# Polyphenylene dendrimers *via* Diels–Alder reactions: the convergent approach

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**Polyphenylene dendrimers and dendrons can be obtained using [2 + 4]cycloaddition and Knoevenagel cyclocondensation in a convergent approach.**

Due to their outstanding properties, such as molecular shape- and size-persistence and narrow molecular weight distribution, dendrimers are the object of increasing interest.[1] In this context we developed a divergent method to synthesize polyphenylene dendrimers based on the selective Diels–Alder cycloaddition between tetraphenylcyclopentadienones and ethynyls.[2] We are thus able to synthesize dendrimers up to the fourth generation, which exist as shape-persistent nanoparticles.[3]

While the divergent approach builds dendrimers layer-by-layer from a central core to the periphery, the convergent strategy builds the dendrimer in the opposite manner, from the periphery toward the central core. Thus, the dendrimer branches, also called dendrons, are synthesized first and then added to a central core. This approach not only allows the symmetric functionalization of the dendrimer surface as in the divergent approach, but also the controlled functionalization of the dendrimer by adding differently functionalized dendrons to selectively protected cores.[4]

Here, we present a convergent approach for the synthesis of polyphenylene dendrons and dendrimers based on two alternating orthogonal reactions: (i) the Diels–Alder cycloaddition of tetraphenylcyclopentadienones to phenylene-substituted ethynyls, and (ii) the Knoevenagel condensation of benzils with 1,3-diphenylacetones to give cyclopentadienones.

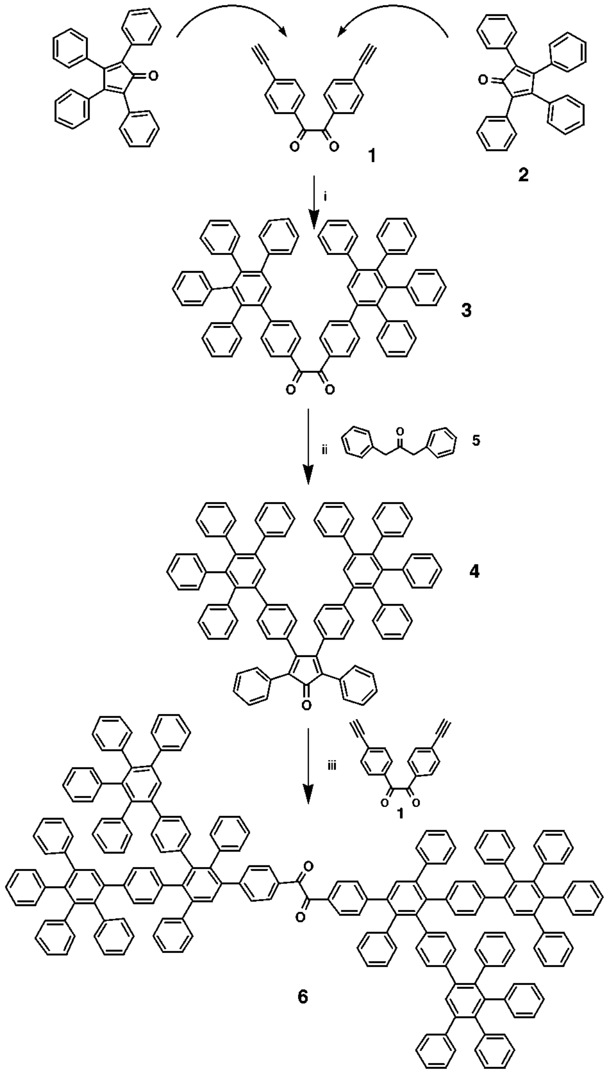
The starting point of the synthesis is 4,4′-diethynylbenzil **1** which contains two ethynylic dienophile units and one ethanedione function which can react in a Knoevenagel condensation (Scheme 1). The starting material **1** is prepared *via* the Sonogashira[5] coupling of triisopropylsilylacetylene and 4,4′-dibromobenzil and subsequent cleavage of the TIPS groups with KF in DMF (70%, yellow crystals).

