, **17** with their enhanced lipophilic character are found to form large aggregates in solution and form complexes with lipophilic molecules *trans*-β-carotene and astaxanthin in water.

The solubilization of these hydrophobic guest molecules was not accomplished by just a mere mixing of the host with the guest but required mechanical energy supplied by grinding in a mortar and pestle. Thus, a set of experiments were carried out involving the mixing of equimolar quantities of *p*-benzylcalix[*n*]arene sulfonates ($n$ = 4, 5, 6, 7, 8) and *trans*-β-carotene, the solid mixture being ground together until a uniform powder is obtained (*ca.* 1 min). Grinding was continued after adding distilled water for another minute. The resulting slurry was twice filtered with standard filter paper and once with 0.2 μm porosity filter paper affording a clear transparent solution. For all the calixarenes studied in the grinding experiments, only *p*-benzylcalix[*n*]arene sulfonates ($n$ = 5, 6) **9**, **10** gave intense

† Electronic supplementary information (ESI) available: details of grinding experiments. See http://www.rsc.org/suppdata/p2/b2/b207850c/

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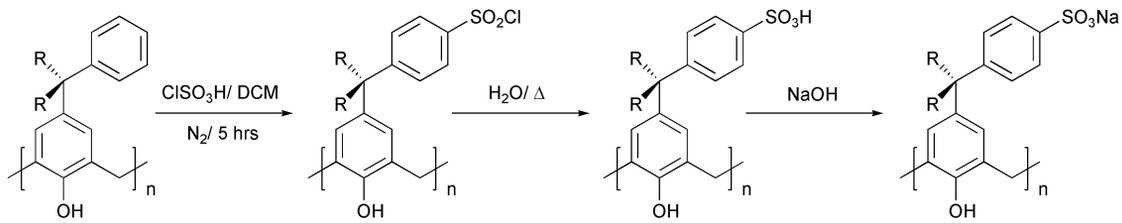
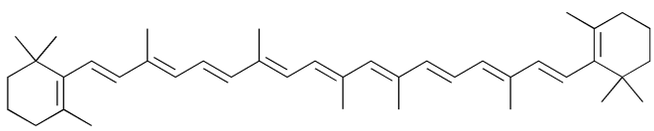



R = H, n = 5, **1**
n = 6, **2**
n = 7, **3**
n = 8, **4**
R = Me, n = 4, **13**
n = 6, **14**

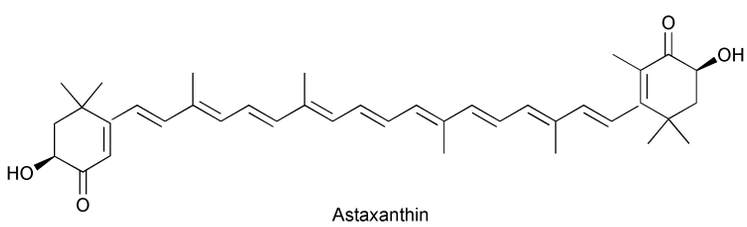
R = H, n = 5, **5**
n = 6, **6**
n = 7, **7**
n = 8, **8**
R = Me, n = 6, **15**

R = H, n = 5, **9**
n = 6, **10**
n = 7, **11**
n = 8, **12**

**Scheme 1** General scheme for the synthesis of chlorosulfonates and sulfonates of *p*-benzyl- and *p*-cumylcalix[*n*]arenes.



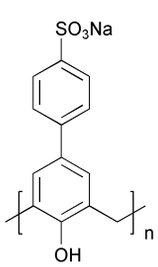
*trans*-β-Carotene




Astaxanthin

orange solutions. *p*-Benzylcalix[*n*]arene sulfonates ($n$ = 4, 8) take up only a trace of *trans*-β-carotene, as indicated by the formation of faint yellow solutions. Likewise, sulfonated *p*-benzylcalix[5,6]arenes also formed complexes with astaxanthin using the same technique as for *trans*-β-carotene.

