

Preparation of Polystyrene Beads with Dendritically Embedded TADDOL and Use in Enantioselective *Lewis* Acid Catalysis¹⁾

by Holger Sellner²⁾, P. Beat Rheiner²⁾, and Dieter Seebach*

Laboratorium für Organische Chemie der Eidgenössischen Technischen Hochschule, ETH-Hönggerberg, CH-8093 Zürich

Dedicated to Professor Barry M. Trost on the occasion of his 60th birthday

A full account is given of the preparation and use of TADDOLates, which are dendritically incorporated in polystyrene beads (*Scheme 1*). A series of styryl-substituted TADDOLs with flexible, rigid, or dendritically branching spacers between the TADDOL core and the styryl groups (2–16 in number) has been prepared (**5–7**, **20**, **21**, **26** in *Schemes 2–4* and *Fig. 1–3*). These were used as cross-linkers in styrene-suspension polymerization, leading to beads of ca. 400- μm diameter (*Schemes 5* and *6, b*). These, in turn, were loaded with titanate and used for the *Lewis* acid catalyzed addition of Et_2Zn to PhCHO as a test reaction (*Scheme 6*). A comparison of the enantioselectivities and degrees of conversion (both up to 99%), obtained under standard conditions, shows that these polymer-incorporated Ti-TADDOLates are highly efficient catalysts for this process (*Table 1*). In view of the effort necessary to prepare the novel, immobilized catalysts, emphasis was laid upon their multiple use. The performance over 20 cycles of the test reaction was best with the polymer obtained from the TADDOL bearing four first-generation *Fréchet* branches with eight peripheral styryl groups (**6**, p-**6**, p-**6**·Ti(OⁱPr)₂): the enantioselectivity (*Fig. 4*), the rate of reaction (*Fig. 5*), and the swelling factor (*Fig. 6*) were essentially unchanged after numerous operations carried out with the corresponding beads of 400- μm diameter and a degree of loading of 0.1 mmol TADDOLate/g polymer, with or without stirring (*Fig. 7*). The rate with the dendritically polymer-embedded Ti-TADDOLate (p-**6**·Ti(OⁱPr)₂) was greater than that measured with the corresponding monomer, *i.e.*, **6**·Ti(OⁱPr)₂ (*Fig. 8*). Possible interpretations of this phenomenon are proposed. A polymer-bound TADDOL, generated on a solid support (by *Grignard* addition to an immobilized tartrate ester ketal) did not perform well (*Scheme 4* and *Table 2*). Also, when we prepared polystyrene beads by copolymerization of styrene, a zero-, first-, or second-generation dendritic cross-linker, and a mono-styryl-substituted TADDOL derivative, the performance in the test reaction did not rival that of the dendritically incorporated Ti-TADDOLate ((p-**6**·Ti(OⁱPr)₂) (*Scheme 7* and *Fig. 10*). Finally, we have applied the dendritically immobilized Cl_2 and $(\text{TsO})_2\text{Ti}$ -TADDOLate as chiral *Lewis* acid to preferentially prepare one enantiomer of the *exo* and the *endo* (3+2) cycloadduct, respectively, of diphenyl nitrene to 3-crotonoyl-1,3-oxazolidinone; in one of these reaction modes, we have observed an interesting conditioning of the catalyst: with an increasing number of application cycles, the amount of polymer-incorporated *Lewis* acid required to induce the same degree of enantioselectivity, decreased; the degrees of diastereo- and enantioselectivity were, again, comparable to those reported for homogeneous conditions (*Fig. 9*).

1. Introduction. – Binding chiral ligands to insoluble polymer supports is a field of growing interest in current chemistry. Heterogeneous catalysis offers the advantages of easy separation of the supported catalyst from the reaction mixture, possible recycling as well as, in many cases, enhanced stability of the polymer-bound catalyst as compared

¹⁾ Preliminary communications: [1][2]; parts of the results have been mentioned in review articles, without experimental detail [3–5].

²⁾ Part of the Ph.D. theses of H.S., ETH Zürich, Dissertation No. 14145, 2001, and of P.B.R., ETH Zürich, Dissertation No. 12773, 1998.

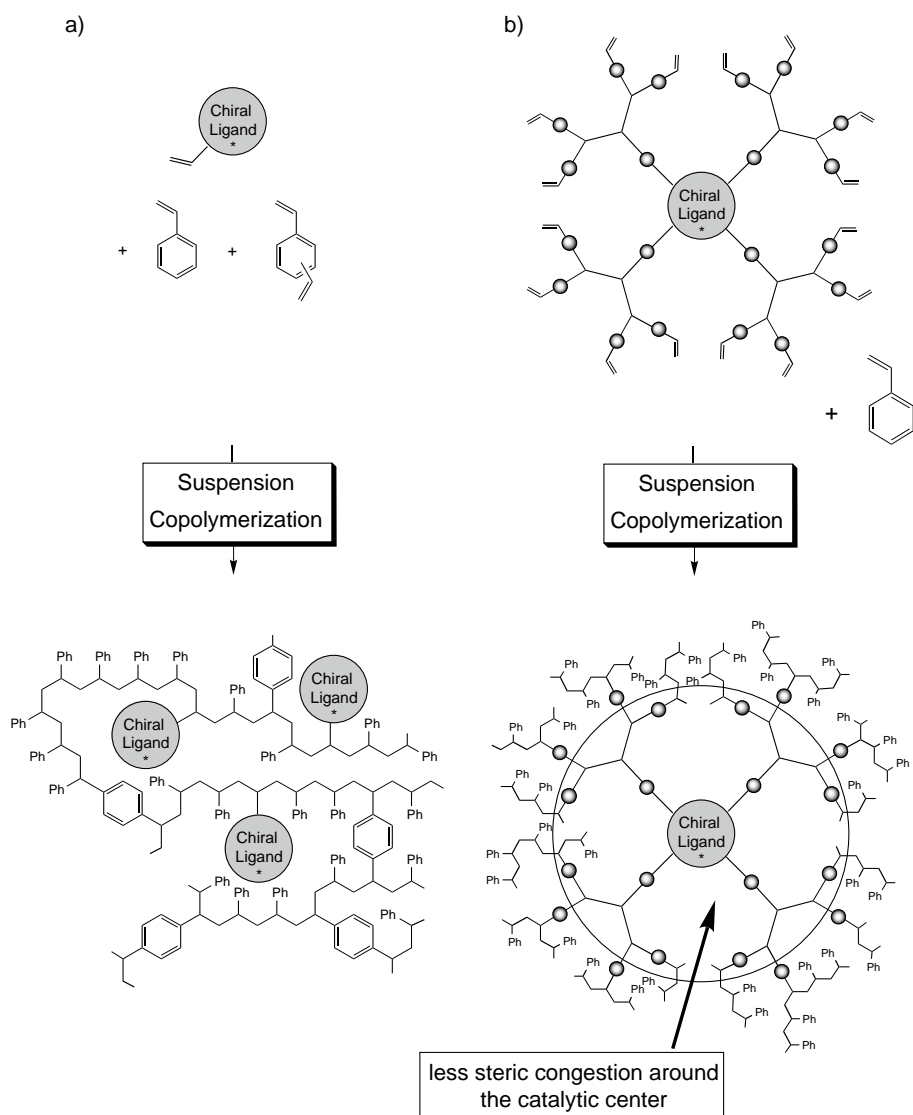
to its soluble analogue [6–14]. In this way, even sophisticated and expensive chiral ligand systems might become attractive for industrial applications. However, more often than not, the activity of supported catalysts is reduced with respect to their soluble analogues used under homogeneous conditions, due to diffusion problems or to the fact that the preferred conformation of the catalytic moiety cannot be adopted on or in the polymer. Therefore, new methodologies for immobilization have to be found that provide a catalytic activity of the polymer-bound catalyst similar to that obtained under homogeneous conditions.

By far, the most frequently used strategy of heterogenization is covalent binding of the catalyst or ligand of choice to a polymer support. In the case of organic polymer supports, this can be achieved either by grafting the desired ligand onto a preformed support containing reactive groups, or by copolymerization of a suitably functionalized ligand with polymerizable monomers and a cross-linker (for the preparation of insoluble polymers). The first approach is often preferred, since many suitable polymer supports for all kinds of applications (*e.g.*, Merrifield resins) are commercially available. Furthermore, the approach of grafting is very convenient, especially for chemists who are not familiar with polymer or solid-state chemistry, since the immobilization process is performed by simply linking the ligand to the polymer resin by means of well-known coupling reactions. In contrast, immobilization by copolymerization of the ligand with suitable vinylic monomers and a cross-linker, although requiring more synthetic effort than immobilization by grafting, offers many more possibilities for generating and controlling a specific environment around the ligands within the polymer matrix. For example, polymeric materials with cavities of molecular dimension around the catalytic centers can be obtained [15] (*cf.* the method of ‘molecular imprinting’, developed by Wulff [16][17]). In most applications, polystyrene is used as polymer support, *i.e.*, a vinyl-substituted ligand is copolymerized with styrene and divinyl benzene (DVB) as cross-linker (*Scheme 1, a*). As can be seen from this schematic representation, in this approach a ligand is directly incorporated into the cross-linked polystyrene resin, and this may result in reduced catalytic activity due to steric congestion around the catalyst moieties.

To circumvent these problems, we have introduced a novel concept: the chiral ligand to be immobilized is placed in the core of a polymerizable dendrimer, followed by copolymerization of the latter with styrene (*Scheme 1, b*). In this approach, no further cross-linking agent, such as DVB, is necessary, since the dendrimer itself acts as cross-linker. The dendritic branches are thought to act as spacer units keeping the ‘obstructing’ polystyrene backbone away from the catalytic centers, leading to better accessibility and, thus, to enhanced catalytic activity. Our work represents the first example of dendrimers used as polymer cross-linkers. Quite recently, Reetz and Giebel introduced an alternative concept for the preparation of dendritically cross-linked materials: triflate-functionalized poly(propylene imine) dendrimers were interconnected by the addition of $\text{Sc}(\text{OTf})_3$ to give a dendrimer cross-linked material, which was used for the heterogeneous catalysis of various Sc Lewis acid mediated test reactions [18].

Both approaches presented in *Scheme 1* have been realized with the chiral TADDOL ligands (TADDOL = $\alpha, \alpha, \alpha', \alpha'$ -tetraaryl-1,3-dioxolane-4,5-dimethanol) developed in our group [4][19]. Mono-styryl-substituted TADDOL ligands were

Scheme 1. a) Immobilization of Mono-Vinyl-Functionalized Chiral Ligands by Copolymerization with Styrene and DVB. b) Novel Approach: Copolymerization of Dendritically Surrounded Chiral Ligands with Styrene.



copolymerized with styrene and DVB as cross-linker to give, after loading with metal salts, polymer-bound TADDOLate complexes of high catalytic activity [20]³). In 1997, we reported for the first time on the copolymerization with styrene of styryl-functionalized TADDOL dendrimers according to *Scheme 1, b* [1]. It turned out that

³) Besides our own work, TADDOL has also been immobilized by other groups [21].

the derived polymeric TADDOLates exhibit excellent catalytic activity with respect to reproducibility of enantioselectivity and of degree of conversion during multiple use as catalyst ligands in a test reaction [2]. Motivated by this success, we have also immobilized the chiral ligands BINOL [22a–e]⁴⁾ and Salen [23] in this way to confirm the potential of this new technique of immobilization, in a variety of different test reactions.

In the present paper, we describe and summarize the results obtained with TADDOL complexes immobilized in a cross-linking fashion in polystyrene. Applications of these new polymer-bound catalysts in various test reactions are presented, and a comparison of the catalytic properties of this new class of supported TADDOLates with those of the already existing systems is provided.

2. Preparation of Styryl-Substituted TADDOLs for Cross-Linking Copolymerization with Styrene.

– We decided to prepare TADDOL cross-linkers for the copolymerization with styrene, in which the spacer units are attached to the *para*-positions of the TADDOL Ph groups. We knew that modification of the TADDOL moiety (with dendritic branches of up to the fourth generation) at these positions has hardly any influence on the catalytic activity of the corresponding metal complexes in solution [24]. A linear benzyl-ether branch **2** [22] and dendritic *Fréchet* branches [25] **3** and **4** of first and second generation [22] were coupled to the TADDOL core unit **1** [1][24] by etherification (*Fig. 1*). The TADDOL cross-linkers **5**, **6**, and **7** were obtained in yields between 65 and 70% after purification by column chromatography (*Fig. 2*). As a result of laborious optimization, we found that heating a suspension of hexol **1** (1 equiv.) and the corresponding benzyl bromide (exactly 4 equiv.) in the presence of K₂CO₃ (4 equiv.) in acetone at 65° were the best conditions to reduce the amount of C₁-symmetrical by-products formed by excess coupling with a fifth branch to one of the TADDOL OH groups [1][24]. Generally, special precautions had to be taken in order to avoid spontaneous polymerization of the vinyl-substituted derivatives: crude products were immediately purified by chromatography or recrystallization, and stored in the refrigerator; only sufficiently dilute solution were heated.

In many cases in the literature, ligands to be immobilized are attached to the polymer support *via* alkyl linkers [21c][26]. A flexible and long spacer moiety reduces interactions between polymer backbone and catalytic site within the polymer, and facilitates the adoption of an optimal conformation of the catalytically active substructure. Furthermore, *Itsuno et al.* introduced the strategy of using flexible poly(ethylene glycol)-derived cross-linkers for the preparation of polystyrene resins [27][28]. The resulting materials exhibited much better swelling properties and mechanical stabilities than polystyrene resins cross-linked with a comparable amount of DVB [29][30]. Therefore, we have also prepared a TADDOL cross-linker with flexible alkyl spacer units instead of the rather rigid benzyl ether moieties of TADDOLs **5–7**. The preparation of the corresponding benzyl bromide branch **14** is presented in *Scheme 2*.

In addition to the flexible spacer moiety **14**, a rather rigid elongation unit **19** of comparable length (containing a 1,1'-biphenyl unit) was prepared (*Scheme 3*): starting

⁴⁾ TADDOL has recently been successfully immobilized also on silica by grafting [21f].

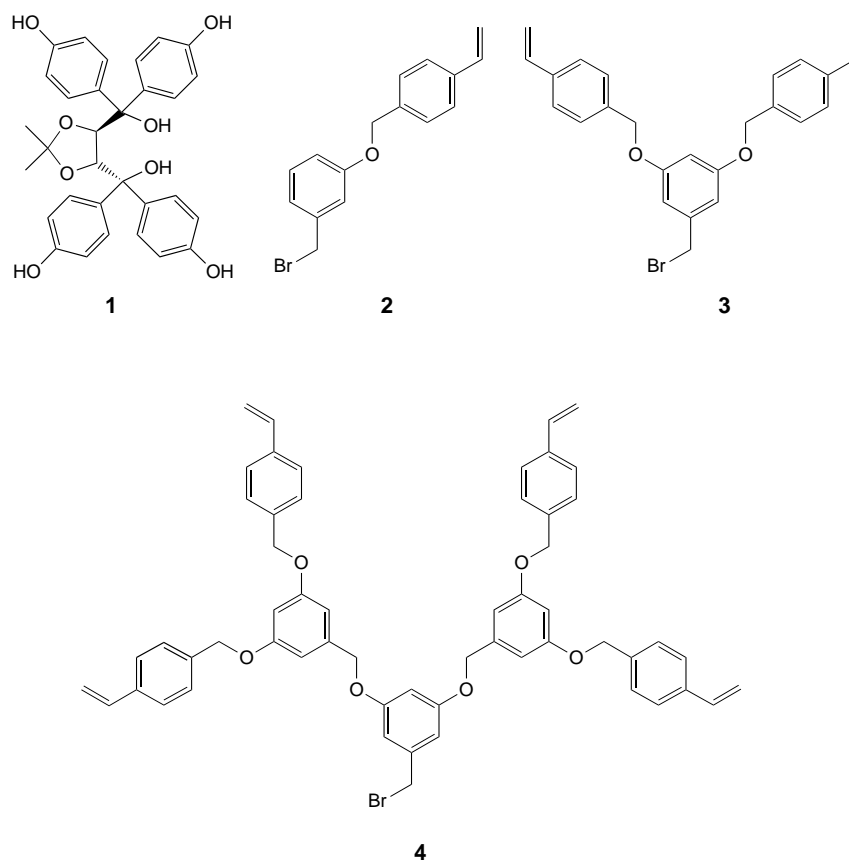


Fig. 1. TADDOL Core unit **1** [1][24] to which the spacer unit **2** [22] as well as first-generation dendritic branch **3** [22] and second-generation dendritic branch **4** [22] are coupled by etherification (K_2CO_3 , acetone, 65°)

from the 1,1'-biphenyl building block **15** [31], the bromide **19** was obtained according to standard procedures, *via* the intermediates **16**–**18** (Scheme 3)⁵⁾).