The two-fold Diels–Alder cycloaddition of an excess of tetraphenylcyclopentadienone **2**, which has to be regarded as a first-generation dendron, to **1** in refluxing xylene leads to the second generation **3** in the form of a benzilic dendron (91%, pale yellow amorphous powder). The Knoevenagel condensation of **3** to the corresponding cyclopentadienone dendron **4** with 1,3-diphenylacetone **5** is achieved in dioxane and in the presence of $Bu_4NOH$ as base. Like **3**, the cyclopentadienone dendron **4** can be easily precipitated in EtOH as a pale red solid in 85% isolated yield.

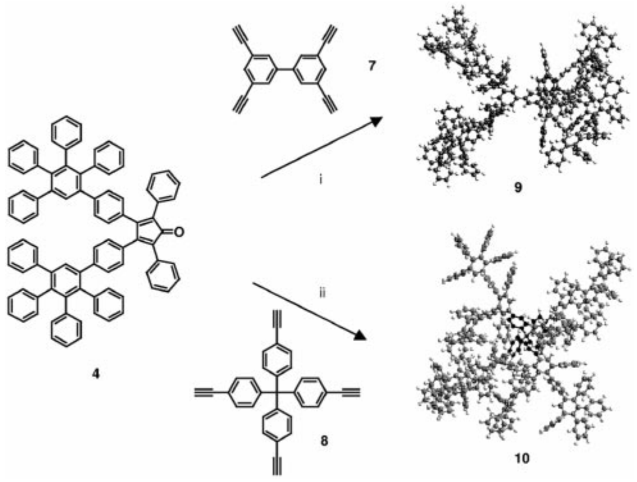
The next generation benzil **6** is obtained, similar to the second generation, by addition of an excess of dendron **4** to **1** in refluxing xylene. Isolation after precipitation in EtOH affords the benzil **6** as an amorphous yellow powder in 89% yield. Further base-catalyzed condensation of **6** with 1,3-diphenylacetone **5** provides a complex mixture of products, determined by mass spectrometry, consisting of small amounts of third generation cyclopentadienone dendron and further side-products of the polycondensation of **5** with **6**. This can be explained by the high steric hindrance of the polyphenylenic branches of the benzil **6**, which will prefer a conformation where the dendrons (and thus the vicinal carbonyls) are oriented in opposite directions. This arrangement prevents the favourable orientation of the benzilic carbonyls required for the nucleophilic attack of **5** and subsequent formation of the cyclopentadienone ring (see Scheme 1).

The four-fold cycloaddition of an excess of cyclopentadienone dendron **4** to the tetraethynylbiphenyl **7** and the tetrakis(ethynylphenyl)methane **8** in $Ph_2O$ at 200 °C leads to dendrimers **9** and **10**, respectively (see Scheme 2). The products are isolated by precipitation from the reaction mixture using EtOH (89 and 85% isolated yield, respectively). Molecules **9** and **10** correspond to the second generation polyphenylene dendrimer previously made by the divergent method.[6]

Whereas in the synthesis of dendrimer **9** the reactants have to be heated for two days, the reaction time in the case of dendrimer **10** is about one week. The MALDI-TOF mass spectra taken at various stages during the reaction reveal that three ethynyl groups of both cores react rapidly with dendron **4**,



**Scheme 1** *Reagents and conditions*: i, xylene, 14 h, 91%; ii, **5**, 1,4-dioxane, $Bu_4NOH$, 100 °C, 1 h, 85%; iii, **1**, xylene, reflux, 14 h, 89%.



**Scheme 2** *Reagents and conditions*: i, **7**, $Ph_2O$, 200 °C, 2 days, 89%; ii, **8**, $Ph_2O$, 200 °C, 7 days, 85%.

while the reactivity of the last group depends on the flexibility of the core. In this view the tetraethynylbiphenyl core **7** allows rotation about the phenyl–phenyl bond of the core, so that the fourth ethynyl group can be brought into a favorable position for the sterically demanding cycloaddition of dendron **6**. In contrast the fourth ethynyl groups of the tetrakis(ethynylphenyl)methane core **8** does not have such mobility.

