

Functionalized aromatics aligned with the three Cartesian axes: Extension of centropolyindane chemistry*

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Abstract: The unique geometrical features and structural potential of the centropolyindanes, a complete family of novel, 3D polycyclic aromatic hydrocarbons, are discussed with respect to the inherent orthogonality of their arene units. Thus, the largest member of the family, centrohexaindane, a topologically nonplanar hydrocarbon, is presented as a “Cartesian hexabenzene”, because each of its six benzene units is stretched into one of the six directions of the Cartesian space. This feature is discussed on the basis of the X-ray crystal structures of centrohexaindane and two lower members of the centropolyindane family, viz. the parent tribenzotriquinacenes. Recent progress in multiple functionalization and extension of the indane wings of selected centropolyindanes is reported, including several highly efficient six- and eight-fold C–C cross-coupling reactions. Some particular centropolyindane derivatives are presented, such as the first twelve-fold functionalized centrohexaindane and a tribenzotriquinacene bearing three mutually orthogonal phenanthroline groupings at its molecular periphery. Challenges to further extend the arene peripheries of the tribenzotriquinacenes and fenestrindanes to give, eventually, graphite cuttings bearing a central bowl- or saddle-shaped center are outlined, as is the hypothetical generation of a “giant” nanocube consisting of eight covalently bound tribenzotriquinacene units. Along these lines, our recent discovery of a related, solid-state supramolecular cube, containing eight molecules of a particular tribromotrinitrotribenzotriquinacene of the same absolute configuration, is presented for the first time.

Keywords: orthogonal orientation; centropolyindanes; polycyclic aromatics; cross-coupling reactions; topologically nonplanar structures; triquinacenes; fenestrindanes; propellanes; spirocyclic systems; indane hydrocarbons.

INTRODUCTION

In the past decades, a number of novel polycyclic hydrocarbon frameworks have been developed. Some of these classes comprise strictly one- or two-dimensional key motifs. For example, acetylenic building blocks have been combined to give linear arrangements [1], and benzene units have been annealed to generate extended planar polycondensed aromatic networks, such as graphite cuttings [2]. Such linear and planar carbon frameworks can be bent out-of-line and out-of-plane by various means, and the cyclophanes [3], benzoannelated annulene-type polyacetylenes [4], corannulenes [5], and fullerenes [6] are

*Paper based on a presentation at the 11th International Symposium on Novel Aromatic Compounds (ISNA-11), St. John's, Newfoundland, Canada, 14–18 August 2005. Other presentations are published in this issue, pp. 685–888.

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lucid examples for this extension of hydrocarbon frameworks consisting essentially of sp - and sp^2 -hybridized carbon atoms.

By contrast, the strict combination of sp^3 -hybridized carbon centers leads to quasi-2D or 3D skeletons. Thus, formal condensation of cyclohexane and/or cyclopentane units gives rise to steroids or polyquinanes [7], or adamantanes, representing cuttings of truly 3D carbon frameworks, e.g., the diamond scaffold [8]. Particularly remarkable are the attempts to construct 3D frameworks consisting exclusively of saturated, five-membered rings, culminating in the chemistry of dodecahedrane [9], but also in repeated efforts to build the elusive centrohexaquinane (see below) [10].

The combination of building blocks of different types has also been pursued in various ways. The cyclophanes of various types fall also into this category, and the superphanes, in particular, may be considered truly 3D alkylaromatic molecules [11]. The triptycenes comprise sp^3 -hybridized bridgehead carbon atoms with aromatic building blocks, giving rigid and extendable 3D frameworks [12]. Systematic insertion of the linear acetylene units into the diamond framework would also produce rigid 3D carbon networks, such as the hypothetical “Dutch diamond” [13].

The present work is also focused on truly but rather unusual 3D polycyclic alkylaromatic molecular scaffolds, viz. the “centropolyindanes”. From the particularly systematic principle of their construction, the versatility of their rigid frameworks and the great potential to extend their skeleton and introduce a multitude of functionalities, it appears that centropolyindane chemistry can contribute to future development of materials science. It is hoped that this report will inspire readers in this and many other respects.

THE CENTROPOLYINDANES: PRINCIPLES OF CONSTRUCTION

The centropolyindanes, a novel family of alkylaromatic polycyclic hydrocarbons, also combine a saturated, truly 3D motif, neopentane **1**, with the 2D motif of benzene. The formal construction of the centropolyindanes follows the systematics of the “centropolycyclanes”, presented by Gund and Gund in 1981 [14]. Thus, the tetrahedral core of **1** can be bridged up to six times, as depicted in **2** (Chart 1). Such a complete bridging would generate centrohexaquinane if six ethylene (1,2-ethano, $-\text{CH}_2-\text{CH}_2-$) bridges, and the likewise elusive centrohexaquinacene, if six vinylene (1,2-etheno, $-\text{CH}=\text{CH}-$) bridges were incorporated. Notably, a related C_3 -symmetrical triether bearing three $-\text{CH}_2-\text{O}-$ units has been known since 1981 [15–17]. Bridging neopentane **1** by six *ortho*-phenylene (“*ortho*-benzeno”, 1,2-*c*- C_6H_4) groups leads to the highest member of the centropolyindanes, centrohexaindane **3** [18], which can be synthesized in gram amounts through three independent routes [19] and represented the first, topologically nonplanar, “ K_5 ” hydrocarbon [20]. All of the lower members of the centropolyindane family, **4–9**, are envisageable by systematic removal of one or more 1,2-benzeno units from centrohexaindane (Chart 2). With the exception of the smallest propellane-type centrotriindane, viz. “triptindane” (**7**), which was synthesized for the first time by Thompson in 1966 already [21] and made easily accessible by us in 1991 [22], all other congeners were synthesized in the past two decades [23,24]. Thus, five instead of six indane units being fused centrally form centropentaindane **4**, four indane units give either the *trifuso*-centrotetraindane (**5**) or the *tetrafuso*-centrotetraindane (**6**), coined “fenestrindane”, and only three mutually fused indanes lead to three triindanes, i.e., *monofuso*- (**7**), *difuso*- (**8**-), and *trifuso*-centrotriindane, which is represented as its *centro*-methyl derivative **9** here [25]. 2,2'-Spirobiindane and one of the *fuso*-diindanes (not shown) belong to the centropolyindane family as well, though not being true “poly”-indanes [23,24,26].

From a geometrical point of view, the complete or partial bridging of the neopentane core by *ortho*-phenylene groups is equivalent to fusing several pentagons with pairs of the four C_{3v} axes of a tetrahedron. Thus, the bond angles of 108° of up to six pentagons fit almost perfectly with the six angles of $109^\circ 28'$ formed by the four axes at the center of the tetrahedron. Therefore, angular strain effects within the parent centrohexasindanes are negligible and, as a consequence, the structures of the lower congeners can be considered cuttings of the highest one, centrohexasindane (**3**). This holds in particular for those members which have only one conformational minimum, viz., centropentaindane (**4**), *trifuso*-centrotetraindane (**5**), and the tribenzotriquinacenes (e.g., **9**). This especially close geometrical relation between the centropolyindanes has been corroborated by X-ray single crystal structure analyses [27–29].

CENTROHEXAINDANE: A “CARTESIAN HEXABENZENE”

It is worth noting that centrohexasindane (**3**) is a unique arene because all of its polycyclic surfaces are concave. Therefore, crystal packing without inclusion of solvent molecules is extremely difficult, and, in fact, elucidation of the solid-state structure of **3** was hampered for several years because of this reason. Nevertheless, this unusual, high-melting $C_{41}H_{24}$ hydrocarbon (m.p. $> 420^\circ\text{C}$) has been characterized unambiguously by mass spectrometry, NMR spectroscopy [$\delta(\text{H}^{\text{AA}'}) = 7.29$, $\delta(\text{H}^{\text{BB}'}) = 7.79$; $\delta(\text{C}^{\text{centro}}) = 95.0$] and UV/vis spectroscopy ($\lambda_{\text{max}} = 276.5 \text{ nm}$, $\epsilon = 5800$) [18]. The electronic absorption, being close to that of indane itself, shows that there is almost no electronic interaction between the six benzene units of **3** (and of those of its lower congeners).

We recently succeeded to perform complete X-ray analyses with single crystals of **3** obtained from *para*-xylene and from triethylamine [28a]. In both cases, the six central C–C–C bond angles were found to be identical, and identical with the ideal “tetrahedral” angle between the C_{3v} axes of a tetrahedron, as expected from the construction principle (Fig. 1 and Table 1). Thus, interstitial packing of *para*-xylene or triethylamine does not disturb the perfect T_d molecular symmetry of **3** in the crystals. More important, however, is the fact that the perfect T_d symmetry of centrohexasindane confirmed by X-ray analysis implies that its three 2,2'-spirobiindane units are oriented orthogonally to each other and are perfectly aligned with the three axes of the Cartesian coordinate system if the central carbon is placed at its origin (Fig. 2). As a consequence, the two benzene units within each of the 2,2'-spirobiindane units are oriented at 180° to each other (with a dihedral angle of 90° of their planes), two benzene units belonging to different 2,2'-spirobiindane units are oriented at 90° to each other (with a dihedral angle of 120° of their planes) [19]. Thus, centrohexasindane (**3**) can be considered a “Cartesian hexabenzene” containing six electronically independent but spatially completely fixed arene units pointing towards the six directions of the 3D space.

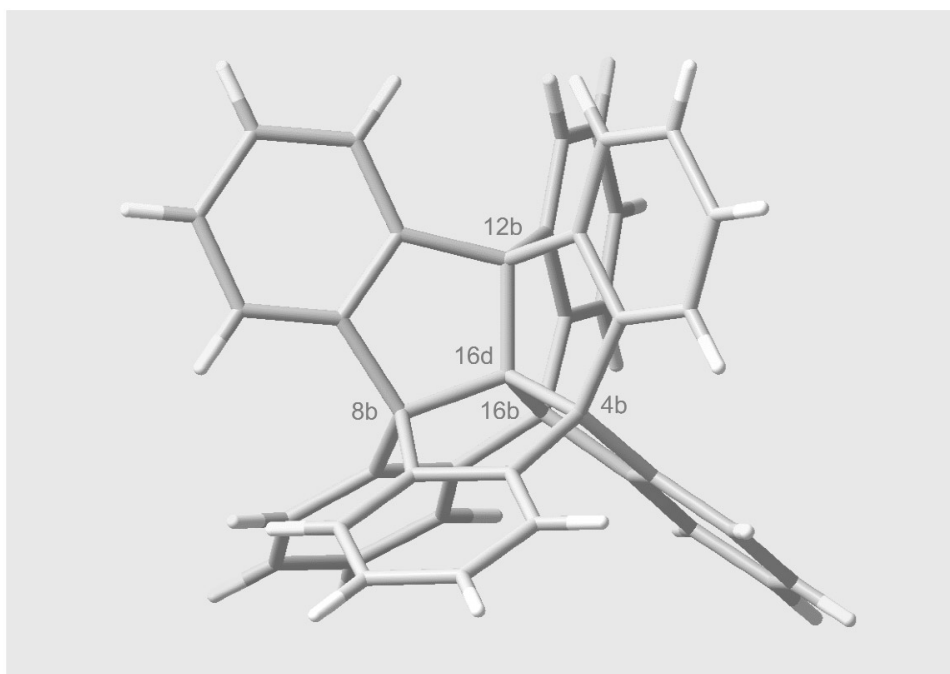


Fig. 1 The molecular structure of centrohexaindane (**3**), as determined by X-ray structure analysis of single crystals obtained from *para*-xylene. For the values of the six C–C–C bond angles at the central carbon atom, see Table 1.