Coupling TADDOL core unit **1** with spacer units **14** and **19** under the usual conditions afforded TADDOL cross-linkers **20** and **21** (Fig. 3).

The TADDOL cross-linkers described so far carry the spacer units on the aryl moieties, while, in all previous approaches directed towards immobilization of TADDOL on polystyrene or silica, the TADDOL moieties were attached to the support *via* the acetal center [20][21]. Therefore, we decided to prepare also a TADDOL cross-linker bearing two styryl groups at the acetal center (Scheme 4). Starting from 4-vinylbenzaldehyde [20a], the ketal **24** of a benzophenone was obtained

⁵⁾ During the coupling of 4-vinylbenzyl chloride with alcohol **16** in the presence of NaH as base, migration of the silyl protecting groups occurred, so that the yield of the desired product was rather low.

⁶⁾ Br/OH Exchange **18**→**19** under Appel conditions (CBR_4/PPh_3) failed due to formation of an inseparable product mixture. However, with PBr_3 in Et_2O , the desired bromide **19** was obtained in pure form without formation of by-products, even though **18** was insoluble in Et_2O .

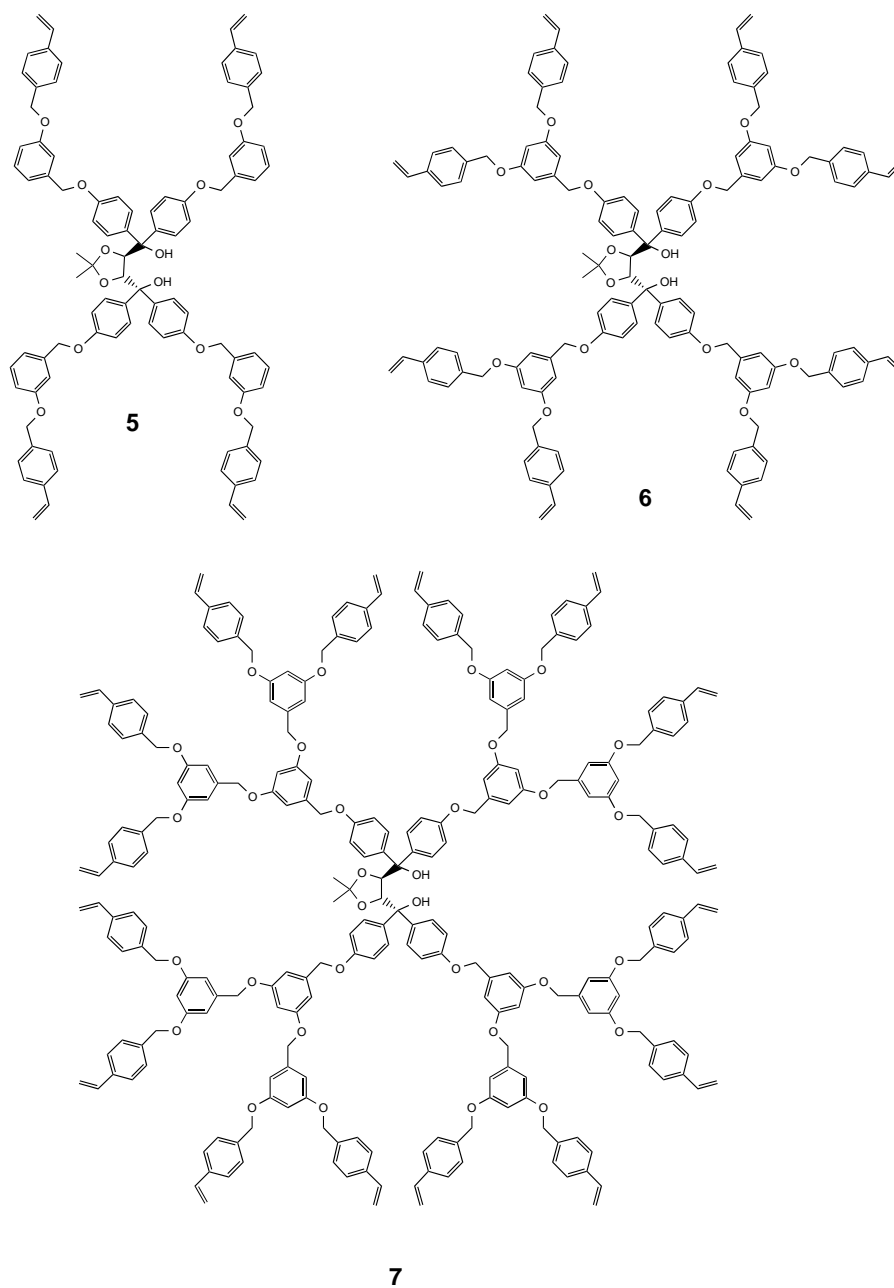
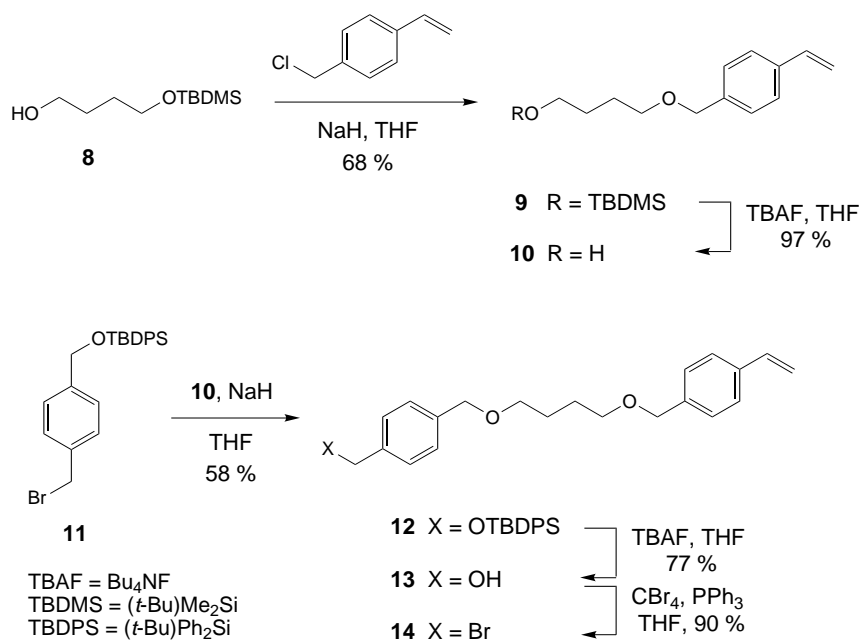
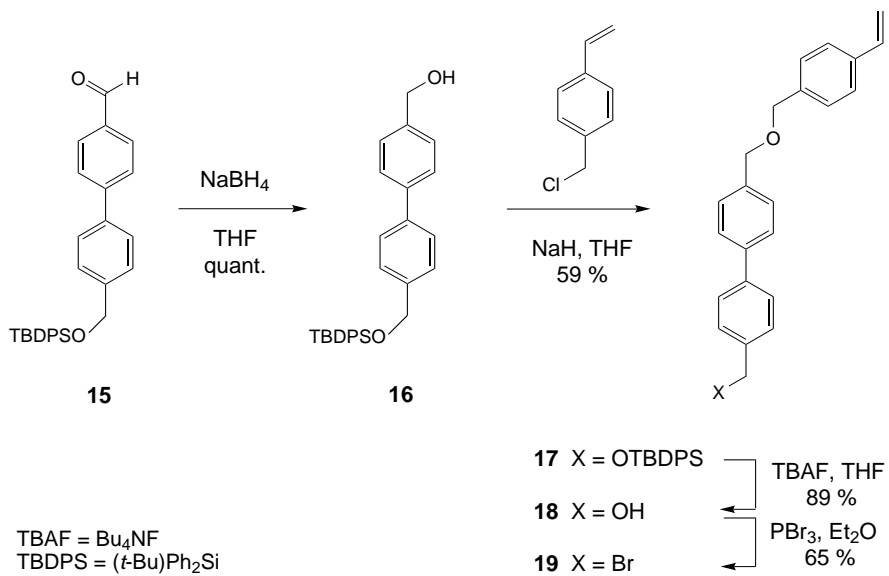


Fig. 2. TADDOL Cross-linker 5, and first- and second-generation dendritic TADDOL cross-linkers 6 and 7

Scheme 2. Preparation of the Spacer Unit **14** Starting from the Mono-silylated Butane-1,4-diol **8** via the Intermediates **9–13**Scheme 3. Preparation of the 1,1'-Biphenyl Spacer Unit **19** Starting from Aldehyde **15** [31] via the Intermediates **16–18**

in a three-step sequence. *Transacetalization* of **24** with (*R,R*)-diethyl tartrate at 0° in the presence of $\text{BF}_3 \cdot \text{OEt}_2$ afforded diester **25** (without formation of polymeric by-products), which was converted to the TADDOL derivative **26** by the addition of PhMgBr .

3. Copolymerization of Cross-Linking TADDOLs with Styrene. – TADDOL Cross-linkers **5–7**, **20**, **21**, and **26** were copolymerized with styrene, according to a procedure first proposed by *Itsuno, Fréchet*, and co-workers [29]. Thus, a solution of the cross-linking TADDOL, styrene, and α, α' -azobis(isobutyronitrile) (AIBN) in benzene/THF was mixed with an aqueous phase containing poly(vinyl alcohol) (PVA) and heated with constant slow overhead stirring for 48 h at 90° (*Scheme 5, a*). During this process, spherical beads (average diameter of 400 μm) of polystyrene with incorporated

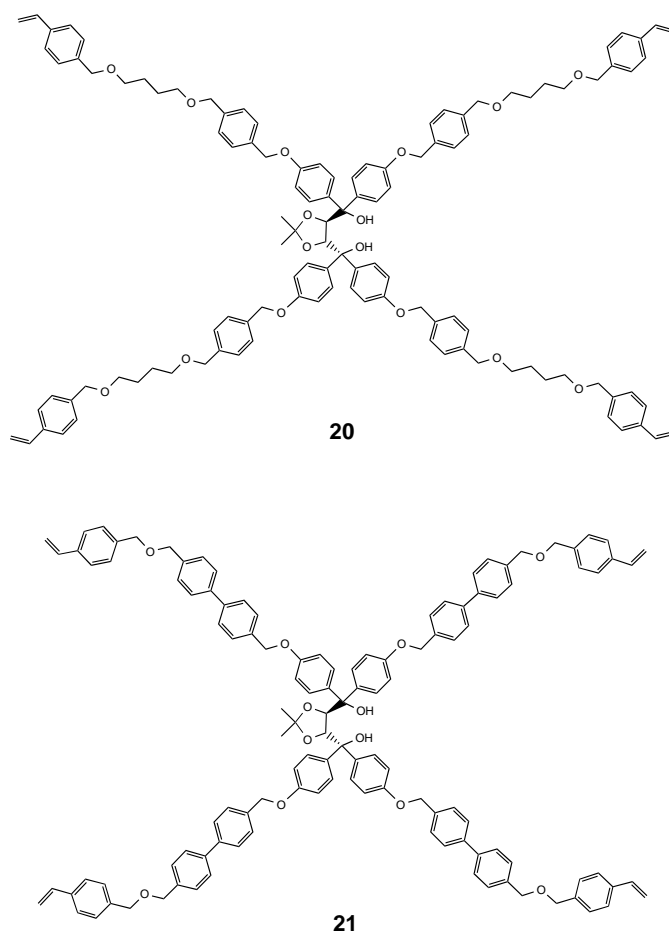
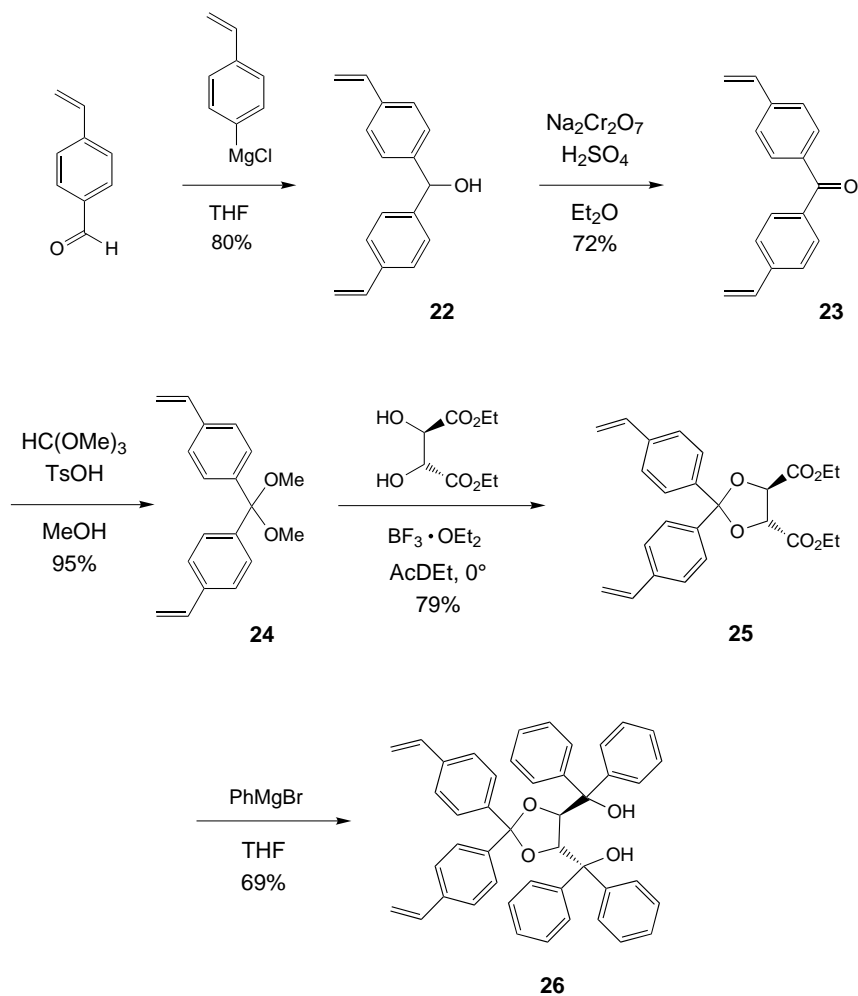


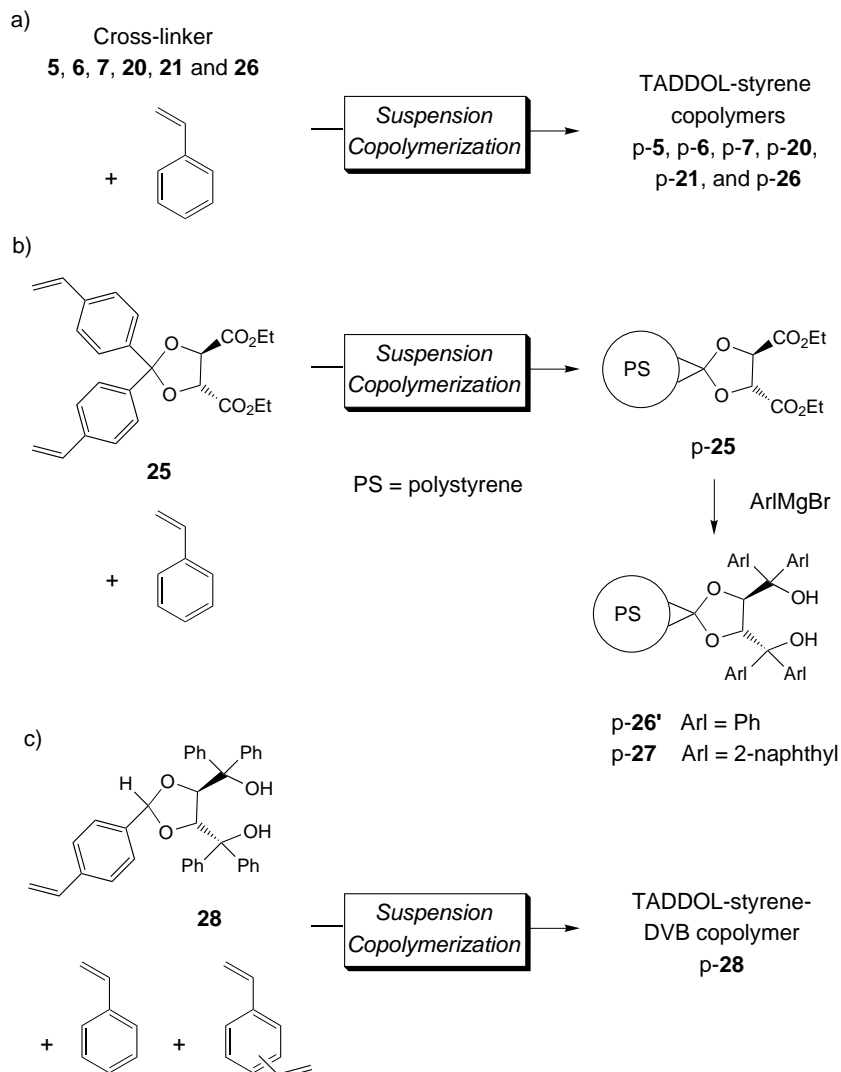
Fig. 3. TADDOL Cross-linkers **20** and **21**, prepared from the TADDOL core unit **1**, and the spacer units **14** and **19**, respectively

Scheme 4. Preparation of TADDOL **26** via the Intermediates **22**–**25**

TADDOLs were formed. The beads were isolated by filtering, washing, and drying, and then collected by size with a set of sieves. Usually, the yield of the polymers was quantitative so that the loading could be directly calculated from the relative amounts of comonomers used (mmol TADDOL per g polymer).