Sulfonated *p*-phenylcalix[5,6]arenes, **16** and **17** show similar interactions with *trans*-β-carotene and astaxanthin. The preparation of the complexes of sulfonated *p*-phenylcalix[5,6]arenes with the carotenoids was achieved by the grinding method described above for the sulfonated *p*-benzylcalix[5,6]arenes. The carotenoid complexes resulted in bright orange solutions of the carotenoid in water, with the integrity of the carotenoids maintained, as determined by UV–VIS studies which show no significant shifts of their characteristic bands relative to uncomplexed carotenoids. This has implications in the model for the complexes (see below). UV–VIS experiments for comparison purposes were also conducted in methanol since the carotenoids are insoluble in water.




n = 5, **16**
n = 6, **17**

The selective binding of carotenoid by only sulfonated *p*-benzylcalix[5,6]arenes and *p*-phenylcalix[5,6]arenes suggests inclusion complex formation and not an apparent surfactant effect. This claim is reinforced by the inabilily of the extreme ring sizes to solubilise these hydrophobic guest molecules. Seemingly, sulfonated *p*-benzylcalix[4,8]arenes and *p*-phenylcalix[4,8]arenes are either too small or too large for the inclusion to occur. In order to establish the composition of the sulfonated *p*-benzylcalix[5]arene–*trans*-β-carotene complex, *p*-benzylcalix[5]arene sulfonate was ground with *trans*-β-carotene at different molar ratios. Upon filtration, the dark red residue, presumably uncomplexed *trans*-β-carotene, was collected and washed with excess water, dried and weighed. The filtrates were further filtered using 0.2 μm filter paper and the solutions obtained were brought to dryness *in vacuo*. The resulting orange-amber solids were weighed and at all ratios the uptake of *trans*-β-carotene by the calixarene was estimated at approximatively one mole of *trans*-β-carotene to two moles of the calixarenes. UV–VIS spectra of these complexes at different molar ratios of *trans*-β-carotene to the calixarene are illustrated in Fig. 1.

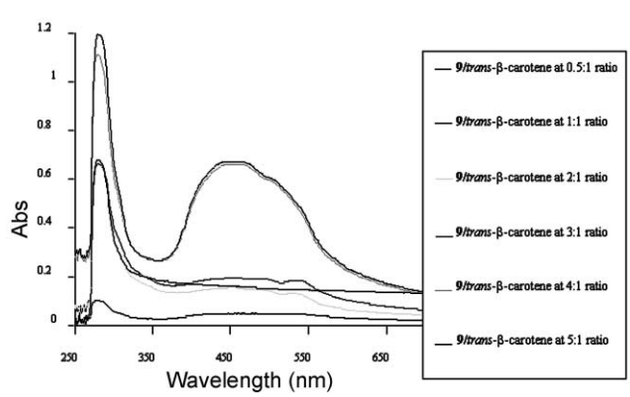



**Fig. 1** UV–VIS spectra of sulfonated *p*-benzylcalix[5]arene/*trans*-β-carotene complexes in water prepared at different molar ratios.

The stability of the carotenoid complexes (*i.e.* **9**–*trans*-β-carotene and **10**–*trans*-β-carotene) is striking. Attempts to dissociate these complexes for the retrieval of the carotenoid and to achieve a reversible process were challenging. Extraction methods using an organic solvent were tried but were unsuccessful. Addition of lanthanum salt in the form of $La(NO_3)_3$ to

the orange solutions of these complexes forms orange gels. Surprisingly, acidification of the gel using 1 M HCl and addition of dichloromethane resulted in extraction of the carotenoid.

In order to determine the composition of the complex in solution, $^1$H NMR studies were recorded on **9**–*trans*-β-carotene complex. Removal of water under reduced pressure resulted in an orange-amber solid. The $^1$H NMR spectrum of this solid dissolved in $D_2O$ gave broad chemical shifts precluding determination of its composition. In contrast, in $d_6$-DMSO the chemical shifts become resolved and show the presence of both calixarene and carotenoid. Because of overlapping peaks the exact molecular ratio was difficult to discern but nevertheless is close to 2 : 1, suggesting that the carotenoid is encapsulated by two sulfonated calixarene molecules. Molecular modelling of the postulated encapsulation mode is depicted in Fig. 2(a). Similarly, the ratio of the components in the *trans*-β-carotene–sulfonated *p*-benzylcalix[6]arene complex is also found to be approximately 2 : 1, two sulfonated *p*-benzylcalix[6]arene to one *trans*-β-carotene molecule. Following the same analogy, the possible interaction of *trans*-β-carotene with sulfonated *p*-benzylcalix[6]arene is illustrated in Fig. 2(b).