Table 1 Central C–C–C bond angles in centrohexaindane (**3**), as obtained by X-ray structure analysis of single crystals obtained from *para*-xylene and from triethylamine [12].

Central bond angles [°]	C ₄₁ H ₂₄ ·0.5 <i>p</i> -xylene	C ₄₁ H ₂₄ ·NEt ₃
C(4b)-C(16d)-C(8b)	109.56(11)	109.45(10)
C(4b)-C(16d)-C(12b)	109.52(11)	109.32(15)
C(4b)-C(16d)-C(16b)	109.43(11)	109.45(10)
C(8b)-C(16d)-C(12b)	109.68(11)	109.54(10)
C(8b)-C(16d)-C(16b)	109.22(11)	109.53(15)
C(12b)-C(16d)-C(16b)	109.42(11)	109.54(10)
Average	109.47	109.47

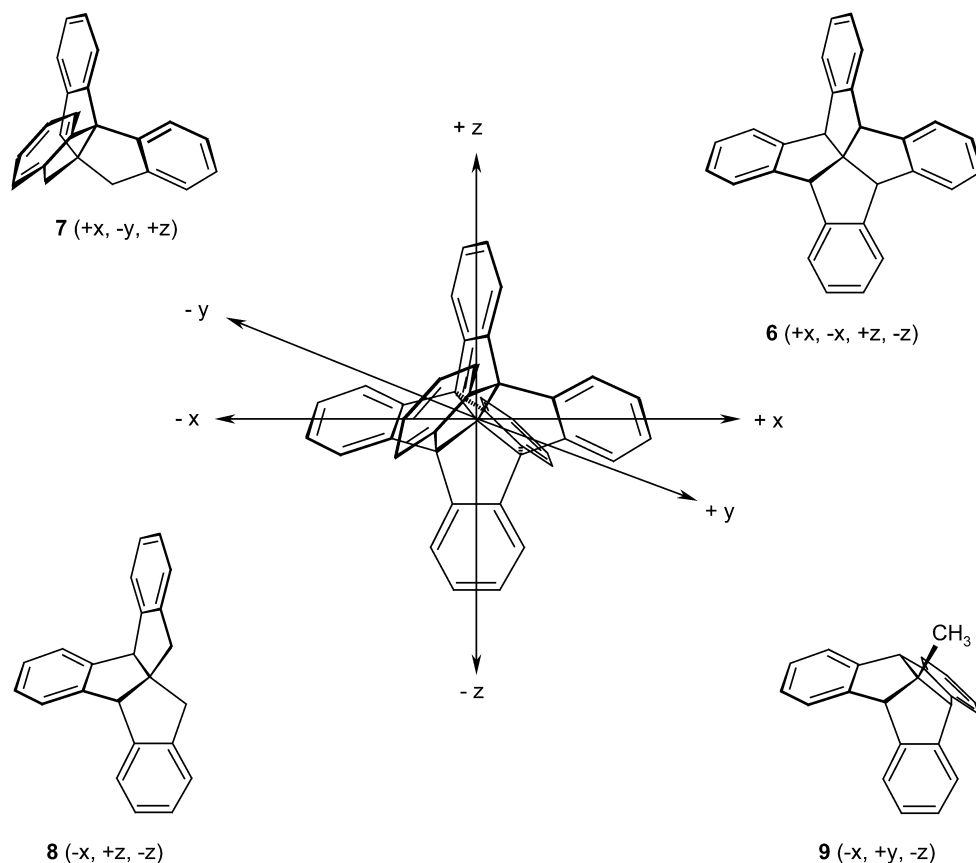


Fig. 2 Mutually orthogonal orientation of the indane wings of centrohexasindane (**3**) and of four lower centropolyindane congeners (**6–9**).

ORTHOGONALITY OF THE CENTROPOLYINDANE FRAMEWORKS

Still another consequence of these insights is the fact that the arene units of the lower congeners of **3** should also be orientated at right angles in space, as depicted in Fig. 2 for four of the lower congeners. In fact, almost perfect “Cartesian” orientation of the arene units has been confirmed by experiment for the particular rigid congeners **4** [27], **5** [28b], and **9** [29] and, most recently, for the parent “nor” analog, tribenzotriquinacene (**10**), itself [30].

Geometrical analysis of the tribenzotriquinacenes **9** and **10** is particularly fruitful; therefore, both their crystal and molecular structures will be addressed briefly. The X-ray structure analyses of these two prototypical *trifuso*-centrotriindanes, colloquially coined the “methyl hat” **9** and the “nor-hat” **10**, were found to be very similar. Both homologues crystallize in the same space group ($R3m$) and the molecules form co-parallel (i.e., unidirectional) stacks, in which the convex surface of each molecule fits perfectly into the concave surface of the next one, without any turn along the common molecular and crystallographic C_{3v} axis (Fig. 3). The rapport between equivalent atoms of adjacent molecules within the stacks of the methyl compound **9** is ca. 6.0 Å [29], but it decreases to 4.8 Å in the stacks of the nor compound **10** itself [30]. This highly regular feature is the main reason for the drastic increase of the melting points, viz. 244 °C for former vs. 390–391 °C (decomp.) for the latter hydrocarbon.

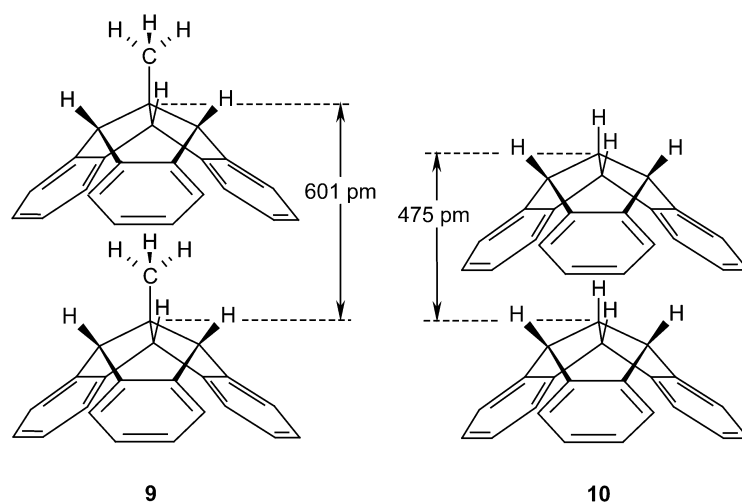


Fig. 3 Highly regular packing within the molecular stacks in solid-state 10-methyltribenzotriquinacene (**9**) and its “nor-analog”, tribenzotriquinacene (**10**), as adapted from the X-ray single crystal structure analyses.

The fact that, in tribenzotriquinacene **9**, three indane wings have formally been removed from centrohexaindane in a propellane-type manner does not lead to marked distortions from orthogonality. The X-ray data reveal that the planes of the three remaining indane units of solid-state **9** are mutually oriented at dihedral angles of 117° [29]. The respective dihedral angles of **10** are very similar. Accordingly, the three axes passing through the central carbon atom and the centers of the outer peripheral arene C–C bonds cross each other at the central carbon at 87° in the case of **9** [29]. The strictly orthogonal orientation of the three indane units of the tribenzotriquinacene framework can be illustrated simply on the basis of the X-ray structural data of the methyl derivative **9** (Fig. 4).

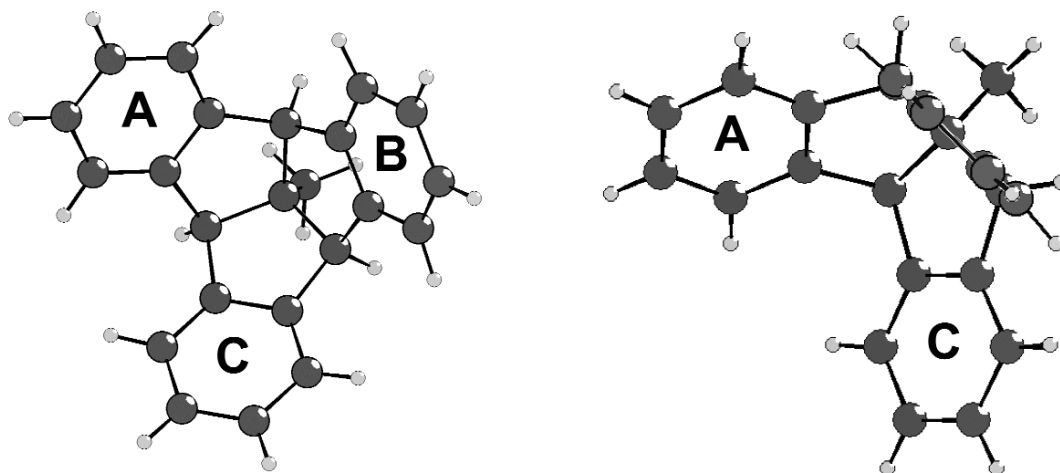


Fig. 4 Two views of the molecular structure of 10-methyltribenzotriquinacene (**9**), as determined by X-ray single crystal structure analysis, illustrating the mutual orthogonality of the three indane wings in the tribenzotriquinacene framework.