In addition to copolymerizing preformed TADDOL derivatives with styrene (*Scheme 5,a*) we attempted to generate polymer-bound TADDOL by solid-phase synthesis (*Scheme 5,b*). For practical reasons, this might have been an attractive alternative route, through a precursor that could be transformed (on the polymer) to a variety of different polymer-bound TADDOL ligands. Thus, the diester **25** was copolymerized with styrene to give polystyrene-bound diester p-**25**, which was then treated with two different aromatic *Grignard* reagents to give the corresponding

Scheme 5. Immobilization of TADDOL a) by Copolymerization of Cross-Linking TADDOLs **5–7**, **20**, **21**, and **26** with Styrene, b) by Copolymerization of the Diester **25** with Styrene, Followed by Grignard Addition, and c) by Copolymerization of TADDOL **28** with Styrene and DVB. Conditions for suspension copolymerization: benzene, THF/H₂O, PVA; AIBN, 90°, 48 h.



polymer-bound TADDOLs p-26' (the 'prime' is added in order to emphasize that p-26' was prepared in a way different from that leading to p-26) and p-27 (Scheme 5, b)⁷). In line with observations by Mayoral and co-workers and Irrure *et al.* [21a–d], who had

7) IR Spectroscopy of a sample of beads of p-26' showed that the signal of the C=O ester group at $\nu = 1735 \text{ cm}^{-1}$ had completely disappeared, indicating formation of the desired TADDOL moieties.

tried to generate polymer-bound TADDOLs by a comparable approach, it turned out to be difficult to remove the magnesium salts after the reaction.

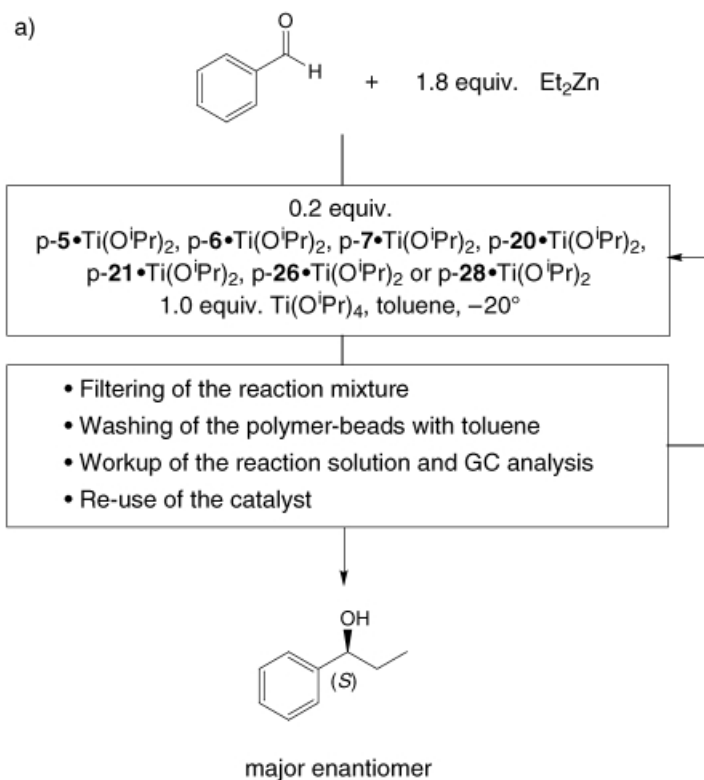
The best method was to first remove excess *Grignard* reagent by extensive washing of the beads with THF, followed by stirring in a mixture of THF/1N HCl.

To compare the results achieved with polymers prepared with cross-linking TADDOLs (following the approaches outlined in *Scheme 5, a* and *b*) with existing polymer-bound versions of this ligand, polymer **p-28** was prepared by copolymerization with styrene and DVB of the mono-vinyl derivative **28** of TADDOL, according to a procedure developed previously in our group (*Scheme 5, c*) [20].

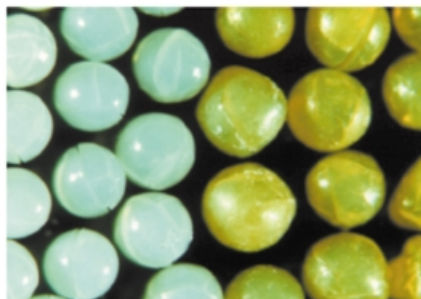
4. Application of Polymer-Bound Ti-TADDOLate Complexes in Enantioselective Additions of Et₂Zn and Bu₂Zn to PhCHO. – The addition of Et₂Zn to PhCHO catalyzed by (iPrO)₂Ti-TADDOLate complexes offers several advantages, making it an attractive test reaction for polymer-bound TADDOLs. Besides high enantioselectivities, with which 1-phenylpropan-1-ol is formed (up to 99%), and high conversions that are generally observed under homogeneous conditions [32], the analysis is simple and can be performed by capillary gas chromatography (CGC). Therefore, this reaction allows for a fast interpretation of catalytic properties. Very importantly, the Ti-TADDOLate-mediated addition of Et₂Zn to PhCHO shows a linear correlation between the enantiomer purity of the TADDOL employed and that of the alcohol formed [32], indicating that the catalytically active species is monomeric, in contrast to reactions with a so-called ‘nonlinear effect’ (NLE) that are very likely to proceed *via* nonmonomeric catalyst complexes [33]; of course such reactions are not promising candidates for being tested with a polymer-bound catalyst, since aggregation of catalytic moieties is (usually) prevented in or on a polymer, due to site isolation.

The reactions were generally performed in the presence of 0.2 equiv. of supported Ti-TADDOLate catalyst (*Scheme 6, a*). The desired amount (0.2 equiv.) of polymer-bound TADDOL **p-5**–**p-7**, **p-20**, **p-21**, **p-26**, or **p-28** was suspended in toluene, followed by evaporation of the solvent under high vacuum to remove traces of H₂O. The beads were resuspended in toluene, and an equimolar amount of Ti(OⁱPr)₄ (0.2 equiv.) was added for loading of the beads with titanate. The beads thereby adopted a yellow color (*Scheme 6, b* and *c*). After stirring at room temperature for 14 h, the solvent was evaporated under reduced pressure for removal of *i*-PrOH. The polymer-bound Ti-TADDOLates **p-5**·Ti(OⁱPr)₂–**p-7**·Ti(OⁱPr)₂, **p-20**·Ti(OⁱPr)₂, **p-21**·Ti(OⁱPr)₂, **p-26**·Ti(OⁱPr)₂ or **p-28**·Ti(OⁱPr)₂ were resuspended in toluene, Ti(OⁱPr)₄ (1 equiv.) as well as PhCHO (1 equiv.) were added, and the reaction mixture was cooled to –20°, followed by addition of a 2M solution of Et₂Zn (1.8 equiv.) in toluene under Ar. After 2 h, the solvent was removed by syringe, preventing contact of the polymer-bound Ti-TADDOLates with air. The beads were washed several times with toluene, the combined organic fractions were extracted with 1M aqueous HCl, and the products were isolated from the organic phases. The conversions and enantioselectivities were determined by GC on a chiral column with the crude products. The polymer beads were dried, resuspended in the reaction solvent, and recharged with substrates for a new run (*Scheme 6, a*). The conversions and enantioselectivities observed in the Et₂Zn-to-PhCHO addition with polymer-bound Ti-TADDOLates

Scheme 6. a) Multiple Use of Polymer-Bound Ti-TADDOLates in the Addition of Et_2Zn to PhCHO . b) Polymer Beads of **p-6** (diameter ca. 400 μm) before (colorless) and after Loading with Titanate (yellow). c) Two Round-Bottomed Flasks Containing a Suspension of Beads of **p-6** Swollen in Toluene before (colorless) and after Loading with Titanate (yellow).



b)



c)



p-5· $\text{Ti}(\text{O}^i\text{Pr})_2$ –**p-7**· $\text{Ti}(\text{O}^i\text{Pr})_2$, **p-20**· $\text{Ti}(\text{O}^i\text{Pr})_2$, **p-21**· $\text{Ti}(\text{O}^i\text{Pr})_2$, **p-26**· $\text{Ti}(\text{O}^i\text{Pr})_2$, or **p-28**· $\text{Ti}(\text{O}^i\text{Pr})_2$ are listed in *Table 1*.

In most cases the enantiomer ratios and conversions observed with these polymer-bound *Lewis* acids were similar to those observed with *Ti-TADDOLate* complexes

Table 1. Conversions and Enantiomer Ratios in the Formation of 1-Phenylpropan-1-ol by Addition of Et₂Zn to PhCHO, Catalyzed by Polymer-Bound Ti-TADDOLates. If not stated otherwise, 20 mol-% of supported catalyst was employed.

Polymer	Loading [mmol g ⁻¹]	Conversion [%]	(S)/(R)
p- 5 · Ti(O ⁱ Pr) ₂	0.25	84	97:3
	0.10	97	98:2
p- 6 · Ti(O ⁱ Pr) ₂	0.10 ^{a)}	54	91:9
	0.10 ^{b)}	71	95:5
	0.25	78	97:3
	0.14	92	97:3
	0.10	99	98:2
p- 7 · Ti(O ⁱ Pr) ₂	0.14	78 ^{c)}	89:11
	0.11	quant. ^{c)}	93:7
p- 20 · Ti(O ⁱ Pr) ₂	0.25	76	98:2
	0.10	76 ^{d)}	98:2
p- 21 · Ti(O ⁱ Pr) ₂	0.25	60	94:6
	0.10	70 ^{d)}	99:1
p- 26 · Ti(O ⁱ Pr) ₂	0.21	quant.	97:3
p- 28 · Ti(O ⁱ Pr) ₂	0.10	99	98:2

^{a)} 2 mol-% of catalyst are used. ^{b)} 5 mol-% of catalyst are used. ^{c)} Reaction time 14 h. ^{d)} [PhCHO] = 0.05M.

under homogeneous conditions (thus, with Ti-TADDOLate **28** · Ti(OⁱPr)₂ in solution: (S)- and (R)-1-phenylpropan-1-ol were obtained in a 99:1 ratio, with complete conversion after 2 h). Importantly, polymers p-**5** · Ti(OⁱPr)₂–p-**7** · Ti(OⁱPr)₂, p-**20** · Ti(OⁱPr)₂, p-**21** · Ti(OⁱPr)₂, and p-**26** · Ti(OⁱPr)₂, prepared by copolymerization of cross-linking TADDOLs with styrene by novel approach led, in most cases, to similar results as those obtained with DVB-cross-linked polymer p-**28** · Ti(OⁱPr)₂ [20] (*cf. Scheme 5,c and Table 1*). Generally, the catalytic performance of the polymer-supported TADDOLates with respect to conversion and enantioselectivity increased with decreasing loading (*e.g.*, results with polymer p-**6** · Ti(OⁱPr)₂ in *Table 1*). This can be rationalized by the fact that, with our polymers, a lower degree of loading corresponds to a lower degree of cross-linking, and that the accessibility of the catalytic sites is better in the case of less highly cross-linked polymer resins. In the same context, the lower enantioselectivities observed with p-**7** · Ti(OⁱPr)₂ (of degrees of loading similar to the other polymers) can be interpreted as resulting from the high degree of cross-linking achieved with the second-generation TADDOL cross-linker **7** bearing as many as 16 peripheral styryl groups. Interestingly, also polymer p-**26** · Ti(OⁱPr)₂ leads to very good results although two polystyrene chains are interconnected at the TADDOL acetal center, close to the metal-bonding site.

As mentioned in the *Introduction*, one aim of employing heterogeneous catalysts is to re-use them as often as possible in consecutive catalytic runs with as little as possible loss of activity in order to justify the synthetic effort of their preparation (first the synthesis of suitable monomers and then the copolymerization). Therefore, we have set the main focus of our investigations on this issue. Polymers p-**6** · Ti(OⁱPr)₂, cross-linked with first-generation TADDOL dendrimer **6** with three different degrees of loading were re-used in 20 consecutive runs for the addition of Et₂Zn to PhCHO, according to the protocol outlined in *Scheme 6*. As can be seen from *Fig. 4,a*, the polymer with a

loading of 0.10 mmol g^{-1} gave rise to a stable performance without any loss in enantioselectivity over 20 cycles. When increasing the loading ($\rightarrow 0.14 \text{ mmol g}^{-1} \rightarrow 0.25 \text{ mmol g}^{-1}$), a slight decrease of the enantiomer purity of the product alcohol was encountered during recycling. The enantiomer purities of 1-phenylpropan-1-ol obtained with polymers $\text{p-5} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, $\text{p-20} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, $\text{p-21} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, and $\text{p-28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ with a degree of loading of 0.10 mmol g^{-1} are presented in Fig. 4, b. Whereas $\text{p-5} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and $\text{p-28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ gave rise to stable enantioselectivities during recycling, comparable to $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, polymers $\text{p-20} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ (containing TADDOL cross-linker **20** with flexible alkyl spacers) and $\text{p-21} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ (containing TADDOL cross-linker **21** with rigid 1,1'-biphenyl spacers) showed an erratic and

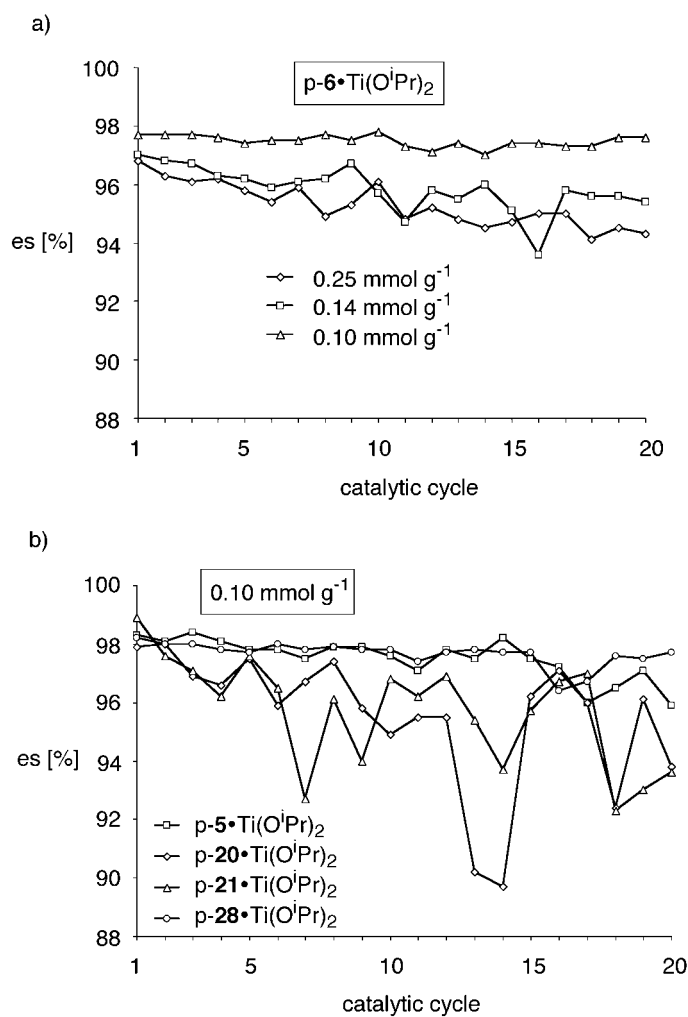


Fig. 4. Enantioselectivities for the formation of 1-phenylpropan-1-ol during recycling of a) polymer $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ with different degrees of loading and of b) polymers $\text{p-5} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, $\text{p-20} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, $\text{p-21} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and $\text{p-28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ with degrees of loading of 0.10 mmol g^{-1}

unstable performance accompanied by an overall loss of the enantioselectivity with which 1-phenylpropan-1-ol was formed during multiple use.