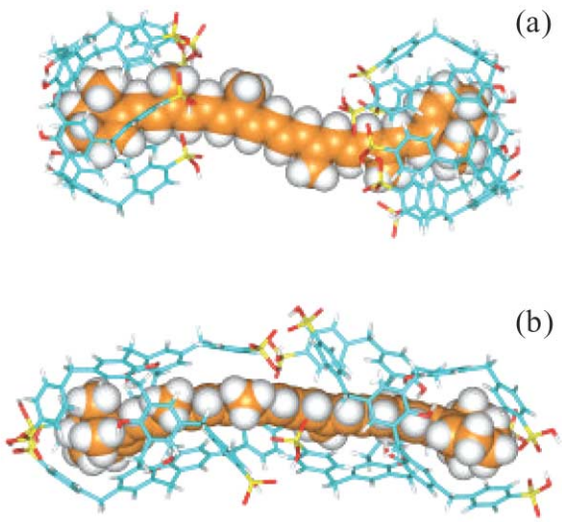



**Fig. 2** Molecular model of the possible encapsulation of *trans*-β-carotene with sulfonated *p*-benzylcalix[5]arene (a) and with sulfonated *p*-benzylcalix[6]arene (b).

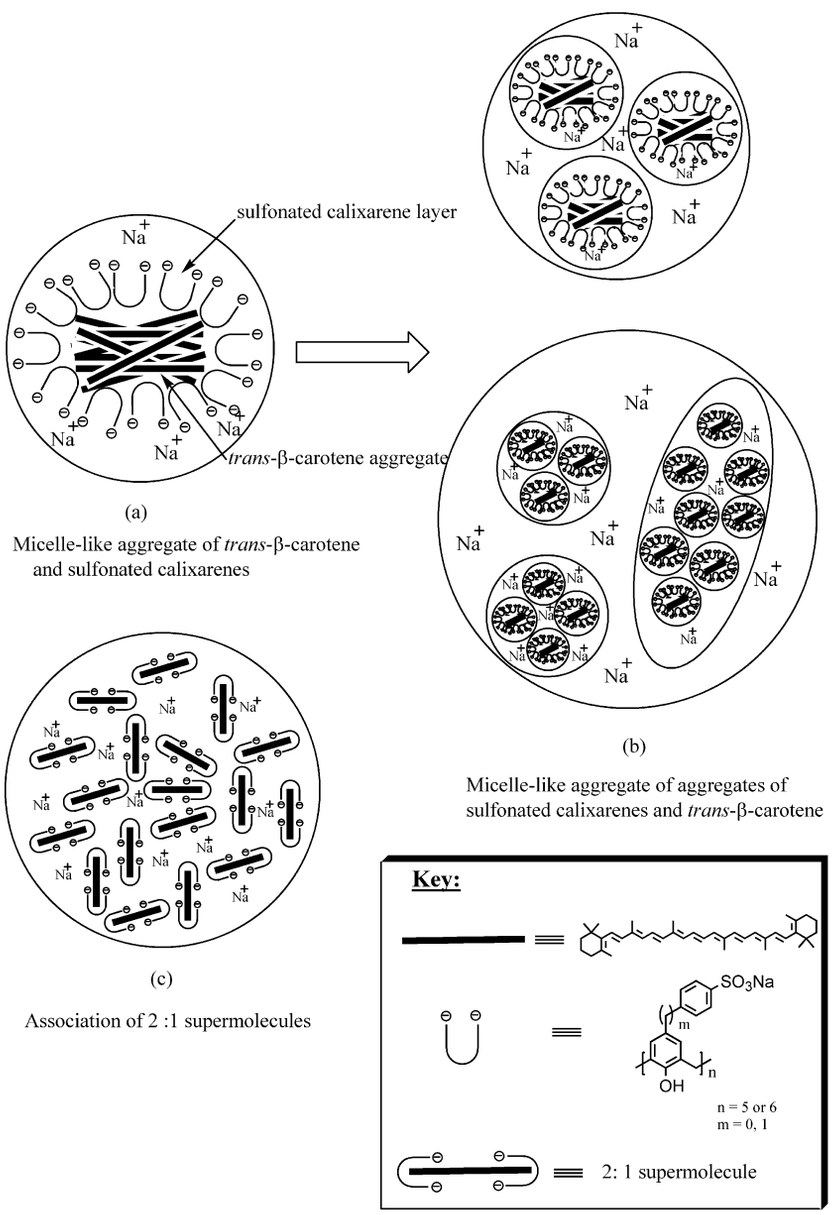



**Fig. 3** Models for the the possible encapsulation/aggregation of *trans*-β-carotene with sulfonated *p*-benzyl-, *p*-phenyl-calix[5,6]arene; (a), (b) micellar aggregation and (c) inclusion complex formation and association of the supermolecules by sodium cations.