SELECTED SYNTHESSES OF FUNCTIONALIZED CENTROPOLYINDANES

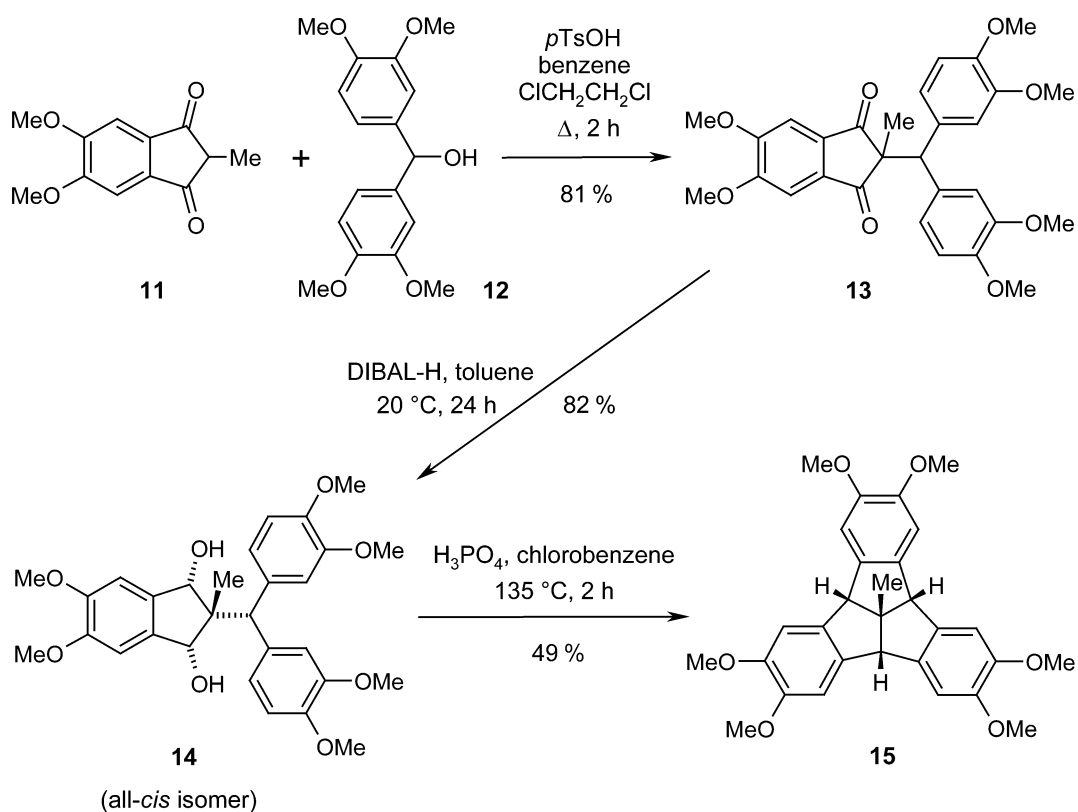
Owing to the strictly orthogonal orientation of the three indane units in the tribenzotriquinacenes, in particular, and the centropolyindanes, in general, the introduction of functional groups at the arene peripheries of these truly 3D molecular frameworks is a promising goal for several reasons. Because of the highly regular geometry of the centropolyindanes, the extension of their framework to larger molecular scaffolds and to covalently and noncovalently bound aggregates containing several centropolyindanes units should give rise to novel and interesting structures and networks on the molecular and supramolecular level, respectively. Some functionalized lower centropolyindanes were described very early [21,31], but the systematic development of multiply functionalized congeners of this family has been started only after their syntheses had been accomplished, and this work promises to be a very fertile field of future research [29,32–36].

Two different major strategies have been pursued: (i) Use of appropriately substituted or functionalized building blocks in the construction of the centropolyindane framework. Thus, besides several methyl-substituted centrohexaindanes, a number of methoxy-functionalized tribenzotriquinacenes, triptindanes, fenestrindanes, and centrohexaindanes have been synthesized. The most recent examples are collected below. (ii) Introduction of several identical functional groups by electrophilic aromatic substitution of suitable centropolyindanes. This approach has enabled us to extend the molecular framework of the parent congeners by use of various condensation reactions, including modern C–C cross-coupling methods. Various examples concerning this strategy are also presented below.

By far not all of this potential has been explored to date. “Mixed” approaches (i.e., functionalization of suitably “presubstituted” centropolyindanes) offer access to a vast variety of derivatives. Moreover, an approach to variously functionalized and chiral fenestrindanes, in particular, is strongly invoked in recent work that was focused on organo-catalyzed enantioselective condensation leading to *spiro*-condensed fenestrindane precursors [37].

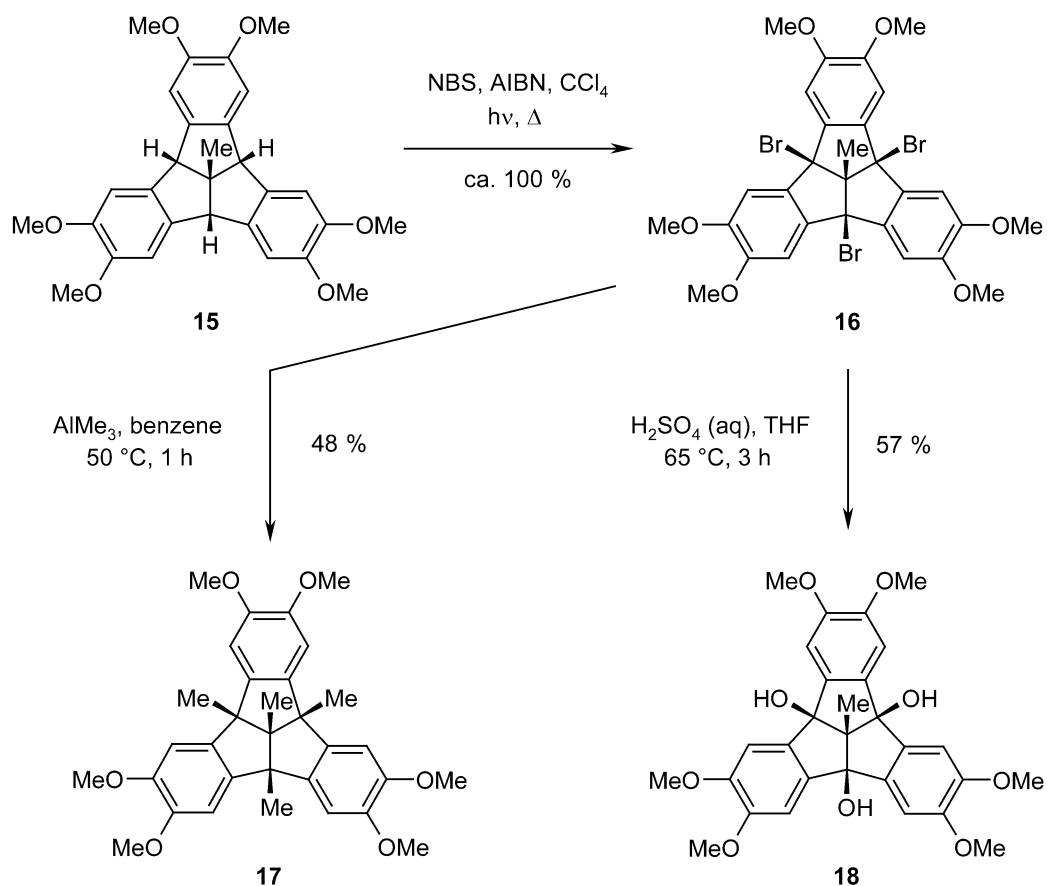
Multiply methoxy-substituted centropolyindanes

Tribenzotriquinacenes bearing six methoxy groups at the arene periphery have been synthesized and characterized recently [32]. Similar to the parent compound **9**, the *centro*-methyl-substituted hexamethoxytribenzotriquinacene **15** is accessible with surprisingly high efficiency (Scheme 1). 5,6-Dimethoxyindane-1,3-dione (**11**) and 3,3',4,4'-tetramethoxybenzhydrol (**12**) can be condensed under carefully controlled conditions to give the benzhydrylindandione **13**, reduction of which by use of DIBAL-H affords the all-*cis*-indane-1,3-diol **14** in good yield. Surprisingly, the subsequent bicyclization step proceeds under conventional conditions with markedly higher isolated yields (49 %) [32] than in the case of the parent compound **9** (30–33 %) [25]. The X-ray structure analysis reveals the almost ideal C_{3v} -symmetrical molecular structure of **15**, as expected, but the crystal structure no longer contains molecular stacks in this case [32].



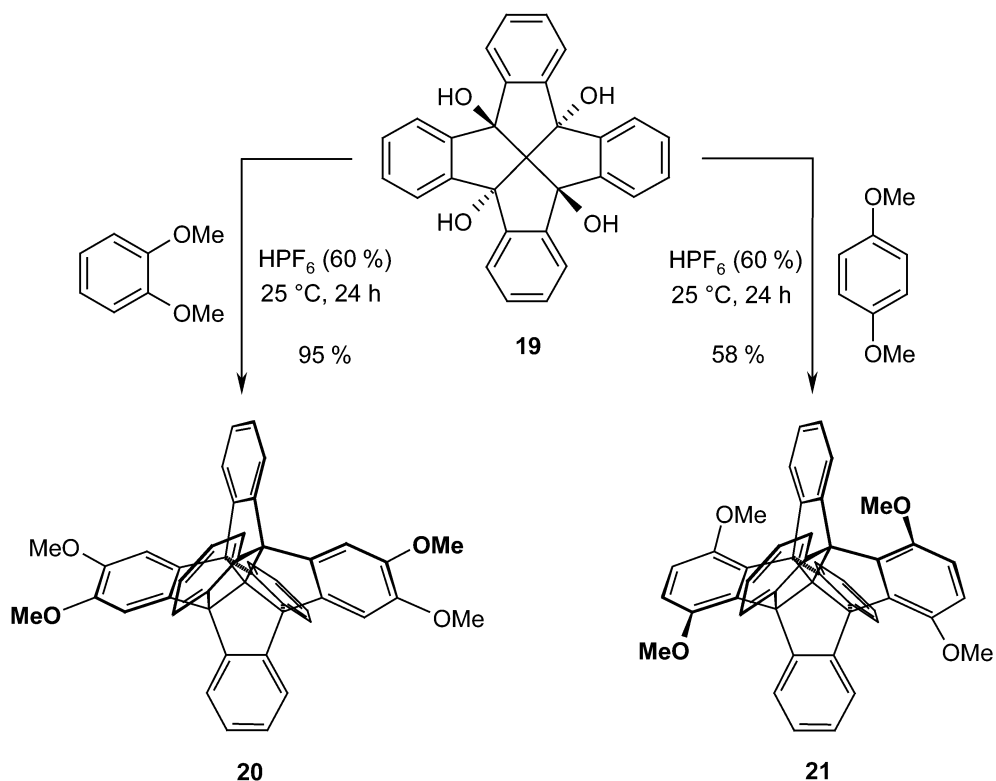
Scheme 1 Synthesis of hexamethoxytribenzotriquinacene **15**.

Bridgehead functionalization of **15** is easily performed by radical-induced bromination affording **16**, which can be quenched with trimethylaluminum to give the tetramethyl derivative **17** or hydrolyzed to give triol **18** (Scheme 2). However, various attempts to achieve electrophilic substitution, e.g., nitration, at the electron-rich *ortho* positions of **15** proved to be inefficient or gave rise to ring-opening reactions [32].