Besides maintaining a constant enantioselectivity, polymer-bound catalysts should also be recyclable with no or only minor loss in reaction rate. The kinetics of the Et_2Zn to PhCHO additions can be easily followed by GC analysis of samples taken from the reaction mixture. Some representative examples of reaction kinetics during recycling, measured with different polymers of 0.10 mmol g^{-1} loading, are presented in Fig. 5. Besides a constant performance with respect to enantioselectivity (cf. Fig. 4, a) polymer p-6 · $\text{Ti}(\text{O}^i\text{Pr})_2$, cross-linked with first-generation TADDOL dendrimer **6**, also gave rise to very stable reaction rates during recycling (Fig. 5, a). Within experimental error, the reaction rate in the 20th run is identical to the one in the first run (!). All polymers p-5 · $\text{Ti}(\text{O}^i\text{Pr})_2$, p-20 · $\text{Ti}(\text{O}^i\text{Pr})_2$, and p-21 · $\text{Ti}(\text{O}^i\text{Pr})_2$, prepared with nondendritic TADDOL cross-linkers, showed a decline in reaction kinetics during multiple use. The reaction rates measured with p-20 · $\text{Ti}(\text{O}^i\text{Pr})_2$ constitute a representative example (Fig. 5, b): with each recycling step, the conversion dropped step by step. The decline of the reaction kinetics during re-use was even more pronounced, when we increased the degree of loading of the polymers: the polymer pores get blocked more easily with increasing degrees of cross-linking, thus leading to a faster decline in catalytic activity (of both reaction rate and enantioselectivity, cf. Fig. 4, a). DVB-Cross-linked polymer p-28 · $\text{Ti}(\text{O}^i\text{Pr})_2$ had given rise to a constant performance with respect to enantioselectivity during recycling (cf. Fig. 4, b), like p-6 · $\text{Ti}(\text{O}^i\text{Pr})_2$. In contrast, however, the reaction rates gradually dropped (Fig. 5, c), in pronounced contrast to polymer p-6 · $\text{Ti}(\text{O}^i\text{Pr})_2$ (Fig. 5, a). This means that only with dendritically cross-linked polymer p-6 · $\text{Ti}(\text{O}^i\text{Pr})_2$ can a constant performance with respect to enantioselectivity *and* reaction rate be achieved. All other polymers investigated gave rise to a decline of the catalytic properties during recycling.

What might be the origin of the excellent stability of the dendritically cross-linked p-6 · $\text{Ti}(\text{O}^i\text{Pr})_2$ in contrast to the other polymers? The majority of catalytic sites are located in the interior of the polymer beads. Therefore, swelling of the polymer resin in the reaction solvent is indispensable to allow access to the catalytic centers throughout the polymer network. Thereby, the polymer chains move apart, and the reactants are allowed to penetrate into the resin. To guarantee a long-term stability of a polymer-bound catalyst, the swelling properties of the polymer have to remain unchanged during recycling. We decided to measure swelling factors of our polymers in the reaction solvent toluene prior to and after 20 recycling steps. The results are presented in Fig. 6. It is obvious that, only in the case of dendritically cross-linked p-6, is a constant swelling behavior encountered: although the original swelling factor (ca. 2.5 in toluene) is the lowest of all polymers tested it remains unchanged during 20 recycling steps (!). The swelling factors of all other polymers decline, which results in restricted diffusion of substrates into the polymer resin; this explains the loss of catalytic activity of these polymers during re-use. Especially polymer p-20 · $\text{Ti}(\text{O}^i\text{Pr})_2$, containing TADDOL cross-linker **20** with flexible alkyl spacers, underwent a most drastic loss in swelling ability after 20 runs (from a factor of 4.0 to 1.7), so that only a fraction of catalytic sites might still have been accessible for substrates, which accounts for the pronounced decline in activity (cf. Fig. 4, b, and Fig. 5, b). It appears that the use of the first-generation dendritic TADDOL cross-linker **6** leads to a polymer p-6 with a

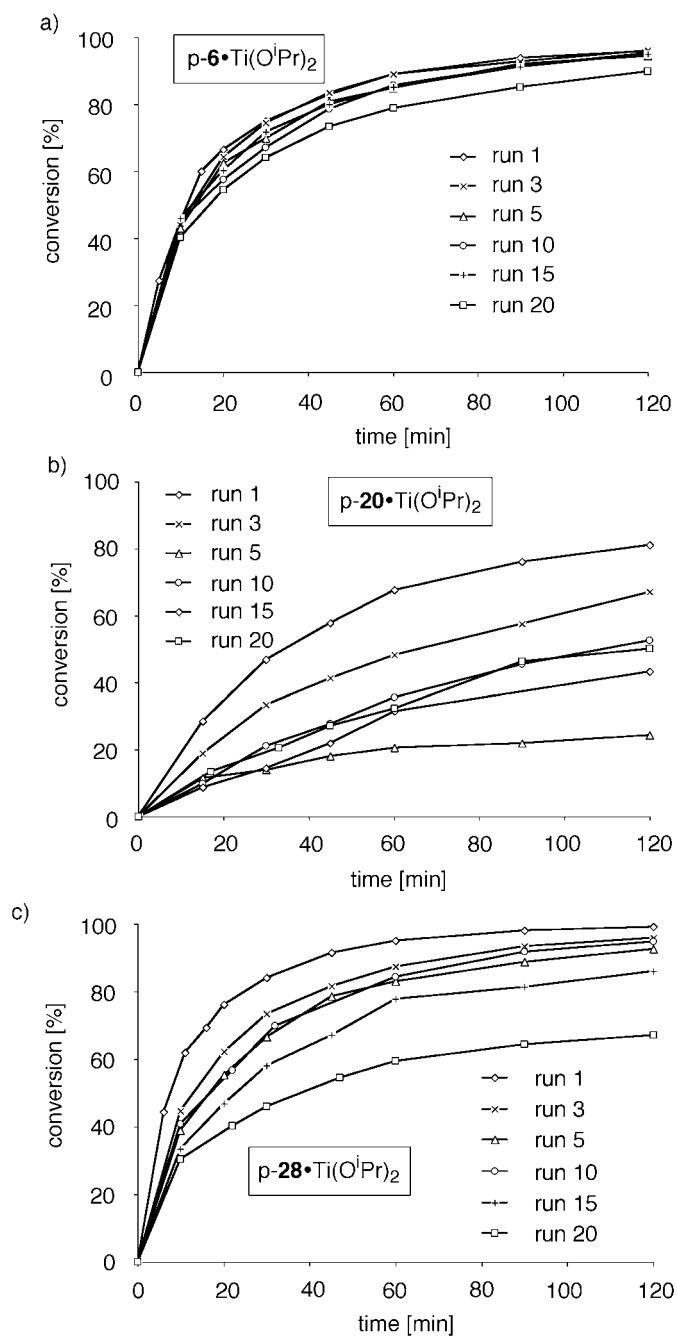


Fig. 5. Reaction kinetics during recycling of polymer a) $p-6 \cdot Ti(OiPr)_2$ b), $p-20 \cdot Ti(OiPr)_2$, and c) $p-28 \cdot Ti(OiPr)_2$ with degrees of loading of 0.10 mmol g^{-1}

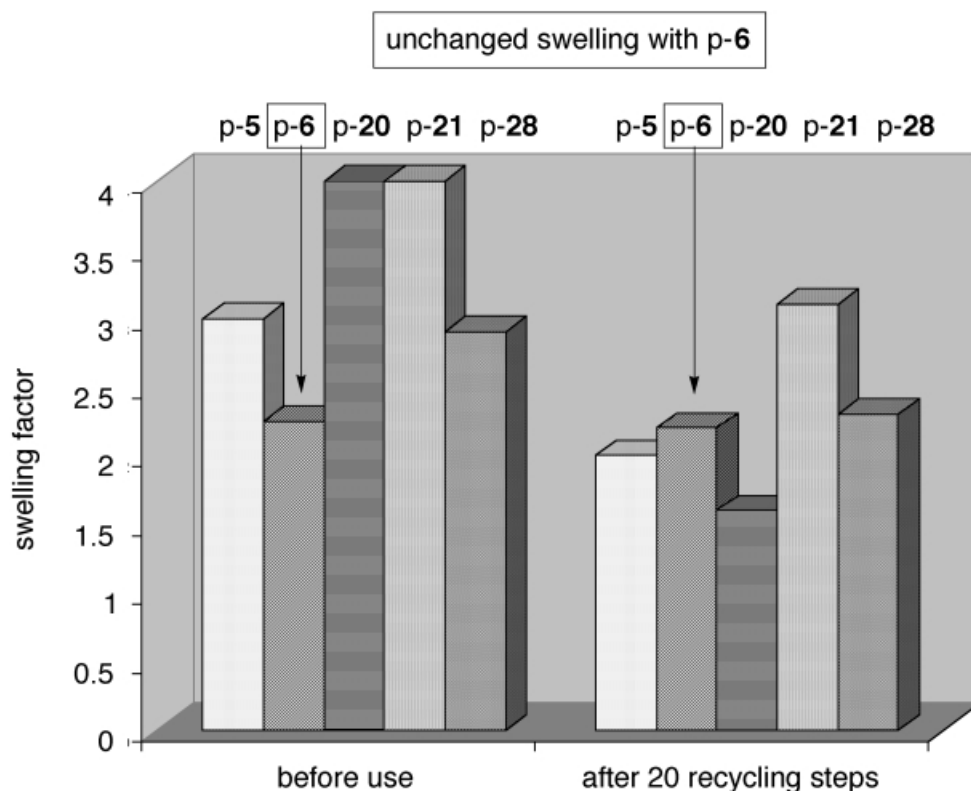


Fig. 6. Swelling factors in toluene of different polymers prior to use and after 20 recycling steps in the addition of Et_2Zn to PhCHO

very persistent and stable morphology, which explains its superior catalytic performance.

To learn more about the factors that influence the reaction kinetics observed with $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ several additional experiments were performed (Fig. 7): *i*) It was shown that the reaction rate depends on the degree of loading of the polymers: the higher loaded (and, therefore, also the higher cross-linked) the polymer, the slower the rate (Fig. 7,a), due to restricted diffusion of substrates. *ii*) A quantity of smaller beads has a larger surface area than the same mass of larger beads, so that the total area for diffusion of substrates into the polymer beads is larger when using smaller beads; if the diffusion of substrates into the polymer is rate-limiting, the reaction rate is expected to be faster with smaller beads; this was actually the case with polymer beads of $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$: beads with a diameter of *ca.* 400 μm gave rise to a faster reaction rate than beads with a diameter of *ca.* 800 μm (Fig. 7,b) with the same degree of loading of 0.10 mmol g^{-1} . *iii*) Stirring the reaction mixture with different rpm did not have any influence on the kinetics: an unstirred suspension gave the same reaction rate as that stirred at 600 rpm (Fig. 7,c); this offers, of course, the possibility to perform the reactions without stirring, so that abrasion of the beads is avoided.

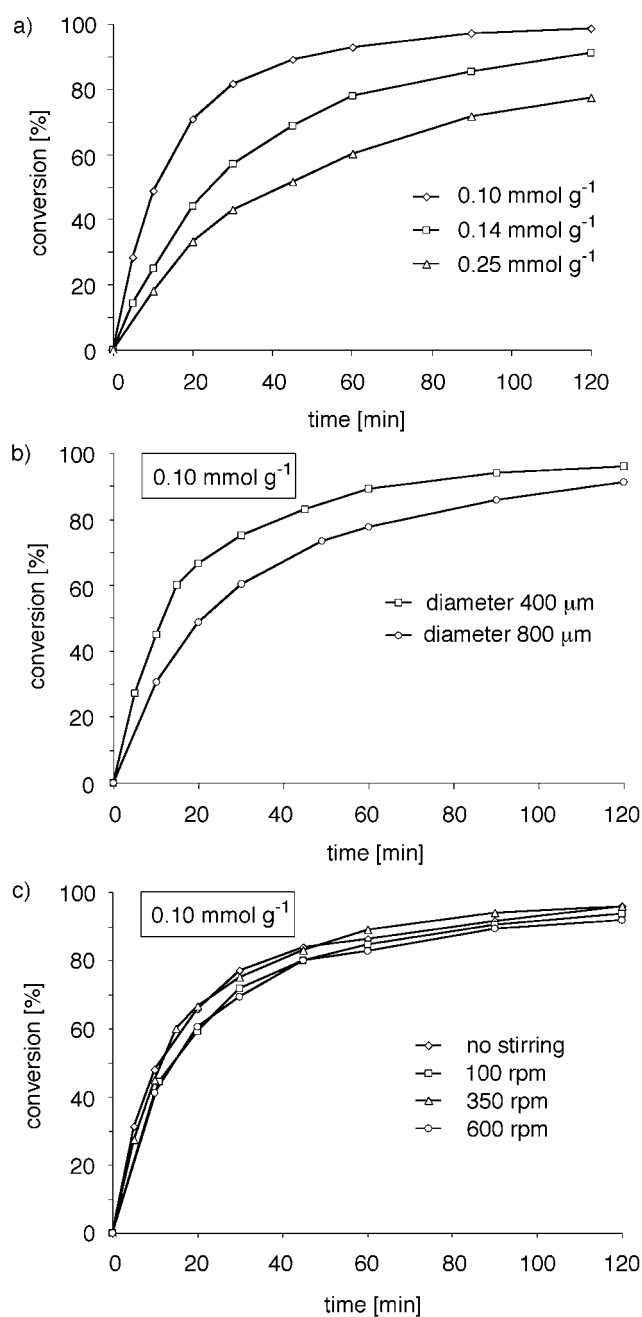


Fig. 7. Dependence of the reaction kinetics with polymer $p\text{-6}\cdot\text{Ti}(\text{O}^i\text{Pr})_2$ on a) the degree of loading, b) the diameter of the polymer beads, and c) the stirring speed of the reaction mixture

Usually, the rate of a catalytic reaction in solution is expected to be faster than the corresponding rate measured with a polymer-bound catalyst, due to hindered diffusion of the substrates to the catalytic centers within the polymer. This was indeed found when we compared the reaction rates caused by DVB-cross-linked polymer $p\text{-}\mathbf{28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ with those observed when we used the corresponding monomer $\mathbf{28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ under homogeneous conditions (Fig. 8,a). However, when comparing the kinetics of the dendrimer complex $\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ in solution and the dendritically cross-linked polymer $p\text{-}\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ under heterogeneous conditions, the opposite was the case: the reaction rate measured with the polymer-bound catalyst was *faster* than that under homogeneous conditions (!) (Fig. 8,b), a result that was reproduced several times.