Dynamic light scattering experiments indicate that all of the sulfonated calixarenes are self-associated in solution with particle diameters ranging from 54 to 200 nm for the sulfonic acids of the *p*-benzyl systems, and 96 to 225 nm for the corresponding sodium salts. The systems are polydisperse with effective diameters approximately independent of concentration. Except for the calix[8]arene system, **12**, there is a significant increase in size of the particles formed by aggregation of the sodium salts relative to the acids. This may be related to the metal ions effectively linking sulfonated calixarenes together through complexation of sulfonate groups from different supermolecules. In this context it is noted that addition of lanthanides to the calixarenes (either the acids or the sodium salts) results in the spontaneous formation of gels. This can be explained by the linking of the aggregates present in solution, beyond complexation within aggregates. Intercalixarene complexation is highlighted by numerous structures in the literature, for example the lanthanide complex of *p*-sulfonated calix[5]arene.[10] Moreover, the addition of lanthanide ions to the carotenoid complexes, also affording gels, can be similarly explained, *viz* inter-aggregate complexation as well as intra-aggregate complexation. Perhaps the disruption of the *trans*-β-carotene–calixarene interplay by the lanthanum would explain the release of the guest molecule, as evident by its uptake in an organic solvent, upon addition of solutions of acidified (1 M HCl) lanthanum(III) ions.

The light scattering experiments also show a significant reduction (~0.5) in particle diameter 100–150 nm on complexation of the sodium salts of the calixarenes with the carotenoids. The reduction in the particle size upon complexation is also consistent with the expected host–guest inclusion of the *trans*-β-carotene and astaxanthin by these sulfonated calixarenes.

In turning to the model for the uptake of the caretenoids it is noteworthy that the ratio of host to guest approximates to 2 : 1. The significance of this ratio can be understood in relation to the structure of the bis-*p*-benzylcalix[5]arene complex of $C_{60}$ which has been structurally authenticated.[11] Here the two calixarenes shroud the fullerene with the benzyl groups directed away from the core of the supermolecule. There is no structural precedent for carotenoid inclusion complexes with calixarenes, but in order to keep the 2 : 1 ratio, it is likely that supermolecules are also present with two calixarenes surrounding the rod shaped carotenoid. This has been modelled for the sulfonated *p*-benzyl calix[5 and 6]arenes for *trans*-β-carotene. Thus for both types of included molecules the proposed model is the aggregation of the 2 : 1 supermolecules into large nanometer size particles, through hydrophobic interactions between the calixarenes from adjacent supermolecules, noting the calixarenes have large hydrophobic surface areas, as well as hydrogen bonding interactions, and coordination interplay, Fig. 3(c). This explains the 2 : 1 integrity of the host and guest molecules. Alternative models such as the aggregation of the caretenoids into a single or multiple array surrounded by the sulfonated calixarenes, Figs. 3(a) and (b) respectively can be ruled out on the basis that the ratio is unlikely to be stochiometric, and in the case of the nanometer size particle of aggregated *trans*-β-carotene surrounded by a layer of sulfonated calixarenes Fig. 3(a), the ratio of carotenoid could far exceed that of calixarene, for the size of the particle established. Moreover, aggregation of *trans*-β-carotene is not consistent with the UV–VIS data. Various types of aggregation of carotenoids have been identified and they show a marked shift, either a significant red shift or blue shift, as the so-called J- or H-aggregates, respectively.[12] This is in contrast to minimal change in the present study.

Overall, beside the synthesis of novel water soluble calixarenes, significant advances have been made in host–guest chemistry of carotenoids in water, and a model has been proposed to understand the chemistry.

## Experimental

### General

*trans*-β-Carotene and asthaxantin were purchased from Aldrich and were used without further purification.