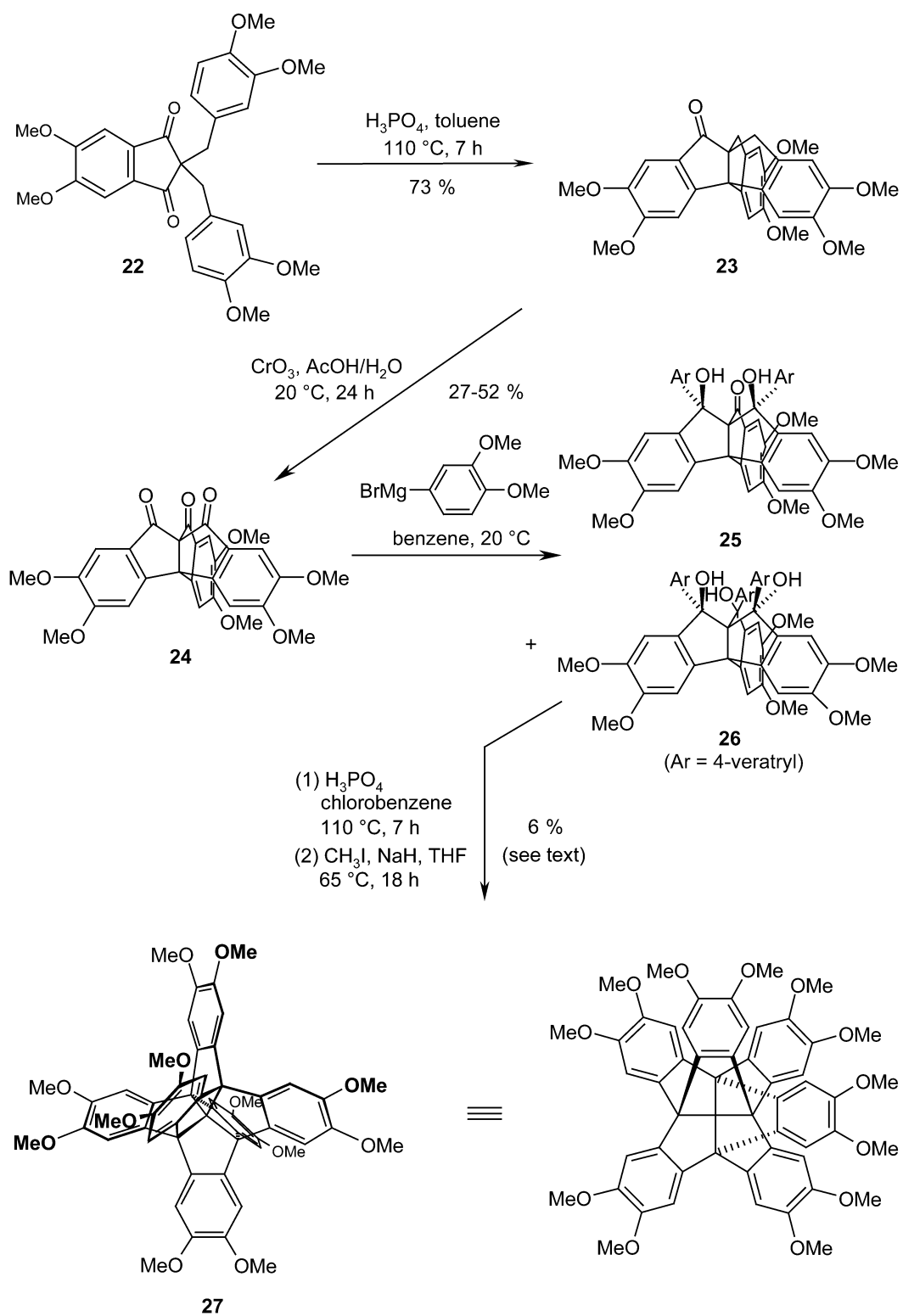
Scheme 2 Synthesis of bridgehead-substituted hexamethoxytribenzotriquinacenes.

Several multiply methoxy-substituted centrohexasindanes have been synthesized recently through two of the three major routes leading to their topologically nonplanar carbon framework [19]. Starting from fenestrindanetetrol **19**, the “fenestrane route” opens the way to several centrohexasindanes bearing the functionalization at opposite indane units, such as the bis(veratrole) derivative **20** and the corresponding bis(hydroquinone dimethyl ether) **21** (Scheme 3). The latter is particularly remarkable because each of the four functional groups points into one of the four 3D “bays” of the centrohexasindane skeleton [36].



Scheme 3 Synthesis of tetramethoxy-substituted centrohexaindanes **20** and **21** from fenestrindanetetrol **19** by the fenestrane route.

The “propellane” route provides an alternative access to the centrohexaindane framework and, in fact, has also proven most useful for the closest preparative approach to the parent centropolycyclane, the still elusive centrohexaquinane, because it opens the access to a tribenzo and a dibenzo derivative and, albeit in very minor yields, even to the monobenzo analog of the latter [17,38]. Recently, the propellane route enabled us to synthesize the first twelve-fold functionalized centrohexaindane, **27** (Scheme 4) [39]. In analogy to the established concept, the hexamethoxy-substituted 2,2-dibenzylindanedione **22** was prepared and subjected to bicyclization to give the propellane skeleton of triptindanone **23**. Oxidation to the corresponding triketone **24** turned out to be difficult; best but rather moderate yields were achieved only by use of chromium(VI) oxide in acetic acid at ambient temperature. Under suitable conditions, the rather electron-rich and sterically hindered triketone **24** did react twice and even thrice with 4-veratrylmagnesium bromide, and the mixture of the propellane diolone (**25**) and -triol (**26**) adducts was subjected to cyclodehydration. In fact, the three-fold cyclization took place, but some of the methoxy groups were cleaved concomitantly. However, re-methylation and repeated chromatography of the product mixture eventually furnished pure 2,3,6,7,10,11,14,15,20,21,26,27-dodecamethoxycentrohexaindane **27** in 6% yield. Mass spectrometry and NMR spectroscopy of this $\text{C}_{53}\text{H}_{48}\text{O}_{12}$ compound unequivocally proved its identity and T_d molecular symmetry [m.p. > 360 °C, EI-MS: m/z 876 (100%), ^1H NMR (500 MHz, CDCl_3): $\delta(\text{H}^{\text{arom}}) = 7.14$, $\delta(\text{OCH}_3) = 3.89$ ppm, ^{13}C NMR (126 MHz, CDCl_3): $\delta(\text{C}^{\text{centro}}) = 100.0$ ppm] [38].

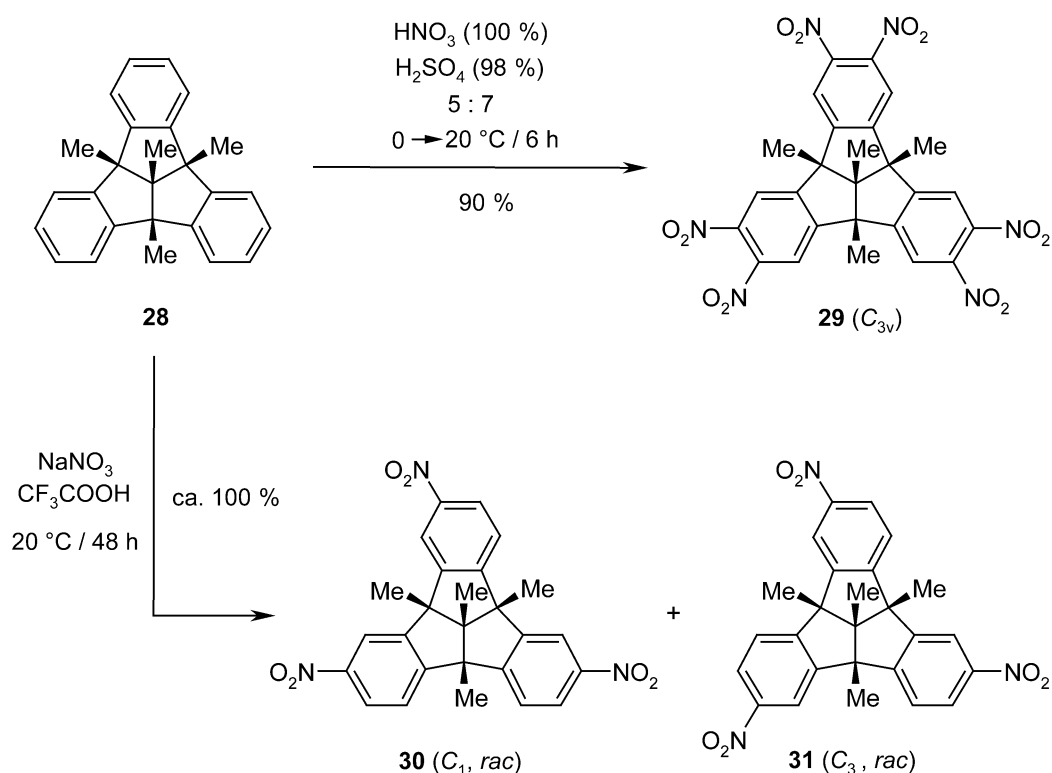


Scheme 4 Synthesis of the first 12-fold functionalized centrohexasindane (**27**) by the propellane route.

Polyfunctionalized centropolyindanes by aromatic substitution

Multiple functionalization of suitable centropolyindanes at their outer peripheral arene positions by nitration, bromination, and iodination was studied in detail during recent years. The results proved to be encouraging, but it turned out that the experience made with a given (lower) congener cannot be simply transferred to a higher one. At present, this is particularly evident in view of our goal to synthesize 12-fold functionalized centrohexasindanes bearing more versatile groups than methoxy substituents, but this is not a trivial task. On the other hand, the achievable functionalizations have already brought about major progress in extending the framework of tribenzotriquinacenes and fenestrindanes [29,33–35].

Nitration of the “bridgehead-blocked” tetramethyltribenzotriquinacene **28** is particularly efficient under special conditions, viz. by use of a mixture of HNO₃ (100 %) and H₂SO₄ (98 %), giving the C_{3v}-symmetrical hexanitro derivative **29** in excellent yield (Scheme 5) [33]. This is remarkable since the presence of several quaternary benzhydrylic bridgeheads in **28** could allow for ring cleavage processes. Other HNO₃/H₂SO₄ mixtures used give only a large variety of different nitrated derivatives. However, use of NaNO₃ in trifluoroacetic acid was found to convert **28** into a mixture of the C₁- and C₃-symmetrical trinitro derivatives **30** and **31** as a ca. 3:1 mixture of two racemates [40]. In contrast to the former method of nitration, the latter allowed us also to prepare the corresponding trinitro derivatives of the parent compounds **9** (see below) and **10** [40b].