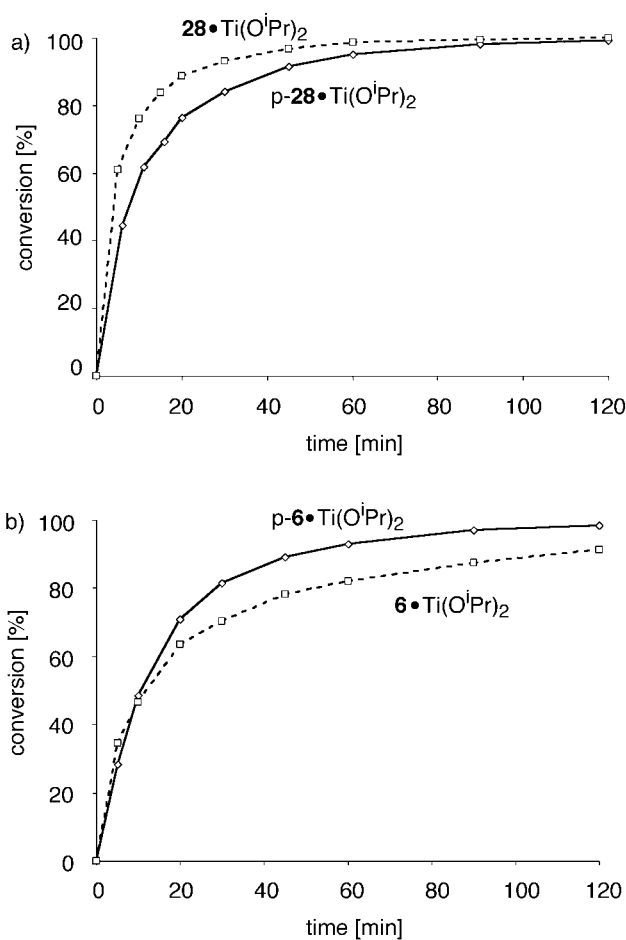


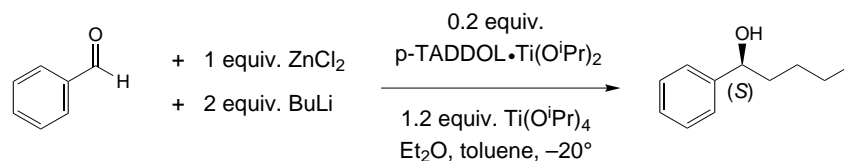
Fig. 8. Comparison of the reaction kinetics under homogeneous and heterogeneous conditions: a) $\mathbf{28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and $p\text{-}\mathbf{28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$; b) $\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and $p\text{-}\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$

One interpretation of this phenomenon might be that, in solution, the dendritic arms of complex $\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ are wrapped around the TADDOL core, thus hindering access of substrates to the catalytic center. When these arms are ‘fixed’ in the polymerization process, they are immobilized away from the TADDOL moiety, and a better diffusion of reactants to and from the catalytic centers, although now located within a polymer resin, is provided. A second possible explanation is based on the principle of ‘molecular imprinting’ [16][17]. TADDOL Cross-linker $\mathbf{6}$ is chiral (C_2 symmetry), so that, in the copolymerization with styrene, chiral cavities within the polymer matrix are likely to be generated. In an enzyme-like way, such chiral cavities around the catalytic centers could reinforce the catalytic activity. In contrast, polymer p-28 , generated with achiral DVB as cross-linker, would contain an achiral polymer backbone. Finally, the catalytic centers in $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ are located in a more polar environment within the apolar polystyrene matrix due to the ‘oxygen-rich’ dendritic benzyl ether branches surrounding the TADDOL cores; this could lead to an accumulation of the polar substrates (PhCHO , Et_2Zn and $\text{Ti}(\text{O}^i\text{Pr})_4$) in these regions, leading to higher local concentrations and, therefore, a higher reaction rate. This is not the case with polymer $\text{p-28} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and may serve as a third rationale supporting a higher reaction rate with polymer $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ (under heterogeneous conditions), as compared to the monomer $\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ (under homogeneous conditions). Elemental analysis of a sample of $\text{p-6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ indicated that 85% of the TADDOL sites are complexed with Ti. In contrast, all dendritic TADDOL ligands $\mathbf{6}$ must be complexed with Ti-atom under homogeneous conditions. Due to these facts, and since the performance of the polymer-bound catalyst is higher than that of its soluble analogue, the intrinsic activity of each TADDOLate moiety of the polymer-bound catalyst must be higher than that of the soluble analogue (!).

As already mentioned, one aim of our work was to check whether catalytically active TADDOL ligands could be generated by copolymerization of diester $\mathbf{25}$ followed by *Grignard* addition (*cf. Scheme 5, b*). The Ti-TADDOLate-mediated addition of Bu_2Zn to PhCHO was chosen as test reaction for polymers $\text{p-26} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ and $\text{p-27} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ [34] (*Table 2*). The reactions were performed in analogy to the addition of Et_2Zn to PhCHO . The Bu_2Zn was prepared *in situ* by mixing BuLi (solution in hexane) with ZnCl_2 (solution in Et_2O) in toluene and removing LiCl with a syringe filter, prior to addition to the reaction mixture. For comparison, $\text{p-26} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$, prepared by copolymerization of TADDOL $\mathbf{26}$ with styrene, followed by loading with titanate, was also tested in this reaction. It turned out that this polymer gave rise to the highest catalytic activity. The enantiomer purity of 1-phenylpentan-1-ol was only slightly lower than that observed in solution under identical conditions (99% *es* [34]). Although the enantioselectivity achieved with $\text{p-26} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ was only 2% lower, the reaction was markedly slower. It was not possible, as in the case of the addition of Et_2Zn to PhCHO , to simply recycle the polymers by washing and reloading with substrates. The polymer-bound Ti-TADDOLate complexes had to be hydrolyzed with $\text{THF}/1\text{N HCl}$, followed by reloading with titanate, prior to each catalytic run. Probably, the reaction of BuLi with ZnCl_2 was not complete, and these reagents caused inactivation of the polymer-bound Ti complex. Polymer $\text{p-26} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$ was used in two additional runs, resulting in a decline in conversion, but not in enantioselectivity, within experimental error (*Table 2*). When the test reaction was performed with

polymer p-**27**·Ti(OⁱPr)₂, bearing naphthalen-2-yl groups at the TADDOL units, 1-phenylpentan-1-ol was obtained with a lower enantiomer purity in comparison to p-**26'**·Ti(OⁱPr)₂, whereas, in solution, the analogous tetra(naphthalene-2-yl)-TADDOL gave rise to higher selectivities than the corresponding tetraphenyl-TADDOL [34b]. This may mean that only a fraction of the available diester moieties has reacted with the *Grignard* reagent to give polymer-bound TADDOL units. The catalyst was re-used once more, resulting in a better selectivity but poorer conversion (Table 2). In summary, catalytically active TADDOLate complexes can be obtained by this approach. However, the performance of these catalysts is poorer than that of the corresponding TADDOLates prepared by copolymerization of preformed TADDOL ligands with styrene.

Table 2. Addition of Bu₂Zn to PhCHO Catalyzed by Polymer-Bound Ti-TADDOLates. Polymer p-**26** was prepared by copolymerization of preformed TADDOL derivative **26** with styrene, whereas p-**26'** and p-**27** were prepared by copolymerization of diester **25** with styrene, followed by *Grignard* addition (cf. Scheme 5, b).



p-TADDOL (aryl group)	Catalytic cycle	Conversion [%] (reaction time)	(S)/(R)
p- 26 ·Ti(O ⁱ Pr) ₂ (Ph)		68 (4 h)	96:4
p- 26' ·Ti(O ⁱ Pr) ₂ (Ph)	1	67 (5 d)	94:6
	2	61 (5 d)	95:5
	3	43 (4 d)	94:6
p- 27 ·Ti(O ⁱ Pr) ₂	1	70 (14 h)	89:11
	2	40 (5 d)	93:7

5. Application of Polymer-Bound Ti-TADDOLate Complexes in Enantioselective 1,3-Dipolar Cycloadditions of Diphenyl Nitron to [(E)-But-2-enoyl]-oxazolidinone. – By the work presented in the previous section, it was demonstrated that copolymerization of a dendritically surrounded TADDOL **6** with styrene affords a polymeric reagent p-**6**, which, when loaded with titanate and employed in the enantioselective addition of Et₂Zn to PhCHO, gives rise to an unprecedented catalytic activity.

To demonstrate the usefulness of our dendritically cross-linked catalyst p-**6**, we decided to perform 1,3-dipolar cycloadditions as another test reaction. *Jørgensen* and co-workers had successfully employed Ti-TADDOLates for the catalysis of such reactions [35]. It had already been shown in our group that polymer-bound TADDOLates of the type p-**28**·Ti(OⁱPr)₂ can be used for the catalysis of the addition of diphenyl nitron to [(E)-but-2-enoyl]-oxazolidinone (Fig. 9), giving rise to similar selectivities as in solution [20a]. Due to these results and to the fact that a linear correlation was found between the enantiomer purities of the *exo*-cycloadducts **29** and those of the TADDOLate employed, a transition state involving a single catalyst moiety was proposed [20a].

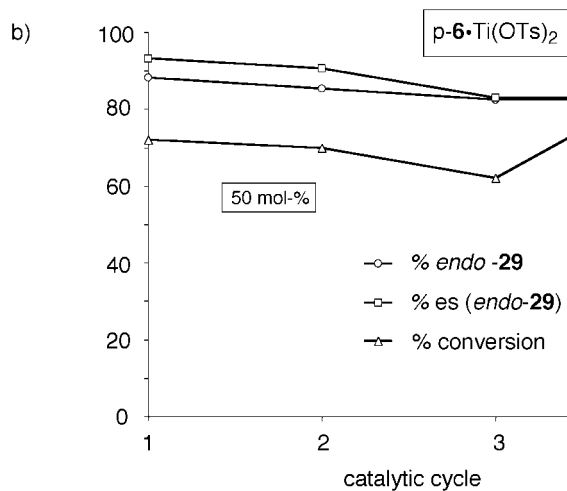
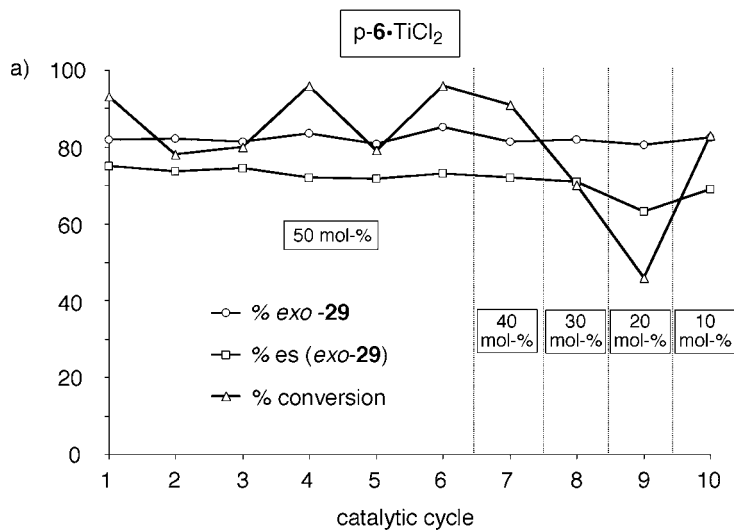
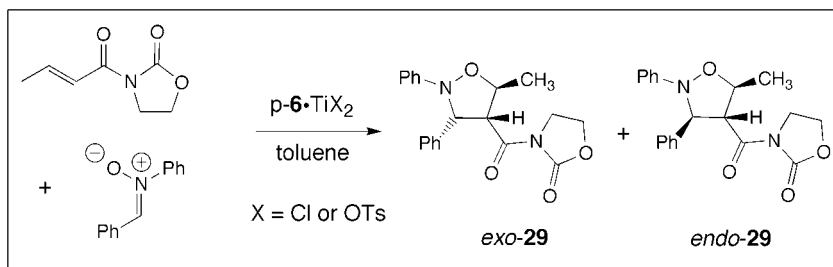


Fig. 9. Reuse of polymers a) $p\text{-}6\cdot\text{TiCl}_2$ or b) $p\text{-}6\cdot\text{Ti}(\text{OTs})_2$ in the 1,3-dipolar cycloaddition of diphenyl nitrene to [(E)-but-2-enyl]-oxazolidinone

Polymer p-6 was loaded with titanate by the addition of a solution of $\text{TiCl}_2(\text{O}^i\text{Pr})_2$ in toluene [36] to the polymer beads suspended in toluene. A solution of diphenyl nitron and [(*E*)-but-2-enoyl]-oxazolidinone in toluene was added, and the mixture was worked up after a reaction time of 40 h at 0°. The cycloadducts were isolated, and the conversion, the *exo/endo* selectivity, as well as the enantiomer ratio of *exo*-29 were determined as described in [35a]. It turned out that high conversions could only be achieved when 50 mol-% of polymer p-6·TiCl₂ were used, whereas the reaction in solution proceeded well in the presence of 10 mol-% of catalyst [20a][35a]. With 50 mol-% of p-6·TiCl₂, the *exo/endo* selectivity (82 : 18), the enantiomer purity of *exo*-29 (75%), and the conversion (93%) were only slightly lower than in solution with 10 mol-% of tetraphenyl-TADDOLate (*exo/endo*(29) 90 : 10, *es*(*exo*-29) 79%, conversion 94% [35a]). Re-using the beads by simply washing (as in the addition of Et₂Zn to PhCHO) was not possible: the subsequent reaction proceeded very slowly and nonselectively. The polymer-bound complexes had to be hydrolyzed by stirring the beads in THF/1N HCl, followed by reloading with titanate. With this protocol, p-6·TiCl₂ was reused six times without decline of the *exo/endo* ratio and of the enantioselectivity. The conversions were between 80 and 96% in all cases (Fig. 9, a).

The following catalytic cycles were performed by steadily decreasing the amount of catalyst by 10 mol-% from one run to the next. As can be seen from Fig. 9, a, the *exo/endo* selectivity and the enantioselectivity remained on a constant level, within experimental error, whereas the conversion in the runs with 30 and 20 mol-% of catalyst decreased. However, the catalytic activity with respect to conversion could be fully re-installed by subjecting the beads to a thorough hydrolysis procedure, prior to run 10. These results indicate that the ‘quality’ of the polymer-bound catalyst has steadily increased during recycling: after a couple of runs in the presence of a larger amount of p-6·TiCl₂, it is possible to perform the cycloaddition with only 10 mol-% of catalyst, which was not possible in the beginning. A very similar observation was made by A. Heckel in our group with silica-supported TADDOLates, so that this peculiar behavior cannot be attributed to the particular polymer support used [37]. After all, it is very remarkable that the polymer-bound catalyst remained active over a period of 10 recycling steps, bearing in mind that hydrolysis and reloading with titanate took place after each run, and that most of the catalytic sites are located inside the polymer beads.

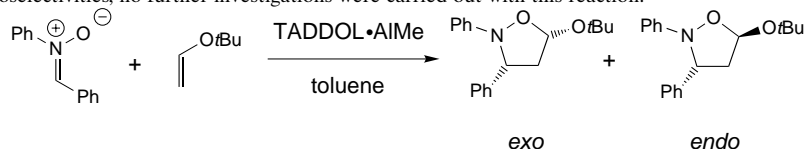
The preferential formation of *exo*-cycloadducts 29 is induced, as shown above, by Cl₂Ti-TADDOLates. However, the formation of the corresponding *endo*-cycloadducts is favored, when (TsO)₂Ti-TADDOLates are employed [35b]. In solution, this reaction gives rise to good results only when 50 mol-% of catalyst are used [35b]. Thus, polymer p-6 (0.5 equiv.) was loaded with titanate by the addition of a solution of Ti(OTs)₂(OⁱPr)₂ in toluene [35b] to give p-6·Ti(OTs)₂, according to the procedure described for the preparation of p-6·TiCl₂, and a solution of the starting materials was added. After a reaction time of 40 h at room temperature, the reaction solution was separated from the polymer beads, and pure *endo*-29 was isolated [35b]. The results observed with p-6·Ti(OTs)₂ (*endo/exo* 88 : 12, *es* (*endo*-29) 93 : 7, conversion 72%) were slightly poorer than with tetraphenyl-TADDOLate in solution (*endo/exo* > 95 : 5, *es* (*endo*-29) 97 : 3, conversion quantitative [35b]). Recycling was, again, possible only after hydrolysis and reloading with titanate. The results are shown in Fig. 9, b. Within experimental error, the diastereo- (*endo/exo*) and enantioselectivity remained un-

changed during four catalytic cycles, the best conversion was even obtained in the fourth run. The fact that comparable results are obtained under homogeneous and heterogeneous conditions suggests that this cycloaddition also proceeds *via* monomeric TADDOLate complexes.