### General procedure for the preparation of compounds 1, 2, 3, 4, 5, 6, 7 and 8

To an ice-cooled solution of *p*-benzylcalix[*n*]arene in dry dichloromethane (20 ml) was added dropwise 10 equiv. of chlorosulfonic acid. The biphasic mixture was stirred initially at 0 °C for 30 min prior to the removal of the ice bath and continuation of stirring at room temperature for *ca.* 5 h. At this stage, the reaction mixture turned turbid with formation of viscous amber coloured material. The reaction mixture was poured onto an ice-cooled water, and dichloromethane was removed under *vacuo* to afford **1**–**4**. The remaining aqueous phase was boiled for 2 h with activated charcoal. Filtration followed by removal of water under *vacuo* leaves an amber residue, which was recrystallized from acetone (for **5** and **7**) or from a mixture of methanol–acetone (for **6** and **8**) affording the sulfonic acid of *p*-benzylcalix[*n*]arenes.

**Compound 1.** $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 3.97 (br-s, 20H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.92 (s, 14H, Ar–H), 7.29 (AA′XX′, 10H, Ph–H, *J* 9.3 Hz), 7.78 (AA′XX′, 10H, Ph–H), 8.85 (s, 5H, OH).

**Compound 2.** $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 3.87 (br-s, 24H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.83 (s, 12H, Ar–H), 7.27 (AA′XX′, 12H, Ph–H, *J* 8.3 Hz), 7.84 (AA′XX′, 12H, Ph–H), 10.30 (br-s, 6H, OH).

**Compound 3.** $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 3.95 (br-s, 28H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.89 (s, 14H, Ar–H), 7.33 (AA′XX′, 14H, Ph–H, *J* 8.3 Hz), 7.90 (AA′XX′, 12H, Ph–H), 10.37 (s, 7H, OH).

**Compound 4.** $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 3.96 (br-s, 32H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.90 (s, 16H, Ar–H), 7.30 (AA′XX′, 16H, Ph–H, *J* 8.3 Hz), 7.80 (AA′XX′, 16H, Ph–H), 9.50 (s, 8H, OH).

**Compound 5.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.65 (br, 10H, Ar–$CH_2$–Ar), 3.69 (s, 10H Ar–$CH_2$–Ph), 6.50 (br-s, COH–SOH–$H_2SO_4$), 6.88 (s, 10H, Ar–H), 7.15 (AA′XX′, 10H, PhH, *J* 9 Hz), 7.53 (AA′XX′, 10H, PhH); $^{13}$C NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 31.56 (Ar–$CH_2$–Ar), 40.50 (Ar$CH_2$–Ph), 126.17 (Ar), 128.34 (Ar), 128.6 (Ar), 128.9 (Ar) 132.19 (Ar), 143.6 (Ar), 144.7 (Ar), 149.84 (Ar–OH); IR(KBr) $\nu_{max}$/cm$^{-1}$ 3415 (OH), 1169 and 1121 ($SO_3$ sym.), 1035 and 1009 ($SO_3$ asym.); MS ($ESI^+$), *m*/*z* 1381.23 $[M + H]^+$, 1403.21 $[M + Na]^+$, $C_{70}H_{60}O_{20}S_5$ (1381), mp = dec. 230 °C.

**Compound 6.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.63 (br, 12H, Ar–$CH_2$–Ph), 3.67 (s, 12H, Ar–$CH_2$–Ar), 6.27 (br-s, COH–SOH–$H_2SO_4$), 6.73 (s, 12H, Ar–H), 7.07 (AA′XX′, 12H, PhH, *J* 8.3 Hz), 7.49 (AA′XX′, 12H, PhH); $^{13}$C NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 31.56 (Ar–$CH_2$–Ar), 40.50 (Ar$CH_2$–Ph), 126.17 (Ar), 128.34 (Ar), 128.6 (Ar), 128.9 (Ar), 132.9 (Ar), 143.6 (Ar), 144.7 (Ar), 149.8 (Ar–OH); IR(KBr) $\nu_{max}$/cm$^{-1}$ 3497 (OH), 1171 and 1069 ($SO_3$ sym.), 1033 and 1006 ($SO_3$ asym.); MS ($ESI^+$), *m*/*z* 1679.7 $[M + Na]^+$; $C_{84}H_{72}O_{24}S_6$ (1656.3); mp = dec. 265 °C.