Scheme 5 Directed six- and three-fold nitration of tetramethyltribenzotriquinacene **28**.

Unfortunately, nitration of the corresponding “bridgehead-blocked” tetramethylfenestrindane **49** (see Scheme 8) [41] and also of centrohexasindane (**3**) with of HNO₃ (100 %) and H₂SO₄ (98 %) did not furnish the desired octanitro and dodecanitro derivatives, respectively; rather, the formation of complex mixtures of partially functionalized analogs was observed. However, both **49** and **3** were converted

to the mixtures of the corresponding likewise four possible tetranitrofenestrindanes **32–35** (Chart 3) [42] and four possible hexanitrocentrohexaindanes **36–39**, respectively (Chart 4) [43]. Interestingly, the relative yields of latter four isomers, each representing a racemic mixture, are close to the 3:1:1:3 ratio expected for random attack at the six pairs of the twelve outer peripheral carbon atoms of **3**, pointing again to the lack of electronic interactions between the six arene rings.

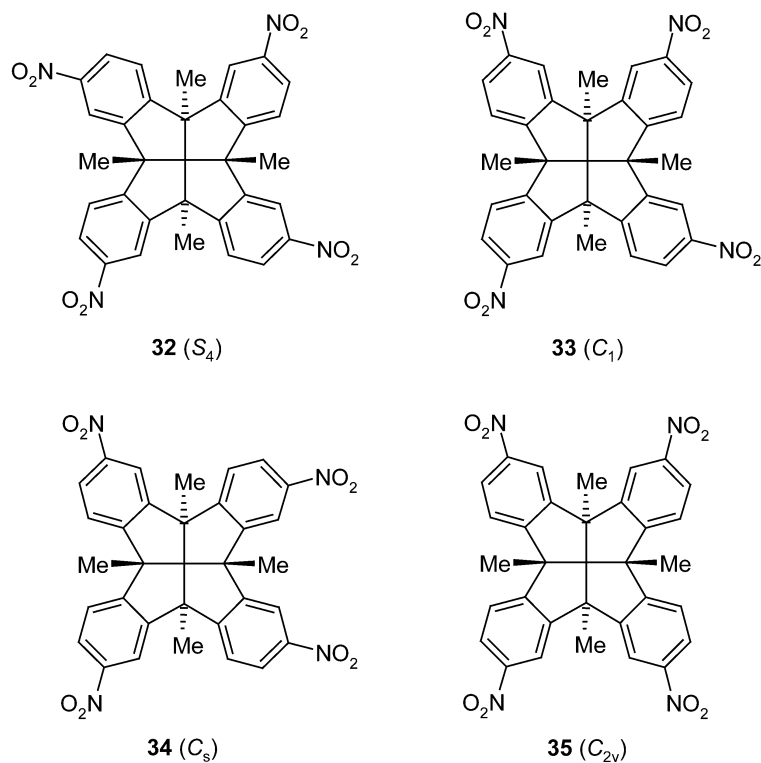


Chart 3 The four tetranitro derivatives obtained by nitration of tetramethylfenestrindane **32**.

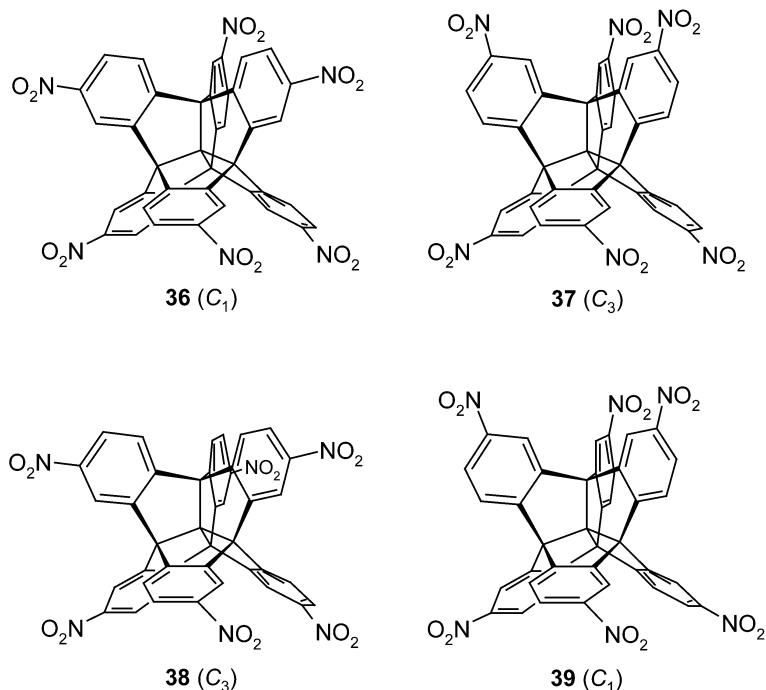
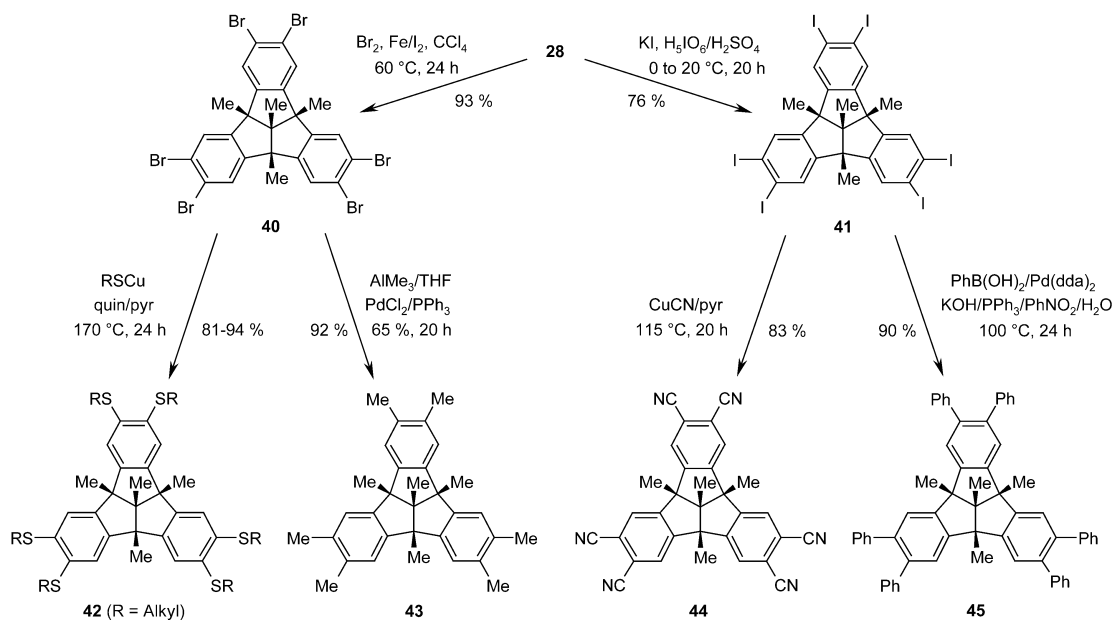
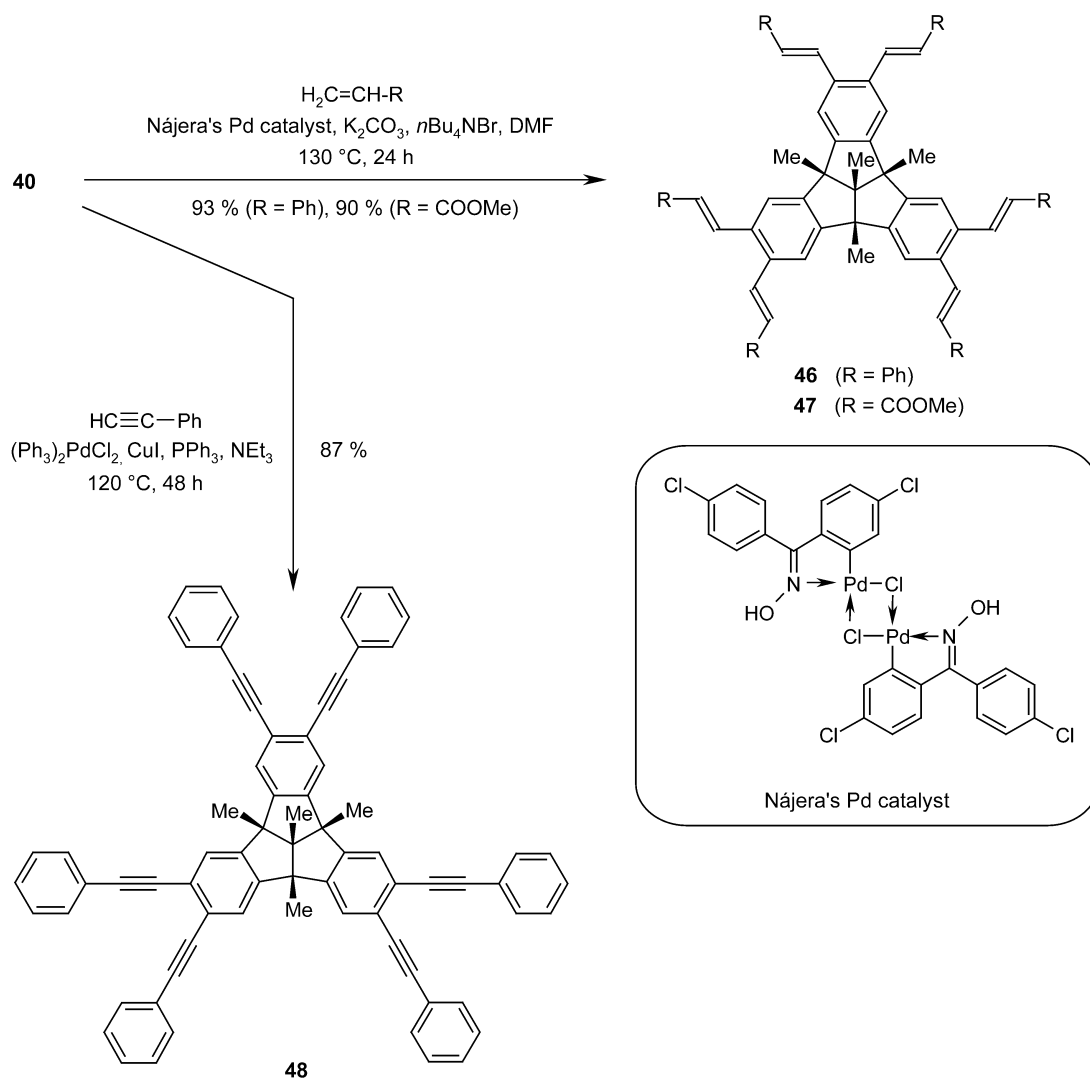


Chart 4 The four hexanitro derivatives obtained by nitration of centrohexaindane (**3**).