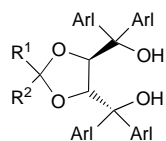
The results presented in this section demonstrate that the dendritically cross-linked TADDOL polymers can also be successfully applied in 1,3-dipolar cycloadditions giving rise to a catalytic performance as under homogeneous conditions⁸⁾.

6. TADDOL Polymers with Achiral Dendrimers as Cross-Linkers. – In the previous sections, it was demonstrated that catalytically highly active TADDOL polymers can be obtained by copolymerizing a dendritically surrounded TADDOL cross-linker with styrene. However, the preparation of these cross-linkers, *e.g.*, **6**, is tedious and requires quite a number of synthetic steps, including a chromatographic purification. Hence, the question arose whether TADDOL polymers with a comparable activity could be prepared in a simpler way, namely by copolymerizing an achiral and, therefore, synthetically easily accessible, dendritic cross-linker with styrene and mono-styryl-substituted TADDOL **28**. Furthermore, we wanted to investigate whether a dendritically cross-linked polystyrene gives rise to special material properties, which account for the observations made with $p\text{-}\mathbf{6} \cdot \text{Ti}(\text{O}^i\text{Pr})_2$. The dendritic cross-linkers **30**, **31**, and **32** of zeroeth, first, and second generation were prepared by etherification of 1,1,1-tris(4-hydroxyphenyl)ethane with 4-vinylbenzyl chloride (\rightarrow **30**) or branches **3** (\rightarrow **31**) and **4**

⁸⁾ In 1999, Jørgensen and co-workers reported on the 1,3-dipolar cycloaddition of diphenyl nitrene to alkyl vinyl ethers using catalytic amounts of MeAl-BINOLates in solution [38]. In most cases, the *exo*-cycloadducts, which were formed almost exclusively, were obtained in enantioselectivities of up to 96%. We have already shown that cross-linking polymer-bound Al-BINOLates give rise to the same catalytic activity as their homogeneous counterparts [22]. In an effort to implement this reaction with MeAl-TADDOLates, we screened several TADDOL ligands and found that the best results in the addition of diphenyl nitrene to *tert*-butyl vinyl ether were obtained, when 20 mol-% of tetra(naphthalen-2-yl)-TADDOL **I** (*exo/endo* 87:13, *es(exo)* 70%) were employed. The same results were achieved in the presence of 20 mol-% of a polymer-bound TADDOLate prepared by copolymerization of TADDOL **II** with styrene and DVB. In contrast to the reaction under homogeneous conditions, it was possible to increase the *exo/endo* selectivity to 96:4 by increasing the amount of polymer-bound catalyst to 50 mol-%, whereas the enantiomer purity of the cycloadducts remained unchanged. The catalyst was recycled up to five times by hydrolysis followed by reloading with AlMe₃, giving rise to a stable performance. However, due to the rather modest enantioselectivities, no further investigations were carried out with this reaction.

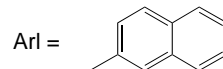


TADDOLs:



I R¹ = R² = Me

II R¹ = styryl, R² = H



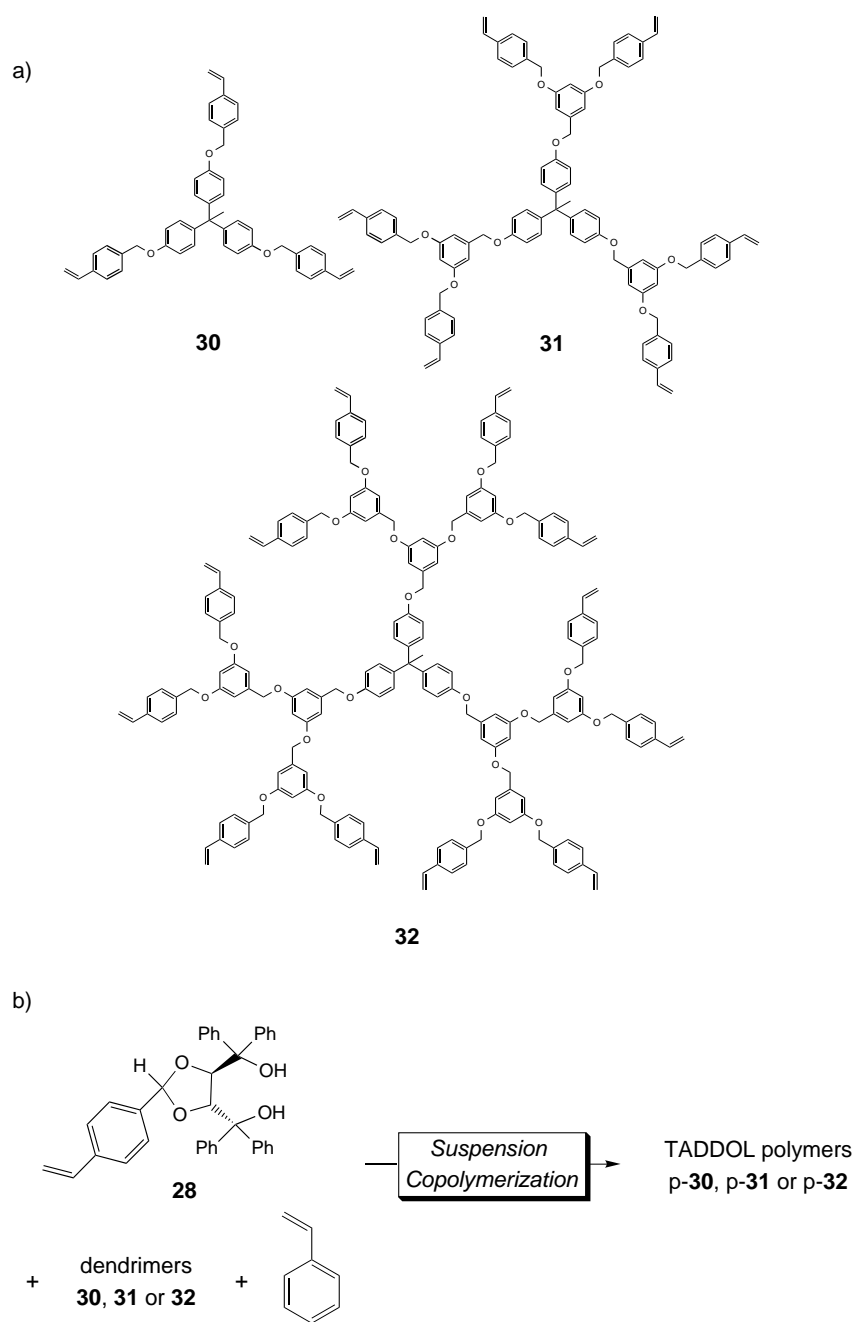
(\rightarrow **32**) in the presence of K_2CO_3 and 18-crown-6 (*Scheme 7,a*). These reactions proceeded cleanly without the formation of by-products, and all three compounds were obtained in yields of *ca.* 90% after chromatography. So far, the best polymer **p-6** with a degree of loading of 0.10 mmol g^{-1} had been obtained by copolymerization of dendrimer **6** (with eight peripheral styryl groups) with 80 equiv. of styrene. Therefore, to achieve a comparable degree of cross-linking in polymers **p-30**, **p-31**, and **p-32**, 10 equiv. of comonomers styrene and TADDOL **28** per styryl end group of the dendritic cross-linker were employed in the copolymerization process (*Scheme 7,b*). The amount of TADDOL **28** was adjusted in such a way that the loading of the resulting polymers was either 0.24 or 0.10 mmol g^{-1} . For example, for the preparation of polymer **p-31** with a loading of 0.10 mmol g^{-1} , 1 equiv. of dendrimer **31** was copolymerized with 59 equiv. of styrene and 1 equiv. of TADDOL **28** (total: 60 equiv. of mono-vinyl-functionalized co-monomers per dendrimer **31** with six peripheral styryl groups).

Polymers **p-30**, **p-31**, and **p-32** with a loading of 0.24 mmol g^{-1} were transformed into the corresponding Ti complexes **p-30** \cdot Ti(OⁱPr)₂, **p-31** \cdot Ti(OⁱPr)₂, and **p-32** \cdot Ti(OⁱPr)₂ by the addition of Ti(OⁱPr)₄, and employed for the catalysis of the addition of Et₂Zn to PhCHO, according to the protocol depicted in *Scheme 6*. Generally, 20 mol-% of supported Ti-TADDOLate was used. The enantiomer purities of 1-phenylpropan-1-ol during multiple uses are collected in *Fig. 10*. The enantioselectivities (between 97 and 98%) in the first run are comparable for all three polymers, and a loss in selectivity between 2 and 3% during 20 recycling steps is generally observed. Whereas the selectivities of 1-phenylpropan-1-ol obtained with polymers **p-31** \cdot Ti(OⁱPr)₂ and **p-32** \cdot Ti(OⁱPr)₂, containing first- and second-generation dendrimers **31** and **32**, respectively, as cross-linkers, are quite stable and reproducible, recycling **p-30** \cdot Ti(OⁱPr)₂ gives rise to rather erratic results. All three polymers showed a decline in reaction rate and swelling ability during recycling. Decreased loading (from 0.24 to 0.10 mmol g^{-1}) did not increase the catalytic performance as it did with **p-6** \cdot Ti(OⁱPr)₂.

In summary, it was not possible by this approach to obtain polymer-bound TADDOLates with a comparable performance as **p-6** \cdot Ti(OⁱPr)₂. A dendritically cross-linked polystyrene support itself is not sufficient to guarantee a long-term stability of the polymer-bound catalyst. It seems that placing the TADDOL unit in the core of a dendritic cross-linker would be necessary to obtain polymers with an outstanding catalytic activity (constant swelling ability over many cycles!).

7. Summary and Conclusion. – In the present paper, we have presented a new way to immobilize chiral ligands on polystyrene: copolymerization of a TADDOL dendrimer **6** with styrene, followed by loading with titanate, affords polymer-bound Ti-TADDOLate complexes with an unprecedented stability and activity during recycling. Our approach is the first example of the use of dendrimers as cross-linkers in polystyrene. Furthermore, we have demonstrated that these polymers **p-6**, in contrast to all other polymers tested, maintain a constant swelling ability during recycling, which might be the reason for their excellent performance. Surprisingly, **p-6** \cdot Ti(OⁱPr)₂ gives rise to a faster reaction rate in the Et₂Zn addition to PhCHO than its soluble precursor **6** \cdot Ti(OⁱPr)₂. We have also shown that it is necessary to place the TADDOL ligand in the core of the dendritic cross-linker; copolymerizing a mono-vinyl-substituted

Scheme 7. Dendrimers **30**, **31**, and **32** (a) Used as Polymer Cross-Linkers for the Copolymerization of Styrene with TADDOL **28** (b)



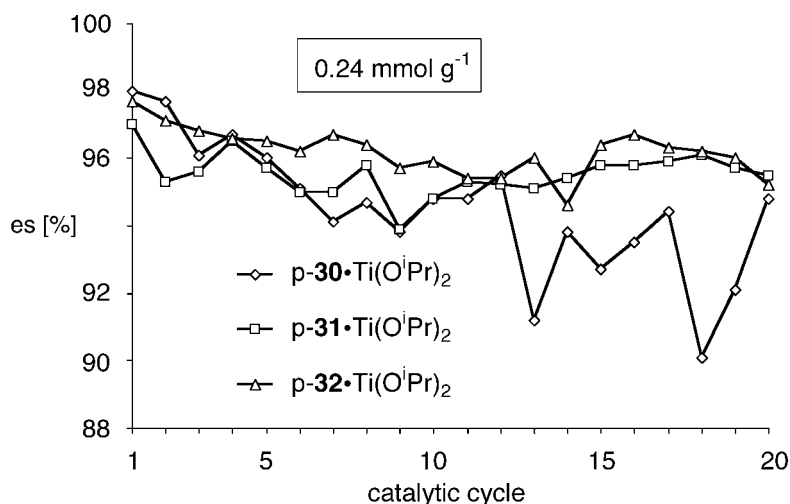


Fig. 10. Recycling of polymers $p\text{-30}\cdot\text{Ti}(\text{O}^i\text{Pr})_2$, $p\text{-31}\cdot\text{Ti}(\text{O}^i\text{Pr})_2$, $p\text{-32}\cdot\text{Ti}(\text{O}^i\text{Pr})_2$ and $p\text{-32}\cdot\text{Ti}(\text{O}^i\text{Pr})_2$ in the addition of Et_2Zn to PhCHO according to the conditions outlined in Scheme 6

TADDOL **28** with styrene and achiral dendrimers as cross-linkers affords a polymeric reagent, which is less active during recycling than polymer **p-6**.

In the meantime, we have also successfully immobilized the chiral ligands BINOL [22] and Salen [23] in a dendritically cross-linking fashion, in order to establish the general applicability of this novel way of immobilization.

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Experimental Part

1. *General*. Reagents: $(i\text{-PrO})_2\text{TiCl}_2$ [35a] and 2M stock soln. of Et_2Zn [32] were prepared according to reported procedures. The compounds **1** [1][24], **2-4** [22], **11** [39], **15** [31], and **28** [20a] were synthesized according to literature procedures. PhCHO was distilled prior to use. All other commercially available chemicals were used as received from *Fluka*, *Aldrich*, or *Acros*. TLC: precoated silica gel 25 *Durasil UV*₂₅₄ plates (*Macherey-Nagel*); visualization by UV_{254} light or by development with phosphomolybdic acid solution (phosphomolybdic acid (25 g), $\text{Ce}(\text{SO}_4)_2\cdot\text{H}_2\text{O}$ (10 g), H_2SO_4 (conc., 60 ml), and H_2O (940 ml)), followed by heating with a heat gun. Flash column chromatography (FC): silica gel 60 (*Fluka*, 0.040–0.063 mm); N_2 -pressure ca. 0.2–0.4 bar. Anal. HPLC: *Waters HPLC system* (*Waters 515 HPLC Pump*, *Waters 484 tunable absorbance detector*, *Waters automated gradient controller*); *Daicel Chiracel OD* (*Daicel Chemical Industries, Ltd.*; 4.6 × 250 mm, 10 μm), eluent: hexane/*i*-PrOH 400:1 to 9:1; UV detection at λ 254 nm. Cap. gas-chromatography (CGC): *Carlo Erba GC 8000*; columns (*Supelco*): a) *α -Dex* (30 m × 0.25 mm i.d.), b) *β -Dex* (30 m × 0.25 mm i.d.); injector temp. 200°, detector temp. 225° (FID); carrier gas: H_2 . M.p.: *Büchi-510* apparatus with open capillaries, uncorrected. Optical rotation $[\alpha]_D^{25}$: *Perkin-Elmer 241* polarimeter (10 cm, 1 ml cell) at r.t.; *p.a.* solvents. IR Spectra: *Perkin-Elmer 1600 FTIR*; solns. in CHCl_3 ; ν in cm^{-1} . NMR Spectra: *Bruker AMX-II-500* (^1H : 500 MHz, ^{13}C : 125 MHz), *AMX-400* (^1H : 400 MHz, ^{13}C : 100 MHz), *AMX-300* (^1H : 300 MHz, ^{13}C : 75 MHz), *Varian XL-300* (^1H : 300 MHz, ^{13}C : 75 MHz), *Gemini-300* (^1H : 300 MHz, ^{13}C : 75 MHz), or *Gemini-200* (^1H : 200 MHz, ^{13}C : 50 MHz); chemical shifts (δ) in ppm downfield from TMS ($\delta = 0$ ppm); J values in Hz; spectra were recorded in CDCl_3 . MS: *Hitachi-Perkin-Elmer RMU-6M* spectrometer (EI), *VG ZAB2-*

SEQ spectrometer (FAB; in a 3-nitrobenzyl-alcohol matrix (3-NOBA)), Finnigan MAT-TSQ 7000 spectrometer (ESI), Bruker ReflexTM spectrometer (positive-ion mode) with N₂ Laser (337 nm) (MALDI-TOF; in a 2,5-dihydroxybenzoic acid (2,5-DHB), a 2-(4-hydroxy phenylazo)benzoic acid (HABA), a 2,4,6-trihydroxyacetophenone (THA), or a dithranol matrix), Ion Spec Ultima 4.7 FT ion cyclotron resonance (ICR) spectrometer (HR-MALDI; in a 2,5-DHB matrix); fragment ions in *m/z* with relative intensities (% of base peak) in parentheses. Elemental analyses (C and H) were performed by the Microanalytical Laboratory of the Laboratorium für Organische Chemie, ETH-Zürich. The Ti analysis was performed by Analytische Laboratorien, Prof. Dr. H. Malissa und G. Reuter GmbH, Lindlar, Germany.