The disparity in reaction times required for obtaining **9** and dendrimer **10** can also be understood examining ball-and-stick models, which are generated using the MM2 (85) force field with the CERIUS 2 program package and applying the Conjugate Gradient 200 algorithm (compare Scheme 2).[7] Whereas dendrimer **9** possesses a dumb-bell like structure, with easily accessible holes close to the phenyl–phenyl bond of the core, the methane center of dendrimer **10** is densely surrounded by phenylene groups which increase the stiffness of the whole molecule and render the core difficult to access.

Neverthless, both the dendrons and the dendrimers are very soluble in organic solvents such as toluene and $CH_2Cl_2$. Characterization was carried out by field-desorption mass spectrometry for the dendrons with molecular masses up to 2000 g $mol^{-1}$ and matrix-assisted laser desorption ionization time of flight mass spectrometry (MALDI-TOF MS) for the higher molecular mass dendrons and the dendrimers. The purity and monodispersity of the analyzed molecules was confirmed by the perfect agreement between calculated and experimentally determined *m/z* ratios.† A characteristic feature of the synthesized dendrimers **9** and **10** is their high thermal and chemical stability. They decompose under air only at temperatures higher than 550 °C according to thermogravimetric analysis. Their chemical stability is also noteworthy. For example boiling in concentrated HCl or in 30% KOH for seven days fails to produce any decomposition. The dendrimers react only with strong electrophiles, like $H_2SO_4$, *via* aromatic electrophilic substitution, but without change in the polyphenylene framework. This opens a way to chemically functionalize dendrimers at their surface.

Compared to the divergent approach, the convergent method at first glance yields the same monodisperse products with similarly high yields. However, though the convergent method can be used to synthesize dendrimers only up to the second generation, this method opens the way to dendritic polymers carrying substituents of more than just one kind. In contrast, the divergent approach may be successfully used up to the fourth generation, but it only allows the ordered attachment of one kind of functional group. Both methods have in common the fact that they yield monodiperse polyphenylene dendrimers in high yield.

In conclusion, we can say that: (i) using a convergent approach, polyphenylene dendrons and dendrimers with more than 60 benzene rings can be obtained *via* [2 + 4] cycloadditions and Knoevenagel condensations; (ii) by attachment of the polyphenylene dendrons to different cores, dendrimers with different shapes are obtained; (iii) the dendrimers show high thermal and chemical stability.

Our current investigations involve the convergent synthesis of dendrimers with various substitution patterns as possible carriers in catalysis.

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## Notes and references

† *Selected data* for **4**: FD-MS: *m/z* 1145.47, calc. for $C_{89}H_{60}O$: 1145.45; $\delta_H$(500 MHz, $C_2D_2Cl_4$, 393 K) 7.49 (s, 2H), 7.25–7.13 (m, 20H), 6.97 (d, $^3J$ 8.25, 4H), 6.90–6.72 (m, 30H), 6.67 (d, $^3J$ 8.25, 4H); $\delta_C$(125 MHz, $C_2D_2Cl_4$, 303 K) 199.0 (C=O), 154.6, 142.5, 142.0, 141.9, 140.9, 140.4, 140.3, 140.1, 140.0, 139.8, 139.4, 131.8, 131.8, 131.7, 131.1, 131.0, 130.5, 130.4, 130.3, 129.7, 129.2, 128.3, 127.9, 127.7, 127.1, 127.0, 126.8, 126.5, 126.0, 125.7, 125.5, 125.2. For **9**: MALD-TOF MS: *m/z* 4720, calc. for $C_{372}H_{250}$: 4720.07; $\delta_H$(500 MHz, $C_2D_2Cl_4$, 393 K) 7.41 (s, 4H), 7.34 (s, 4H), 7.28 (m, 6H), 7.18–6.25 (m, 236H); $\delta_C$(125 MHz, $C_2D_2Cl_4$, 303 K) 199.0 (C=O), 142.3, 142.1, 141.4, 140.8, 140.7, 140.5, 139.5, 139.4, 139.0, 138.7, 138.3, 132.7, 132.0, 131.9, 131.6, 131.3, 130.4, 130.2, 128.9, 128.6, 127.7, 127.2, 127.0, 126.7, 126.3, 125.9, 125.6, 125.4.

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