Six-fold bromination and iodination of tribenzotriquinacene **28** was found to be highly efficient and enabled the subsequent conversion to various new derivatives bearing six other functionalities, such as thioether and nitrile groups, or extended unsaturated residues, including different aryl, vinyl, and acetylene units. The access to the key intermediates, **40** and **41**, and their versatility to generate simple, but also extended tribenzotriquinacene derivatives are illustrated in Schemes 6 and 7. Besides the six-fold Suzuki and Sonogashira cross-coupling reactions, which afford the corresponding hexaphenyl derivative **45** and the “hexatolane” **48** [29,33], respectively, six-fold Heck-type coupling proved to be particularly efficient by use of one of Nájera’s oxime-derived palladium catalysts [44] affording the six-fold vinylated tribenzotriquinacenes **46** and **47** and related compounds [35].

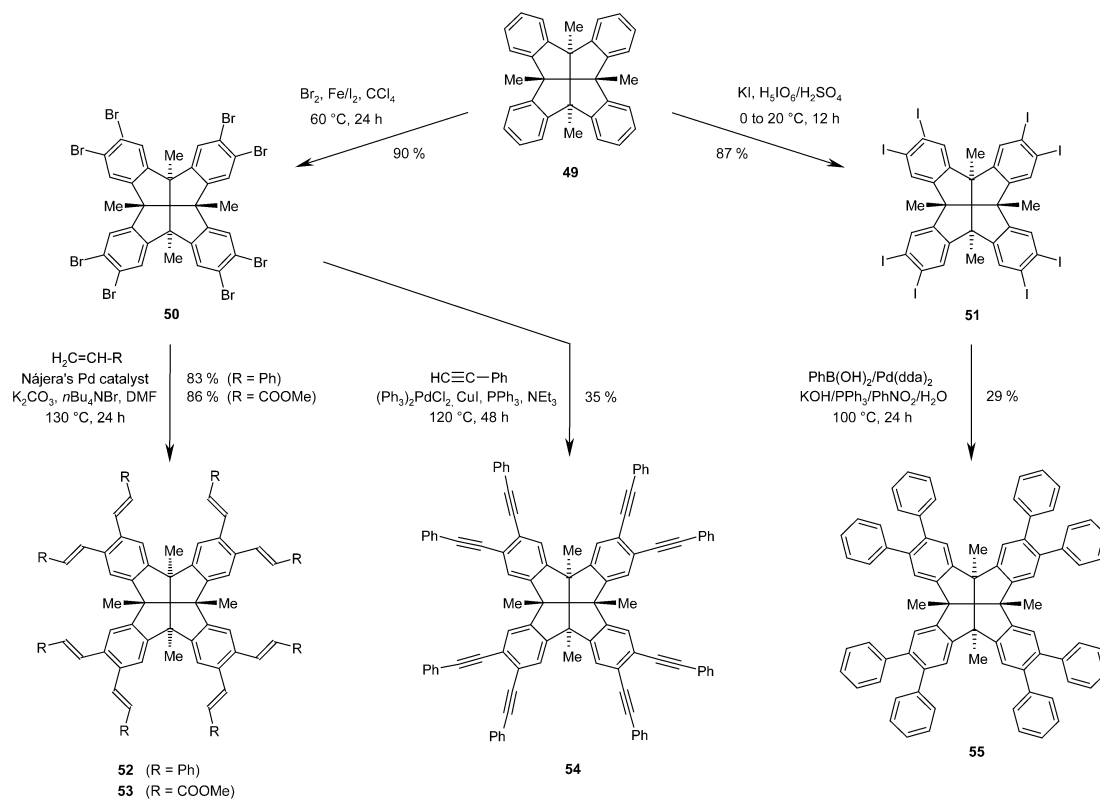


Scheme 6 Synthesis of tetramethyltribenzotriquinacenes bearing six functional groups or substituents at the molecular periphery.



Scheme 7 Six-fold vinylation and ethynylation of the tribenzotriquinacene framework at the molecular periphery.

Again, fenestrindanes undergo the corresponding eight-fold conversions (Scheme 8). Bromination and iodination of the tetramethylfenestrane **49** [41] at its outer arene positions leads to the octahalofenestrindanes **50** and **51**, respectively, in good yields [34]. Suzuki and Sonogashira cross-coupling reactions are also feasible, leading to the corresponding octaphenyl and octa(phenylethynyl) derivatives **55** and **54**, albeit the yields fall short as compared to the respective tribenzotriquinacenes **45** (Scheme 6) and **48** (Scheme 7) [29,33]. The same trend to comparably lower yields was found for other eight-fold conversions of these fenestrindane congeners, e.g., in the preparation of the octacyano derivative of **49** (not shown) from **51** in only 41 % yield [34]. In contrast, the corresponding hexanitride **44** is accessible from **41** in 83 % yield (Scheme 6) [29].



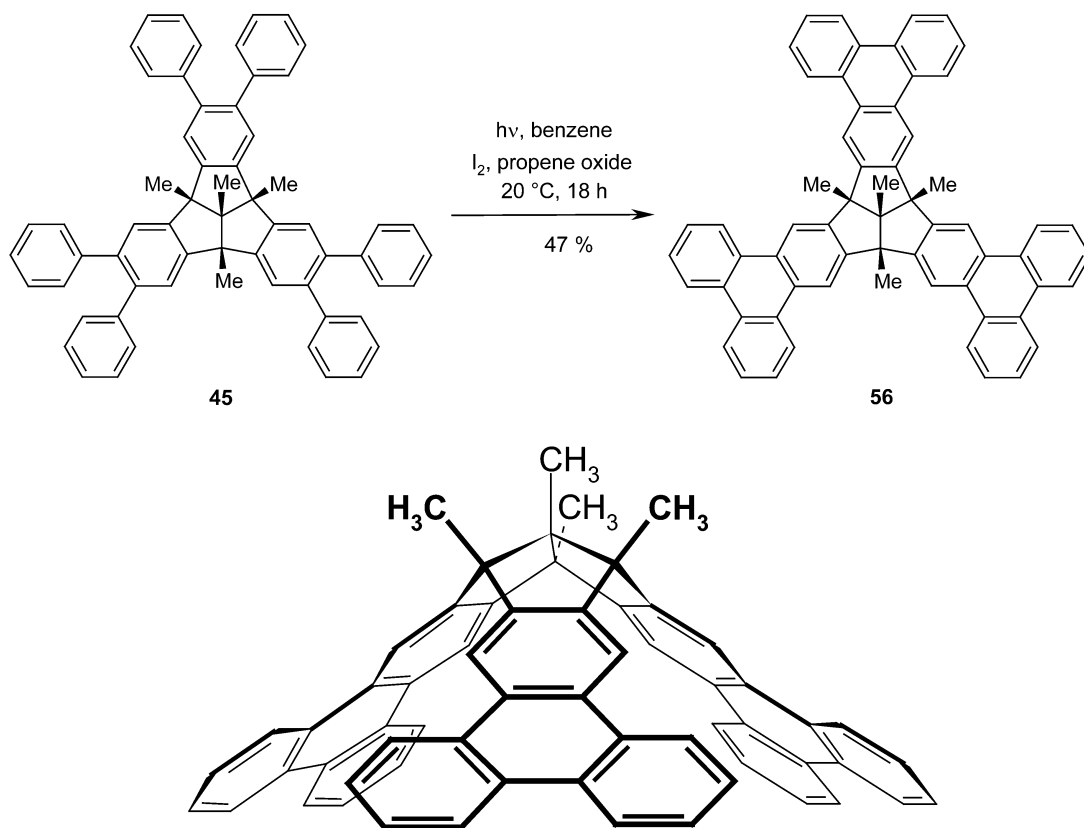
Scheme 8 Eight-fold functionalization and extension of the fenestrindane framework.

Remarkably, the high efficiency of the six-fold Heck-type cross-coupling reactions of hexabromotriquinacene **28** (Scheme 7) recurred also in the respective eight-fold conversions of octabromofenestrindane **50**, giving the fenestrindane-based octa(stilbenes) and octa(acrylates) **52** and **53** (Scheme 8) [36]. It appears that use of Nájera's oxime-derived palladium catalysts [44] is essential in these cases, since the desired multiple vinylation occurred only very reluctantly when conventional Pd catalyst systems were used [35a].

Further extension to centropolyindane-based polycondensed arenes

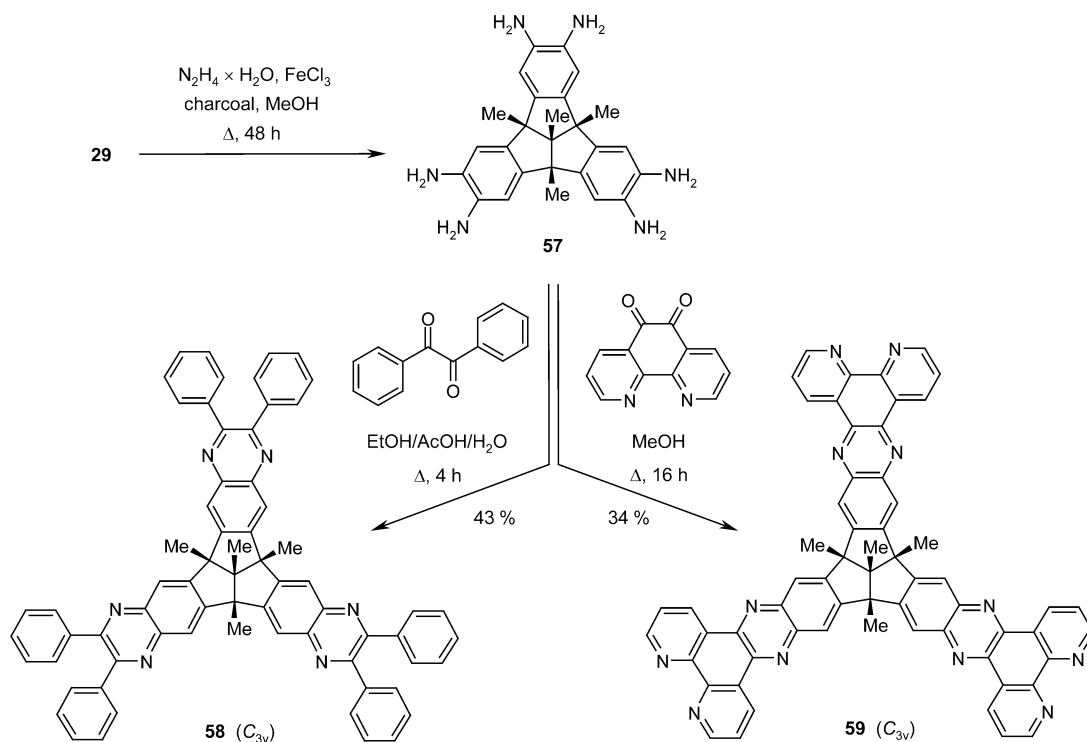
Because of the orthogonal orientation of the arene units in the centropolyindanes, suitable multiple C–C cross coupling and/or functionalization of these central building blocks could open the way to larger molecular frameworks bearing several polycondensed aromatic ring systems that are fixed at right angles to the centropolycyclic core. For example, as a conceivable extension of the triquinacene core, the three benzene rings of **9** could be replaced by larger polycondensed arenes, maybe even by three coronene units, each of which would be aligned essentially to one of the three Cartesian axes of space. First efforts in this direction have been made and are briefly exposed here.