2. *Coupling of Benzyl Bromides with Hexol 1 or with 1,1,1-Tris(4-hydroxyphenyl)ethane to Give Dendritic Cross-Linkers. General Procedure 1 (GP 1).* K₂CO₃ (4 equiv.) was added to a soln. of hexol **1** [1, 24] (1 equiv.) or 1,1,1-tris(4-hydroxyphenyl)ethane (1 equiv.) in acetone, followed by addition of a soln. of the PhCH₂Br (4 equiv.) in acetone. After heating at 50–60° for 20–48 h, the suspension was allowed to cool to r.t., and the salts were filtered off and extensively washed with CH₂Cl₂. After evaporation of the solvent, the residue was redissolved in CH₂Cl₂, and H₂O was added. The org. layer was separated, and the aq. phase was extracted with CH₂Cl₂, followed by drying of the combined org. phases (MgSO₄), evaporation of the solvent, and isolation of the product by FC.

3. *Coupling of Alcohols with Benzyl Halides with NaH as a Base. General Procedure 2 (GP 2).* A soln. of the alcohol (1–3 equiv.) in THF was slowly added to a suspension of NaH (1–3 equiv.) in THF at 0°. After complete addition, the suspension was heated to 50° for 30 min and recooled to 0°. Then, a soln. of the benzyl halide (1 equiv.) in THF was slowly added, and the mixture was heated at 60–70°. For workup, H₂O was carefully added at 0°. After extraction (3 × Et₂O), drying of the combined org. phases (MgSO₄), and evaporation of the solvent, the resulting crude product was purified by FC.

4. *Preparation of TADDOL Cross-Linkers 5–7 and 20, 21.* (4R,5R)-*α,α,α',α'-Tetrakis[4-[3-(4-ethenylbenzyloxy)benzyloxy]phenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (5)*. A suspension of hexol **1** [1,24] (366 mg, 0.6 mmol), benzyl bromide **2** [22] (755 mg, 2.5 mmol), and K₂CO₃ (344 mg, 2.5 mmol) in acetone (25 ml) was heated at 50° for 20 h, according to GP 1. Workup and FC (CH₂Cl₂ → CH₂Cl₂/acetone 99.5:0.5) afforded **5** (580 mg, 66 %). Colorless foam. R_f (hexane/acetone 1:1) 0.55. [α]_D²⁵ = –32.4 (c = 1.0, CHCl₃). IR (CHCl₃): 3360w, 3008m, 2879w, 1710s, 1606s, 1586s, 1509s, 1490m, 1450m, 1406w, 1372s, 1289m, 1264s, 1248s, 1087w, 1016s, 992w, 913w, 884w, 831s. ¹H-NMR (500 MHz, CDCl₃): 1.05 (s, 2 Me); 3.97 (s, 2 OH); 4.48 (s, H–C(4), H–C(5)); 4.97, 5.02, 5.04, 5.05 (4s, 8 CH₂O); 5.24 (dd, *J* = 10.8, 0.9, 4 vinyl H); 5.74 (dd, *J* = 17.7, 0.9, 2 vinyl H); 6.68–6.74 (m, 4 CHCH₂); 6.82 (d, *J* = 9.0, 4 arom. H (TADDOL)); 6.91 (d, *J* = 8.9, 4 arom. H (TADDOL)); 6.68–7.44 (m, 32 arom. H, 8 arom. H (TADDOL)). ¹³C-NMR (125 MHz, CDCl₃): 27.22; 69.76; 69.79; 69.83; 77.60; 81.12; 109.23; 113.54; 113.82; 113.95; 114.10; 114.11; 114.30; 114.34; 114.40; 119.87; 120.02; 126.42; 126.44; 127.72; 128.89; 129.64; 129.73; 135.36; 136.44; 137.35; 137.36; 138.68; 138.70; 157.86; 157.96; 159.02; 159.03. MALDI-TOF-MS (HABA): 1443.0 ([*M* + Na]⁺). Anal. Calc. for C₉₅H₈₆O₁₂ (1419.69): C 80.37, H 6.11; found: C 80.21, H 6.31.

(4R,5R)-*α,α,α',α'-Tetrakis[4-[3,5-bis(4-ethenylbenzyloxy)benzyloxy]phenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (6)*. According to GP 1, K₂CO₃ (0.32 g, 2.3 mmol) was added to a soln. of **1** [1, 24] (0.31 g, 0.58 mmol) in acetone (20 ml), followed by addition of a soln. of **3** [22] (1.00 g, 2.3 mmol) in acetone (5 ml). After heating under reflux for 40 h, the mixture was worked up, and the crude product was purified by FC (CH₂Cl₂ → CH₂Cl₂/acetone 99.5:0.5) to give **6** (0.72 g, 64%). Colorless foam. R_f (hexane/acetone 2:1) 0.36. [α]_D²⁵ = –24.0 (c = 1.00, CHCl₃). IR (CHCl₃): 3374w, 3008m, 1598s, 1509s, 1458m, 1372m, 1294m, 1158s, 1060m, 1017m, 913m, 831m. ¹H-NMR (500 MHz, CDCl₃): 1.05 (s, 2 Me); 3.92 (s, 2 OH); 4.49 (s, H–C(4), H–C(5)); 4.92, 4.98, 4.99, 5.01 (4s, 12 CH₂O); 5.23 (dd, *J* = 11.8, 0.9, 8 vinyl H); 5.74 (dd, *J* = 17.6, 0.8, 8 vinyl H); 6.52, 6.55 (t, *J* = 2.3, 4 arom. H); 6.62 (d, *J* = 2.3, 4 arom. H); 6.67 (d, *J* = 2.6, 4 arom. H); 6.62–6.73 (m, 8 vinyl CHCH₂); 6.80, 6.90 (2d, *J* = 9.0, 8 arom. H (TADDOL)); 7.23 (d, *J* = 7.0, 4 arom. H (TADDOL)); 7.25–7.55 (m, 32 arom. H, 4 arom. H (TADDOL)). ¹³C-NMR (125 MHz, CDCl₃): 27.26; 69.87; 69.89; 81.15; 101.56; 101.61; 106.36; 106.49; 109.27; 113.57; 114.11; 114.33; 126.42; 126.44; 127.55; 127.75; 128.87; 129.7; 135.44; 136.31; 136.33; 136.45; 137.37; 137.39; 138.69; 139.49; 139.52; 157.82; 157.92; 160.12; 160.13. MALDI-TOF-MS (dithranol): 1971.2 ([*M* + Na]⁺). Anal. calc. for C₁₃₁H₁₁₈O₁₆ (1948.4): C 80.76, H 6.10; found: C 80.75, H 6.11.

(4R,5R)-*α,α,α',α'-Tetrakis[4-[3,5-bis[3,5-bis(4-ethenylbenzyloxy)benzyloxy]benzyloxy]phenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (7)*. A suspension of **1** [1,24] (0.51 g, 0.95 mmol), benzyl bromide **4** [22] (3.65 g, 4 mmol) and K₂CO₃ (0.525 g, 3.8 mmol) in acetone (80 ml) was heated under reflux for 48 h, according to GP 1. After workup and purification of the crude product by FC (CH₂Cl₂/hexane 3:1 → CH₂Cl₂ → CH₂Cl₂/acetone 95:5), **7** (2.56 g, 70%) was obtained. Colorless foam. R_f (hexane/acetone 2:1) 0.36. [α]_D²⁵ = –10.2 (c = 1.00, CHCl₃). IR (CHCl₃): 3333w, 3008m, 2379w, 1596s, 1512m, 1456m, 1407w, 1372m, 1295m, 1157s, 1056m,

1017*m*, 991*w*, 913*m*, 833*m*. ¹H-NMR (500 MHz, CDCl₃): 1.02 (*s*, 2 Me); 4.10 (*s*, 2 OH); 4.44 (*s*, H–C(4), H–C(5)); 4.88–4.96 (*m*, 28 CH₂O); 5.21 (*dd*, *J* = 10.9, 0.7, 16 vinyl H); 5.71 (*dd*, *J* = 17.6, 0.6, 16 vinyl H); 6.48–6.52 (*m*, 12 arom. H); 6.57–6.71 (*m*, 16 CHCH₂, 24 arom. H); 6.76, 6.87 (*2d*, *J* = 8.9, 8 arom. H (TADDOL)); 7.18 (*d*, *J* = 8.9, 4 arom. H (TADDOL)); 7.30–7.41 (*m*, 64 arom. H, 4 arom. H (TADDOL)). ¹³C-NMR (125 MHz, CDCl₃): 27.26; 69.83; 69.93; 70.00; 81.18; 101.58; 101.66; 101.69; 106.23; 106.35; 106.45; 109.12; 113.55; 114.09; 114.28; 126.41; 126.58; 127.53; 127.74; 128.90; 129.73; 135.35; 136.30; 136.44; 137.33; 138.59; 139.24; 139.51; 157.75; 157.89; 160.02; 160.06; 160.11. MALDI-TOF-MS (THA/citrate): 3876.7 ([*M* + Na]⁺).

4-[(*tert*-Butyl)dimethylsiloxy]butan-1-ol (**8**). Imidazole (33.2 g, 488 mmol) and (*t*-Bu)Me₂SiCl (36.8 g, 244 mmol) were added to a soln. of butane-1,4-diol (20.0 g, 222 mmol) in DMF (300 ml) at 0°. After stirring at r.t. for 18 h, DMF was evaporated under reduced pressure, Et₂O (300 ml) and H₂O (400 ml) were added, the org. phase was separated, and the aq. layer was extracted with Et₂O (2 × 300 ml). After drying the combined org. phases (MgSO₄), the crude product was subjected to FC (hexane/Et₂O 1:1) to give **8** (18.0 g, 40 %). Colorless oil. ¹H-NMR (200 MHz, CDCl₃): 0.04 (*s*, 2 Me); 0.89 (*s*, *t*-Bu); 1.25 (*s*, OH); 1.57–1.71 (*m*, 2 CH₂), 3.60–3.75 (*m*, 2 CH₂O).

1-[(4-[(*tert*-Butyl)dimethylsiloxy]butoxy)methyl]-4-ethenylbenzene (**9**). A soln. of **8** (18.0 g, 88 mmol) in THF (50 ml) was added to a suspension of NaH (6.4 g, 264 mmol) in THF (400 ml) at 0°, according to GP 2. After heating the suspension at 50° for 30 min, the mixture was recooled to 0°, and a soln. of 4-ethenylbenzyl chloride (17.9 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60° for 72 h. Workup and FC (hexane/Et₂O 2:1 → 1:1) gave **9** (19.2 g, 68%). Yellow oil. *R*_f (hexane/CH₂Cl₂) 0.20. IR (CHCl₃): 3089*w*, 3005*m*, 2932*s*, 2856*s*, 1629*w*, 1512*w*, 1471*m*, 1406*w*, 1389*w*, 1361*m*, 1256*s*, 1088*s*, 1073*s*, 1006*w*, 990*m*, 938*w*, 911*m*, 846*s*, 832*s*. ¹H-NMR (400 MHz, CDCl₃): 0.04 (*s*, 2 Me); 0.89 (*s*, *t*-Bu); 1.57–1.71 (*m*, 2 CH₂); 3.48 (*t*, *J* = 6.5, SiOCH₂); 3.62 (*t*, *J* = 6.3, PhCH₂O); 4.49 (*s*, PhCH₂O); 5.23 (*dd*, *J* = 10.8, 0.9, 1 vinyl H); 5.73 (*dd*, *J* = 17.6, 1.0, 1 vinyl H); 6.71 (*dd*, *J* = 17.6, 10.9, CH₂CH); 7.29, 7.38 (*2d*, *J* = 8.1 Hz, 4 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 18.35; 25.97; 26.24; 29.52; 62.97; 70.26; 72.57; 113.67; 126.21; 127.83; 136.60; 136.87; 138.30. EI-MS: 320.2 (<0.05, *M*⁺), 118.1 (37), 117.1 (100), 116.1 (5), 115.1 (14), 95.6 (19), 91.1 (8), 75.0 (7), 73.1 (6), 57.1 (3).

4-(4-Ethenylbenzyloxy)butan-1-ol (**10**). A soln. of **9** (19.2 g, 60 mmol) in THF (400 ml) was treated with Bu₄NF · 3 H₂O (28.3 g, 90 mmol) at 0°. After stirring at r.t. for 12 h, H₂O (500 ml) and Et₂O (500 ml) were added, the org. phase was separated, and the aq. layer was extracted with Et₂O (2 × 500 ml). Drying of the combined org. phases (MgSO₄), evaporation of the solvent, and purification of the residue by FC (CH₂Cl₂/acetone 5:1 → 3:1) yielded **10** (12.0 g, 97%). Yellow oil. *R*_f (CH₂Cl₂/acetone 2:1) 0.46. IR (CHCl₃): 3629*w*, 3416*m*, 3008*s*, 2938*s*, 2864*s*, 1710*m*, 1629*m*, 1512*m*, 1447*w*, 1406*m*, 1447*m*, 1406*m*, 1361*m*, 1225*s*, 1217*s*, 1098*s*, 1049*m*, 1017*w*, 990*m*, 913*m*, 827*m*. ¹H-NMR (400 MHz, CDCl₃): 1.63–1.75 (*m*, 2 CH₂); 2.25 (*s*, OH); 3.51, 3.64 (*2t*, *J* = 5.9, 2 CH₂O); 4.51 (*s*, PhCH₂O); 5.23 (*dd*, *J* = 11.1, 1.0, 1 vinyl H); 5.74 (*dd*, *J* = 17.6, 0.9, 1 vinyl H); 6.71 (*dd*, *J* = 17.6, 10.9, 1 CH₂CH); 7.29, 7.39 (*2d*, *J* = 8.1, 2 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 26.72; 30.17; 62.74; 70.31; 72.79; 113.84; 126.29; 127.96; 136.52; 137.06; 137.72. EI-MS: 206.2 (14, *M*⁺), 134.1 (20), 133.1 (100), 118.1 (20), 117.1 (90), 116.1 (6), 115.1 (21), 105.1 (16), 91.1 (13), 77.1 (5). Anal. Calc. for C₁₃H₁₈O₂ (206.28): C 75.69, H 8.79; found: C 75.18, H 8.57.

1-[(*tert*-Butyl)diphenylsilyloxy)methyl]-4-[(4-ethenylbenzyloxy)butoxy)methyl]benzene (**12**). A soln. of **10** (4.00 g, 19.4 mmol) in THF (25 ml) was slowly added to a suspension of NaH (1.41 g, 58.2 mmol) in THF (100 ml) at 0°, according to GP 2. After heating at 50° for 30 min, the mixture was recooled to 0°, and a soln. of **11** [39] (9.40 g, 21.3 mmol) in THF (25 ml) was added, whereupon the suspension was heated at 70° for another 14 h. Workup and purification of the crude product by FC (CH₂Cl₂/hexane 3:1) gave **12** (6.40 g, 58 %). Yellow oil. *R*_f (CH₂Cl₂/hexane 3:1) 0.28. IR (CHCl₃): 3074*w*, 3054*w*, 3008*s*, 2932*m*, 2859*s*, 1590*w*, 1512*m*, 1472*m*, 1428*s*, 1362*s*, 1302*w*, 1112*s*, 1088*s*, 1019*m*, 912*m*, 827*s*. ¹H-NMR (400 MHz, CDCl₃): 1.09 (*s*, *t*-Bu); 1.69–1.72 (*m*, 2 CH₂); 3.47–3.40 (*m*, 2 CH₂O); 4.48, 4.49 (*2s*, 2 PhCH₂O); 4.76 (*s*, SiOCH₂); 5.22 (*dd*, *J* = 10.8, 0.8, 1 vinyl H); 5.73 (*dd*, *J* = 17.6, 0.9, 1 vinyl H); 6.70 (*dd*, *J* = 17.6, 10.9, CH₂CH); 7.28–7.70 (*m*, 18 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 19.31; 26.51; 26.52; 26.83; 65.36; 70.07; 70.10; 72.56; 72.72; 113.66; 126.00; 126.20; 127.50; 127.58; 127.70; 127.80; 129.66; 133.53; 135.52; 135.56; 136.58; 136.87; 137.19; 138.26; 140.37. EI-MS: 564.3 (<0.05, *M*⁺), 507.2 (3), 317.1 (4), 313.1 (3), 297.1 (3), 273.1 (2), 235.0 (5), 221.1 (3), 199.0 (23), 117.1 (100), 104.0 (16), 91.0 (6), 77.0 (3). Anal. calc. for C₃₇H₄₄O₃Si (564.83): C 78.68, H 7.85; found: C 78.74, H 7.80.