**Compound 7.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.70 (br, 14H, Ar–$CH_2$–Ph), 3.73 (s, 14H, Ar–$CH_2$–Ar), 5.16 (br-s, COH–SOH–$H_2SO_4$), 6.76 (s, 14H, Ar–H), 7.10 (AA′XX′, 14H, PhH, *J* 8.2 Hz), 7.52 (AA′XX′, 12H, PhH); $^{13}$C NMR (300

MHz, $d_6$-DMSO, 25 °C) $\delta$ 31.03 (Ar–$CH_2$–Ar), 40.50 (Ar$CH_2$–Ph), 125.75 (Ar), 128 (Ar), 128.2 (Ar), 128.5 (Ar) 129.9 (Ar), 142.9 (Ar), 144.9 (Ar), 150 (Ar–OH); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3420 (OH), 1170 and 1069 ($SO_3$ sym.), 1031 and 1008 ($SO_3$ asym.); MS ($ESI^+$), *m*/*z* 2010.7 $[M + 2K]^+$, $C_{98}H_{84}O_{28}S_7$ (1932.3); mp = dec. 191 °C.

**Compound 8.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.69 (br, 16H, Ar–$CH_2$–Ar), 3.75 (s, 16H, Ar–$CH_2$–Ph), 4.90 (br-s, COH–SOH–$H_2SO_4$), 6.73 (s, 16H, Ar–H), 7.10 (AA′XX′, 16H, PhH, *J* 6.6 Hz), 7.54 (AA′XX′, 12H, PhH); $^{13}$C NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 30.9 (Ar–$CH_2$–Ar), 40.50 (Ar$CH_2$–Ph), 125.6 (Ar), 127.74 (Ar), 127.9 (Ar), 128 (Ar) 132.13 (Ar), 142.78 (Ar), 144.73 (Ar), 149.65 (Ar–OH); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3406 (OH), 1167 and 1123 ($SO_3$ sym.), 1035 and 1009 ($SO_3$ asym.); MS ($ESI^+$), *m*/*z* 2231.5 $[M + Na]^+$, $C_{112}H_{96}O_{32}S_8$ (2208.36); mp = dec. 180 °C.

### General procedure

The sodium salt sulfonates of *p*-benzylcalix[*n*]arenes were prepared by titration of sulfonic acid analogues with 1 M sodium hydroxide to neutral pH. Treatment of the crude either with methanol or with ethanol–acetone mixture precipitated the sodium sulfonates of *p*-benzylcalix[*n*]arenes.

**Sodium sulfonates of *p*-benzylcalix[5]arene, 9.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.72 (br-s, 20H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.83 (s, 10H, Ar–H), 7.16 (AA′XX′, 10H, Ph–H, *J* 7.3 Hz), 7.52 (AA′XX′, 10H, Ph–H); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3459 (OH), 1126 ($SO_3$ sym.), 1041 and 1011 ($SO_3$ asym.); MS ($ESI^+$), *m*/*z* 1527.1 $[M + K]^+$, $C_{70}H_{55}O_{20}S_5Na_5$ (1490.1); mp = dec. 300 °C.

**Sodium sufonates of *p*-benzylcalix[6]arene, 10.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.72 (br-s, 24H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.83 (s, 12H, Ar–H), 7.16 (AA′XX′, 12H, Ph–H, *J* 9.4 Hz), 7.52 (AA′XX′, 12H, Ph–H); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3419 (OH), 1174 ($SO_3$ sym.), 1069 and 1007 ($SO_3$ asym.).

**Sodium sulfonates of *p*-benzylcalix[7]arene, 11.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.68 (br-s, 14H, Ar–$CH_2$–Ar) 3.73 (s, 14H Ar–$CH_2$–Ph), 6.81 (s, 14H, Ar–H), 7.11 (AA′XX′, 14H, Ph–H, *J* 6.6 Hz), 7.54 (AA′XX′, 12H, Ph–H); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3441 (OH), 1188 ($SO_3$ sym.), 1042 and 1011 ($SO_3$ asym.).

**Sodium sulfonates of *p*-benzylcalix[8]arene, 12.** $^1$H NMR (300 MHz, $d_6$-DMSO, 25 °C) $\delta$ 3.72 (br, 32H, Ar–$CH_2$–Ar and Ar–$CH_2$–Ph), 6.82 (s, 16H, Ar–H), 7.15 (AA′XX′, 16H, Ph–H, *J* 8.6 Hz), 7.52 (AA′XX′, 16H, Ph–H); IR(KBr) $\nu_{max}$/$cm^{-1}$ 3461 (OH), 1126 ($SO_3$ sym.), 1030 and 1011 ($SO_3$ asym.).