Mallory reaction [45] of the phenyl-substituted triquinacene **45** gives rise to three-fold cyclodehydrogenation to produce the tris(triphenylene)-annulated triquinacene **56** in moderate yields (Scheme 9) [29,33]. Similar multiple annulations were tried with related hexaaryl derivatives of **28**, including the hexa(α -naphthyl) analog, but steric hindrance between the putatively extended arene units prevents the Mallory reaction in this case [40a].



Scheme 9 Synthesis of tris(triphenyleno)triquinacene **56** by three-fold Mallory reaction of tribenzotriquinacene **45**. Bottom: Perspective side view of **56**.

Similar extensions of the arene periphery of **28** were achieved by starting from the hexaamino-functionalized derivative **57**, a versatile intermediate which is easily accessible from the hexanitrotribenzotriquinacene **29** (Scheme 10). Subsequent condensation without isolation of **57** with benzil gives the tris(quinoxalino)triquinacene **58**, whereas the corresponding reaction with phenanthrene quinone failed [33,40a]. More interestingly, three-fold condensation of the tris(phenylenediamine) **57** with phenanthroline quinone leads to triquinacene-based tris(phenanthroline) **59**, a C_{3v} -symmetrical, rigid, and convex–concave structure bearing three metal coordination sites that point perfectly into the three orthogonal directions of the Cartesian space. Systematic complexation studies with metal cations have not been performed yet and are hampered by the moderate yields and, in particular, by the low solubility of such extended centropolyindanes. These problems could be overcome by use of tribenzotriquinacenes bearing larger alkyl groups than methyl at the three outer bridgehead positions to increase solubility. In fact, nonfunctionalized tribenzotriquinacenes, similar to those shown in Scheme 2 but containing three hydroxyl or bromine functionalities at the bridgeheads together with six iodine atoms at the outer arene positions have already been described [29,33].



Scheme 10 Synthesis of hexaaminotribenzotriquinacene **57** and condensation with 1,2-diketones giving derivatives that contain three mutually orthogonal quinoxaline and 1,10-phenanthroline units.

CHALLENGES AND SURPRISES IN THREE DIMENSIONS

The variability and feasibility of 3D extension of centropolyindane cores into three-space has been discussed above, but there appears to be a high potential for even further and considerably more enlarged and novel molecular architecture. Some visions of this theme are briefly outlined here. Finally, a recently discovered unique supramolecular aggregation of tribenzotriquinacene will be disclosed.

Besides the geometrical peculiarities discussed in the outline, the centropolyindanes offer another structural feature, which appears to be promising for extension of their framework. As illustrated in Fig. 5, the 3D bays between two adjacent indane units are well suited for being bridged by diatomic groupings, such as vinylene or *ortho*-phenylene units. This is especially interesting for the tribenzotriquinacenes, cf. **10**, and the fenestrindanes, cf. **6**, because “exhaustive” bridging of their bays would introduce three or, respectively, four seven-membered rings that would complement the bending induced by the five-membered rings. Thus, by the combination of equal numbers of pentagons and heptagons, the out-of-plane bending induced by pentagons would be largely compensated. Further annelation of the triquinacene-based polycyclic arrangement of **10** with (six-membered) benzene units would give rise to bowl-type structures (e.g., **I**), whereas annelation of the [5.5.5]fenestrane-based core of **6** would lead to saddle-type structures (e.g., **II**, Fig. 5). Here again, such centropolyindane-modified graphite cuttings **I** and **II** could even bear long-chain tentacula groups at the bridgehead positions to enable solubilization.

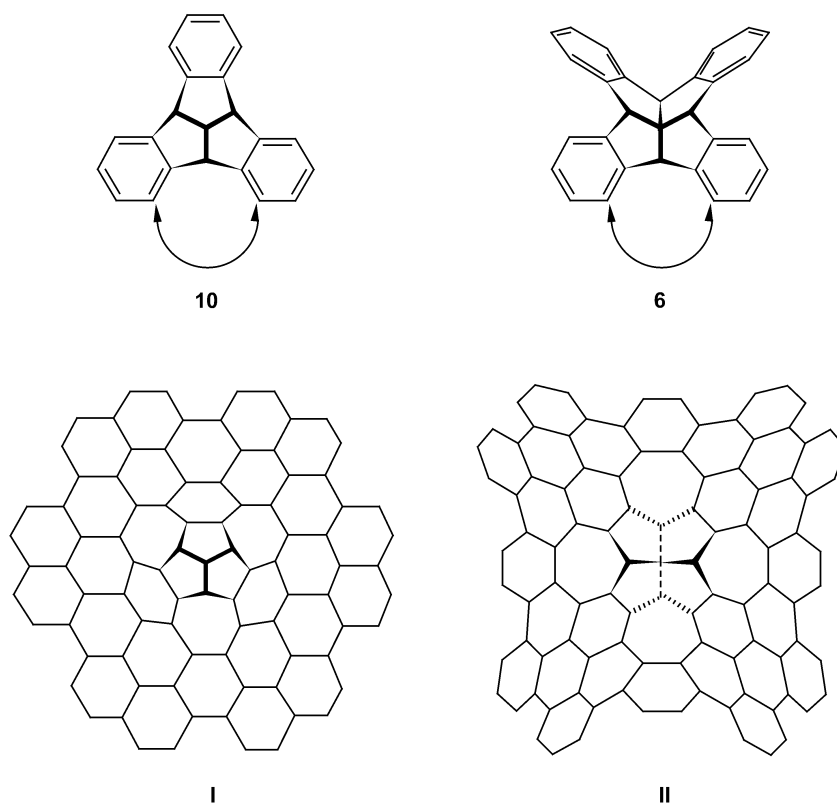


Fig. 5 Hypothetical extension of the tribenzotriquinacene (**10**) and fenestrindane (**6**) frameworks into bowl-shaped (**I**) and, respectively, saddle-shaped (**II**) graphite cuttings. The double bonds in **I** and **II** are omitted for the sake of clarity.

Another experimental challenge based on the geometrical peculiarities of the tribenzotriquinacenes, and of other centropolyindanes containing the tribenzotriquinacene unit, originates from the insight that the three orthogonally fused indane units of **10** may be considered three adjacent edges of a cube, with the central carbon atom representing one of its eight tips. Therefore, *and purely hypothetical to date*, eight molecules of suitably functionalized tribenzotriquinacenes could be mutually fused to generate, by multiple covalent bonding, a large molecular cube (cf. Fig. 6). Molecular mechanics calculations corroborate this idea and show that, for example, a C_{60} fullerene would have ample space in the interior of such an organic (“giant”) nanocube.

Strategies to reach this goal by means of organic synthesis include the availability of tribenzotriquinacenes containing three suitable functional groups at the outer arene positions in a C_3 -symmetrical pattern. Conceptually, a given enantiomer of this building block would then allow up to three other, identical enantiomers to undergo the co-condensation in an all-concave orientation and, eventually, co-condensation of eight of such building blocks would give rise to a tribenzotriquinacene-based molecular cube. Again, solubility problems could be overcome by incorporating three benzydrylic bridgehead substituents larger than methyl.

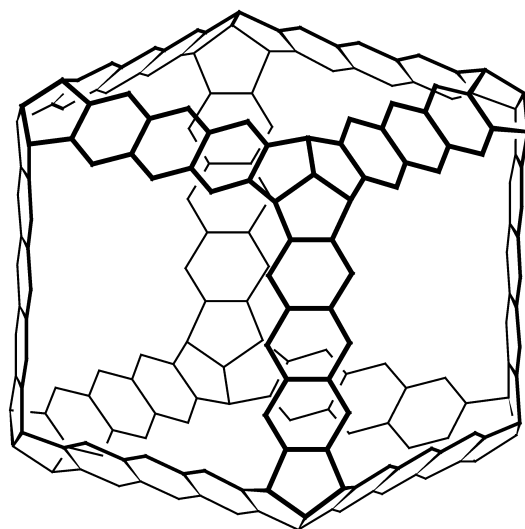
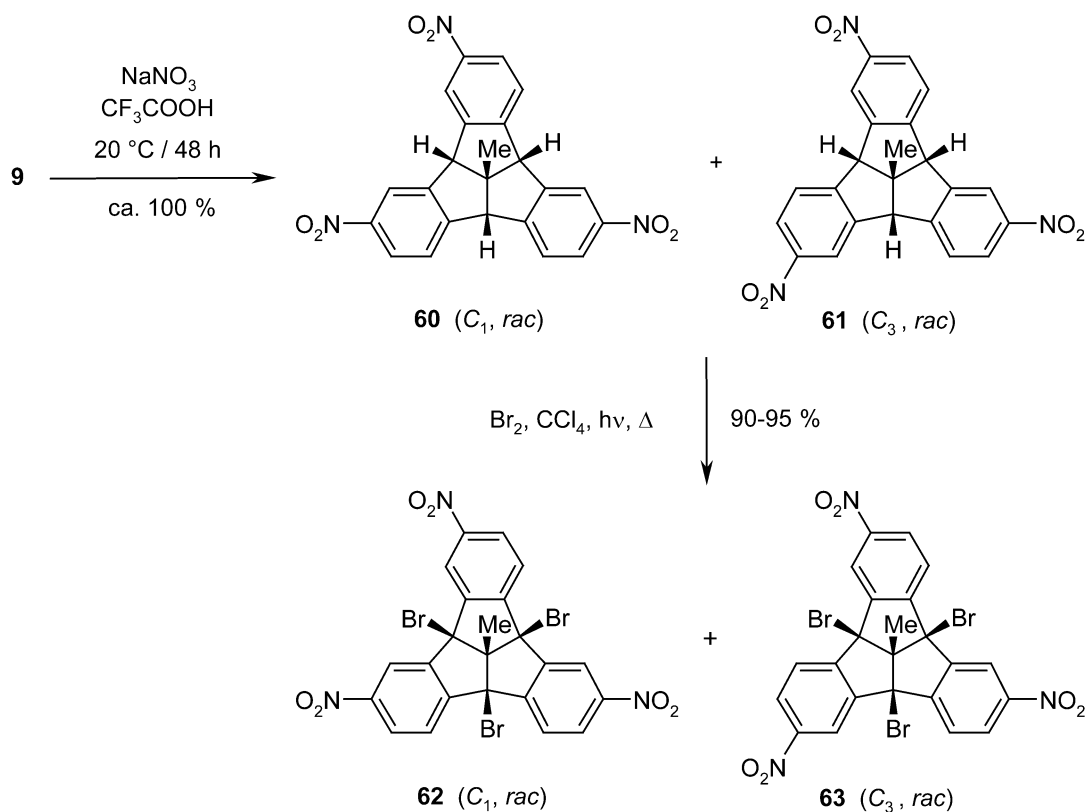


Fig. 6 Sketch of a hypothetical, covalently bound cube containing eight tribenzotriquinacene units (e.g., **10**) at its tips. The double bonds within the anthracene units and all hydrogen atoms have been omitted for the sake of clarity.

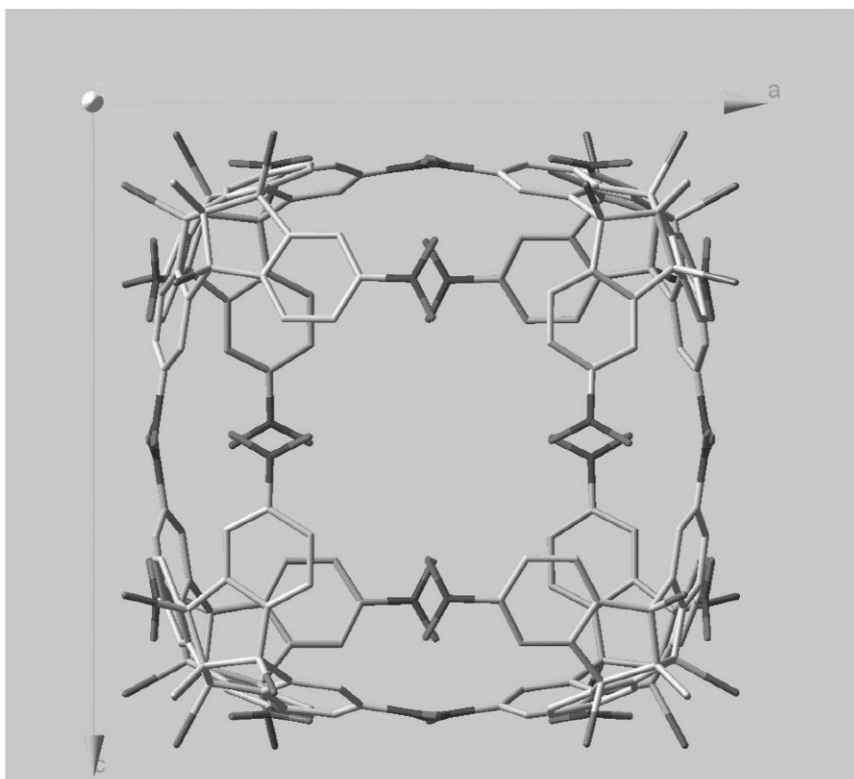
The challenge of this concept may be too great, but serendipity is always around when aims and efforts are put at high level. In fact, one of our first efforts into the research on C_3 -symmetrical, and thus chiral tribenzotriquinacenes bearing, in addition to the three peripheral functional groups, three bridgehead functionalities led to a big surprise. As mentioned above, similarly to its bridgehead-blocked tetramethyl analog **28**, the *centro*-methyltribenzotriquinacene **9** undergoes three-fold nitration to give a ca. 3:1 mixture of the racemic C_1 - and C_3 -symmetrical derivatives **60** and **61**, respectively, in quantitative yield (Scheme 11). Subsequent photoinduced three-fold bridgehead bromination of this material furnished a new mixture of two racemates consisting of the C_1 - and the C_3 -symmetrical tribenzotriquinacenes **62** and **63**. Surprisingly, the solubility of the two racemates is very different; the C_1 -stereoisomer **62** is well soluble, whereas the C_3 -symmetrical tribromotrinitro derivate **63** precipitates readily from the solution. Notably, the crystals of the latter isomer were obtained as small cubes or flattened orthogonal blocks of ca. 0.2–0.5 mm edge length under suitable conditions. And, much to our surprise, the X-ray structure analysis of these single crystals obtained from chloroform or acetone revealed that the unit cell consists of a supramolecular cube that is formed from eight identical enantiomers of **63** in an all-concave arrangement (Fig. 7a) [46]! Thus, each of the cubes' edges within a given crystal is formed by two identical enantiomers of **63**, which apparently fit to each other by coordinating a nitro group of one molecule, nearly in-plane, toward the bare side of the nitrobenzene unit of an adjacent molecule, and vice versa (Fig. 7b). The size of each cube, as measured from the central carbon atom of one tribenzotriquinacene molecule to the central carbon atom of an adjacent tribenzotriquinacene, is $1.25 \times 1.25 \times 1.25$ nm, and the inner volume contains several solvent molecules in disordered arrangement [46]. All of these "octamers" are packed in a perfect cubic lattice of cubes. Various factors that could contribute to the stabilization of this unique crystal structure may be discussed, including the stabilizing interaction between antiparallel nitro substituents within each of the cubes and between them, and also including the intriguingly close contacts between the bromine atoms of the tribenzotriquinacene molecules pointing toward each other at the adjacent corners of eight individual, neighboring cubes.



Scheme 11 Synthesis of the tribromotrinitrotribenzotriquinacenes **62** and **63** from the 10-methyltribenzotriquinacene **9** as a ca. 3:1 mixture of racemates.

First experiments aimed to understand the major factors governing the formation of the particular solid-state supermolecular structure of **63** show that this will be an intriguing challenge on its own. Thus, the corresponding trichloro analog of tribenzotriquinacene **63** (not shown) does not form nanocubes; rather, its crystals were found to be racemic, consisting of enantiopure layers in alternate order [46].

(a)



(b)

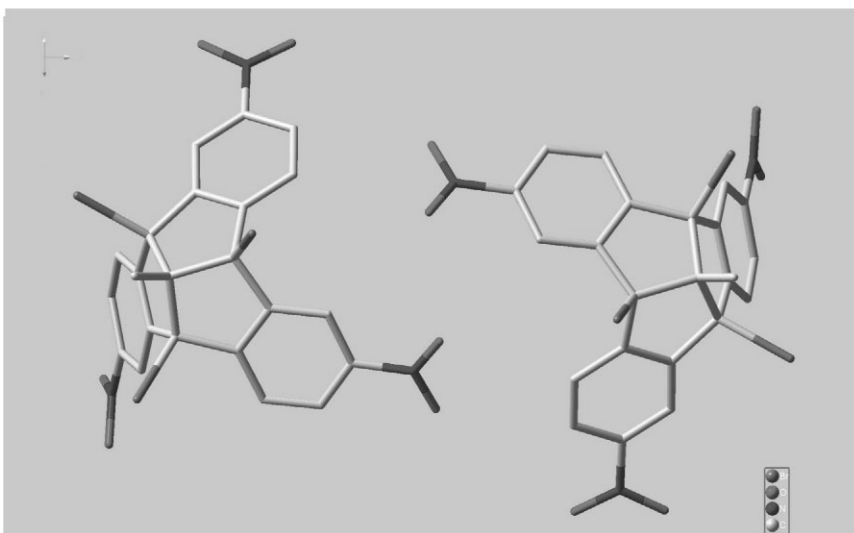


Fig. 7 (a) A supramolecular nanocube consisting of eight C_3 -symmetrical tribromotrinitrotribenzotriquinacenes **63** of the same absolute configuration, as determined by X-ray single crystal analysis (see text). (b) An edge of the nanocube having a distance of 1.25 nm between the two central carbon atoms of the two (identical) tribenzotriquinacene enantiomers.

SUMMARY

The structural manifold of the centropolyindanes, which is characterized by the presence of several indane units that are mutually fused at right angles, has been used to generate a large variety of centropolyindane derivatives bearing functionalities that are directed along the six directions of the Cartesian space. In this respect, the tribenzotriquinacenes, and in particular the *centro*-methyl derivative **9** and its bridgehead-substituted congeners, such as **16–18** and related compounds, represent unique building blocks for the construction of novel, truly 3D polyfunctionalized molecular frameworks bearing three mutually orthogonal arene planes. Polyfunctionalization of the centropolyindane cores enables the construction of extended centropolycyclic skeletons, such as the tris(triphenyleno)triquinacene **56**, and a large variety of C–C coupled derivatives containing six tentacula groups, such as **46–48**. First tridentate phenanthrolines, such as **59**, representing potential “Cartesian” ligands for orthogonal network-like metal-ion coordination in the three-space, have been prepared. Similar strategies were found to be applicable to other members of the centropolyindane family. In particular, the fenestrindanes derived from the parent hydrocarbons **6** and **49** can be converted to the corresponding octafunctionalized and eight-fold C–C cross-coupled derivatives, such as **52–55**. Such efforts have inspired us to design large convex–concave and saddle-like polycondensated arene networks containing a triquinacene or, respectively, an all-*cis*-[5.5.5]fenestrane core.

While extension of centropolyindane chemistry is relatively experimentally straightforward with these lower congeners, polyfunctionalization of the highest member, centrohexasindane (**3**) is still rather limited; however, the first 12-fold functionalized derivative of **3**, viz. the T_d -symmetrical dodecamethoxycentrohexasindane **27**, has been synthesized recently. Finally, some C_3 -symmetrical, and thus chiral, tribenzotriquinacenes have been synthesized on the way to develop a rational synthesis of covalently bound nanocubes containing eight tribenzotriquinacene at their tips. Along these lines, and completely unexpected, a supramolecular “nanocubic” solid-state aggregation has been discovered in the case of a C_3 -symmetrical hexafunctionalized tribenzotriquinacene, viz. the tribromotrinitro derivative **63**. As a fascinating consequence of the orthogonal geometry of the tribenzotriquinacene skeleton, the aggregation of eight identical enantiomers in a nanocube was found to transform into macroscopic, enantiomerically pure cubic or cube-like single crystals.

ACKNOWLEDGMENTS

This ongoing work has been made possible by several highly inspired and talented students and coworkers over the years. Their names are quoted in the references, and I am very thankful to all of them. Financial support by the Deutsche Forschungsgemeinschaft (DFG) and the Fonds der Chemischen Industrie (FCI) is also acknowledged. Special thanks are due to Dr. Michal Cyranski (University of Warsaw, Poland) and to Prof. Dr. Xiaoping Cao (Lanzhou University, P. R. China).

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