**Compound 13.** To a solution of *p*-cumylcalix[4]arene (0.4g, 0.51 mmol) dissolved in 20 ml of dry dichloromethane, 1 ml of chlorosulfonic acid was added dropwise. The biphasic mixture was stirred at room temperature for *ca.* 5 h with formation of viscous amber coloured material. The reaction mixture was poured over ice, and a white precipitate was collected and proved to be the chlorosulfonyl of *p*-cumylcalix[4]arene, **13**. Yield 70%, MS ($ESI^+$), *m*/*z* 1311.2 $[M + Na]^+$, $C_{64}H_{60}O_{12}S_4Cl_4$ (1288.2); $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 1.30 (s, 24H, $CH_3$), 3.40 (d, 4H, Ar–$CH_2$–Ar, $J_{AB}$ 15 Hz), 4.34 (d, 4H, Ar–$CH_2$–Ar), 6.8 (s, 8H, Ar–H), 7.25 (AA′XX′, 8H, Ph–H, *J* 6.1 Hz), 7.75 (AA′XX′, 8H, Ph–H), 9.60 (s, 4H, OH).

**Compound 14.** is prepared in a similar manner as for **13**: Yield 60%, MS ($ESI^+$, *m*/*z* 1955.2 $[M + Na]^+$, 1971.0 $[M + K]^+$, $C_{96}H_{90}O_{18}S_6Cl_6$ (1932.3); $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 1.29 (s, 36H, $CH_3$), 3.45 (br-s, 6H, Ar–$CH_2$–Ar), 4.13 (br-s, 6H, Ar–$CH_2$–Ar), 6.86 (s, 12H, Ar–H), 7.38 (AA′XX′, 12H, Ph–H, *J* 8.85 Hz), 7.85 (AA′XX′, 12H, Ph–H), 10.55 (s, 6H; OH); $^{13}$C NMR ($CDCl_3$, 300 MHz) $\delta$ 23.5 ($CH_3$), 29.10 (Ar–$CH_2$–Ar), 41.6 (Ar-C$(CH_3)_2$-Ph), 123.4 (Ar), 125.2 (Ar), 126.1 (Ar), 126.5 (Ar) 140.3 (Ar), 141.6 (Ar), 149.8 (Ar), 155.0 (Ar–OH).

**Preparation of sulfonic acid of *p*-cumylcalix[6]arene, 15.** Compound **14** was heated to reflux in a mixture of acetone–water (5 : 1) for 3 h and filtered hot. The filtrate was brought to dryness under reduced pressure and the resulting solid was dissolved in hot methanol. Filtration followed by removal of methanol afforded the sulfonic acid of *p*-cumylcalix[6]arene, **15**. IR(KBr) $\nu_{max}$/$cm^{-1}$ 3424 (OH), 1180 ($SO_3$ sym.), 1070 and 1008 ($SO_3$ asym.); $^1$H NMR ($CD_3OD$, 300 MHz) $\delta$ 1.27 (s, 36H, $CH_3$), 3.77 (s, 12H, Ar–$CH_2$–Ar), 5.2 (br-s, COH–SOH, shifts downfield with increasing concentration of $H_2SO_4$), 6.77 (s, 12H, Ar–H), 7.43 (AA′XX′, 12H, Ph–H, *J* 8.7 Hz), 7.85 (AA′XX′, 12H, Ph–H).

### General procedure for the preparation of the carotenoid complexes

A sample of *p*-benzylcalix[5]arene sulfonate–*trans*-β-carotene complex was prepared by a solid-state grinding experiment. Commercial *trans*-β-carotene (2 mg, $3.7 \times 10^{-3}$ mmol) was mixed in a mortar with pentasodium sulfonato-*p*-benzylcalix-[5]arene, **9** (6 mg, $4.02 \times 10^{-3}$ mmol). The solid mixture was grinded until a uniform powder was obtained (*ca.* 1 min). Grinding was continued after adding 2 ml of distilled water for another minute. The resulting orange slurry was twice filtered affording a transparent clear orange solution.

### Light scattering

Particle sizes were effective diameters obtained by dynamic light scattering at 90° using a Brookhaven zeta plus fitted with a BI90 correlator board and a 30 mW 675 nm diode laser.

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