4-[(4-Ethenylbenzyloxy)butoxy)methyl]phenylmethanol (**13**). Bu₄NF · 3 H₂O (7.00 g, 22.2 mmol) was added to a soln. of **12** (6.25 g, 11.1 mmol) in THF (100 ml) at 0°. After stirring at r.t. for 14 h, workup as described for **10** gave **13** (2.80 g, 77%). Colorless oil. *R*_f (CH₂Cl₂/acetone 2:1) 0.32 and FC (CH₂Cl₂/acetone 10:1). IR (CHCl₃): 3602*m*, 3429*m*, 3008*s*, 2941*m*, 2862*s*, 1629*m*, 1512*m*, 1455*w*, 1406*m*, 1362*m*, 1089*s*, 1016*m*,

991m, 912s, 827m. ¹H-NMR (400 MHz, CDCl₃) 1.69–1.71 (m, 2 CH₂); 1.76 (t, *J* = 5.7, 1 OH); 3.46–3.49 (m, 2 CH₂O); 4.47, 4.48 (2s, 2 PhCH₂O); 4.66 (d, *J* = 5.4, CH₂OH); 5.22 (dd, *J* = 10.8, 0.9, 1 vinyl H); 5.73 (dd, *J* = 17.6, 0.9, 1 vinyl H); 6.71 (dd, *J* = 17.6, 10.9, 1 CH₂CH); 7.27–7.38 (m, 8 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 26.51; 65.15; 70.10; 70.13; 72.57; 113.70; 126.21; 127.04; 127.81; 127.85; 136.59; 136.89; 138.10; 138.24; 140.19. EI-MS: 324.2 (<0.05, *M*⁺), 209.2 (2), 205.2 (9), 192.2 (2), 137.1 (24), 134.1 (11), 133.1 (100), 132.1 (4), 131.1 (6), 121.1 (27), 119.1 (12), 118.1 (11), 117.1 (65), 115.1 (9), 105.1 (8), 104.1 (5), 103.1 (5), 91.1 (18), 77.1 (10), 73.1 (15), 55.1 (8). Anal. calc. for C₂₁H₂₆O₃ (326.4): C 77.27, H 8.03; found: C 77.28, H 8.16.

1-(Bromomethyl)-4-[4-(4-ethenylbenzyloxy)butoxymethyl]benzene (14). CBr₄ (4.30 g, 12.4 mmol) and PPh₃ (3.30 g, 12.4 mmol) were added to a soln. of **13** (2.70 g, 8.3 mmol) in THF (100 ml) at 0°. After stirring at 0° for 1 h and at r.t. for 12 h, the solvent was evaporated, and the residue was immediately subjected to FC (CH₂Cl₂/hexane 2:1 → 4:1) to afford **14** (2.88 g, 90%). Yellow oil. *R*_f (hexane/acetone 3:1) 0.47. IR (CHCl₃): 3008s, 2942m, 2861s, 1629m, 1512m, 1448w, 1406m, 1362s, 1091s, 1018m, 990m, 913s, 827m. ¹H-NMR (400 MHz, CDCl₃): 1.69–1.72 (m, 2 CH₂); 3.46–3.49 (m, 2 CH₂O); 4.48–4.49 (m, 2 PhCH₂O, CH₂Br); 5.23 (dd, *J* = 10.9, 0.8, 1 vinyl H); 5.73 (dd, *J* = 17.6, 0.8, 1 vinyl H); 6.71 (dd, *J* = 17.7, 10.9, CH₂CH); 7.25–7.39 (m, 8 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 26.51; 33.36; 70.07; 70.29; 72.38; 72.58; 113.70; 126.21; 127.81; 127.91; 129.08; 136.59; 136.97; 138.25; 139.09. EI-MS: 390.3 (<0.05, *M*⁺), 221.3 (6), 207.2 (10), 205.2 (17), 201.1 (12), 199.1 (13), 185.1 (17), 183.1 (18), 154.9 (4), 134.1 (11), 133.1 (100), 132.1 (4), 131.1 (6), 121.1 (2.4), 120.1 (5), 119.1 (3), 118.1 (9), 117.1 (57), 116.1 (3), 115.1 (10), 105.1 (12), 104.1 (27), 103.1 (7), 91.1 (10), 86.0 (10), 84.0 (14), 77.1 (4), 73.1 (6), 49.0 (4). Anal. calc. for C₂₁H₂₅O₂Br (389.33): C 64.79, H 6.47; found: C 64.87, H 6.61.

4'-[(tert-Butyldiphenylsilyloxy)methyl][1,1'-biphenyl]-4-methanol (16). NaBH₄ (0.34 g, 9.0 mmol) was added to a soln. of aldehyde **15** [31] (4.00 g, 8.9 mmol) in THF (100 ml) at 0°. After stirring at r.t. for 20 h, H₂O (100 ml) was carefully added, and the mixture was extracted with Et₂O (3 × 200 ml). After drying of the combined org. phases (MgSO₄) and evaporation of the solvent **16** (4.30 g, quant.) was obtained as a slightly yellow solid, which was pure according to ¹H-NMR and directly used for further transformations without purification. The ¹H-NMR data corresponded to those in [31].

4'-[(tert-Butyldiphenylsilyloxy)methyl]-4'-[4-ethenylbenzyloxy)methyl]-1,1'-biphenyl (17). A soln. of **16** (5.00 g, 11.1 mmol) in THF (30 ml) was added to a suspension of NaH (0.80 g, 33.2 mmol) in THF (90 ml) at 0°, according to GP 2. After heating at 50° for 30 min, the suspension was recooled to 0°, and a soln. of 4-ethenylbenzyl chloride (2.02 g, 13.3 mmol) in THF (30 ml) was added, followed by KI (5 mg). Then, the resulting mixture was heated at 70° for 20 h. Workup according to GP 2 and FC (hexane/CH₂Cl₂ 3:1 → 1:1) afforded **17** (3.70 g, 59%). Yellow oil. *R*_f (hexane/Et₂O 2:1) 0.61. IR (CHCl₃): 3072m, 3063m, 3008s, 2931s, 2858s, 1907w, 1826w, 1629w, 1589w, 1500s, 1472s, 1428s, 1376m, 1361m, 1308w, 1263w, 1112s, 1027w, 1006s, 939w, 912m, 826s. ¹H-NMR (400 MHz, CDCl₃): 1.11 (s, *t*-Bu); 4.58, 4.59, 4.82 (3s, 3 PhCH₂O); 5.24 (dd, *J* = 10.9, 0.9, 1 vinyl H); 5.76 (dd, *J* = 17.6, 0.9, 1 vinyl H); 6.72 (dd, *J* = 17.6, 10.9, CH₂CH); 7.34–7.73 (m, 22 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 19.34; 26.86; 65.30; 71.81; 71.88; 113.81; 126.28; 126.42; 126.93; 127.11; 127.74; 128.03; 128.27; 129.71; 133.50; 135.60; 136.56; 137.04; 137.15; 137.88; 139.52; 140.21; 140.51. EI-MS: 568.5 (<0.05, *M*⁺), 513.4 (11), 512.4 (32), 511.4 (78), 481.4 (5), 393.3 (7), 315.3 (5), 314.3 (25), 313.3 (100), 199.2 (32), 197.2 (7), 196.2 (5), 195.2 (25), 183.2 (6), 181.2 (19), 180.2 (42), 179.2 (8), 168.2 (7), 167.2 (21), 166.2 (6), 165.2 (13), 152.1 (4), 131.1 (3), 118.1 (11), 117.1 (55), 115.1 (6), 105.1 (8), 91.1 (7), 86.0 (19), 84.0 (30), 77.1 (8), 51.0 (12), 49.0 (34), 47.0 (5), 41.1 (6). Anal. calc. for C₃₉H₄₀O₂Si (568.82): C 82.35, H 7.09; found: C 82.33, H 7.22.

4'-[4-Ethenylbenzyloxy)methyl][1,1'-biphenyl]-4-methanol (18). Bu₄NF · 3 H₂O (3.42 g, 10.9 mmol) was added to a soln. of **17** (3.10 g, 5.5 mmol) in THF (120 ml) at 0°. After stirring at r.t. for 12 h, workup as described for the preparation of **10** and FC (CH₂Cl₂/acetone 10:1) gave **18** (1.60 g, 89%). White solid. M.p. 124.0–126.0°. *R*_f (CH₂Cl₂/acetone 10:1) 0.37. IR (CHCl₃): 3667w, 3600m, 3008s, 2932m, 2860s, 1909m, 1702s, 1610s, 1500s, 1448w, 1384m, 1361m, 1263w, 1082s, 1039w, 1006s, 913w, 816m. ¹H-NMR (400 MHz, CDCl₃): 1.71 (t, *J* = 5.8, 1 OH); 4.58, 4.59, 4.82 (3s, 3 PhCH₂O); 4.74 (d, *J* = 5.1, CH₂OH); 5.24 (dd, *J* = 10.9, 0.9, 1 vinyl H); 5.75 (dd, *J* = 17.6, 1.0, 1 vinyl H); 6.72 (dd, *J* = 17.6, 10.9, CH₂CH); 7.34–7.61 (m, 12 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 65.13; 71.76; 71.91; 113.84; 126.29; 127.14; 127.29; 127.49; 128.03; 128.29; 136.56; 137.07; 137.40; 137.84; 139.92; 140.23; 140.37. EI-MS: 331.2 (13), 330.2 (51, *M*⁺), 226.1 (6), 213.1 (25), 212.1 (6), 199.1 (63), 197.1 (100), 196.1 (15), 195.1 (15), 183.1 (10), 182.1 (5), 181.1 (11), 180.1 (21), 178.1 (6), 169.1 (11), 168.1 (17), 167.1 (64), 166.1 (9), 165.1 (28), 156.1 (5), 155.1 (40), 154.1 (8), 153.0 (12), 152.0 (19), 119.1 (11), 118.1 (79), 117.0 (74), 116.0 (6), 115.0 (19), 105.0 (11), 103.0 (6), 91.0 (16). Anal. calc. for C₂₃H₂₂O₂ (330.42): C 83.61, H 6.71; found: C 83.42, H 6.92.

4-(Bromomethyl)-4'-[4-ethenylbenzyloxy)methyl]-1,1'-biphenyl (19). PBr₃ (0.06 ml, 0.61 mmol) was added to a suspension of **18** (0.20 g, 0.61 mmol) in Et₂O (20 ml) at 0° and stirred at this temp. for 1 h. For workup, H₂O (20 ml) was added, and the mixture was extracted with CH₂Cl₂ (3 × 50 ml). The combined org.

phases were washed with sat. NaHCO_3 soln. (100 ml) and dried (MgSO_4). FC (hexane/ CH_2Cl_2 1:1) gave **19** (155 mg, 65%). White solid. M.p. 104.0–106.0°. R_f (hexane/acetone 2:1) 0.42. IR (CHCl_3): 3008s, 2925m, 2857s, 1910m, 1629m, 1610m, 1500s, 1401m, 1360m, 1083s, 1006s, 990m, 913s, 828s. $^1\text{H-NMR}$ (400 MHz, CDCl_3): 4.55 (s, CH_2Br); 4.58, 4.59 (2s, 2 PhCH_2O); 5.24 (dd, $J = 10.9, 0.9$, 1 vinyl H); 5.75 (dd, $J = 17.6, 0.9$, 1 vinyl H); 6.72 (dd, $J = 17.6, 10.9$, CH_2CH), 7.34–7.59 (m, 12 arom. H). $^{13}\text{C-NMR}$ (100 MHz, CDCl_3): 33.36; 71.72; 71.95; 113.84; 126.29; 127.14; 127.49; 128.02; 128.29; 129.52; 136.54; 136.79; 137.07; 137.68; 137.81; 139.81; 141.09. EI-MS: 394.1 (11), 392.1 (11, M^+), 314.2 (30), 313.2 (100), 262.0 (7), 261.0 (6), 260.0 (7), 259.0 (5), 195.1 (11), 182.1 (12), 181.1 (49), 180.1 (49), 179.1 (5), 178.1 (10), 168.1 (7), 167.1 (24), 166.1 (9), 165.1 (22), 156.7 (8), 152.1 (6), 146.1 (7), 119.1 (5), 118.1 (47), 117.1 (59), 115.1 (13), 105.1 (6), 91.1 (9). Anal. calc. for $\text{C}_{23}\text{H}_{21}\text{OBr}$ (393.32): C 70.24, H 5.38; found: C 70.04, H 5.28.

(4*R*,5*R*)- $\alpha,\alpha,\alpha',\alpha'$ -Tetrakis[4-(4-ethenylbenzyloxy)butoxymethyl]benzyloxyphenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (**20**). According to *GP 1*, a suspension of **1** [**1**][**24**] (578 mg, 0.98 mmol), **14** (1.53 g, 3.93 mmol), and K_2CO_3 (543 mg, 3.93 mmol) in acetone (40 ml) was heated at 55° for 40 h. Workup and FC (hexane/ CH_2Cl_2 /acetone 5:2:0.1 \rightarrow 5:2:0.5) gave **20** (1.13 g, 65%). Colorless foam. R_f (hexane/acetone 2:1) 0.46. $[\alpha]_D^{25} = -30.0$ ($c = 1.00$, CHCl_3). IR (CHCl_3): 3348w, 3056w, 3008s, 2940m, 2861s, 1607s, 1582w, 1509s, 1456w, 1405w, 1362s, 1295w, 1264w, 1090s, 1017m, 910m, 832m. $^1\text{H-NMR}$ (500 MHz, CDCl_3): 1.08 (s, 2 Me); 1.70–1.74 (m, 8 CH_2); 3.48–3.52 (m, 8 CH_2O); 4.00 (s, 2 OH); 4.50–4.51 (m, 8 PhCH_2O); 4.53 (s, H–C(4), H–C(5)); 5.03, 5.08 (2s, 4 PhCH_2O); 5.24 (dd, $J = 11.8, 0.9$, 4 vinyl H); 5.75 (dd, $J = 17.6, 1.1$, 4 vinyl H); 6.70–6.76 (m, 4 CH_2CH); 6.86, 6.95 (2d, $J = 8.9$, 8 arom. H (TADDOL)); 7.26–7.47 (m, 32 arom. H, 8 arom. H (TADDOL)). $^{13}\text{C-NMR}$ (125 MHz, CDCl_3): 26.52; 26.54; 27.23; 69.75; 69.83; 70.11; 70.18; 70.20; 72.56; 72.58; 77.60; 81.15; 109.21; 113.52; 113.69; 114.29; 126.22; 127.51; 127.66; 127.81; 128.91; 129.74; 135.34; 136.25; 136.30; 136.61; 136.90; 138.28; 138.47; 138.49; 138.69; 157.93; 158.01. MALDI-TOF-MS (HABA): 1787.1 ($[M + \text{Na}]^+$).

(4*R*,5*R*)- $\alpha,\alpha,\alpha',\alpha'$ -Tetrakis[4-(4-ethenylbenzyloxy)methyl][1,1'-biphenyl]-4-ylmethoxyphenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (**21**). According to *GP 1*, a suspension of **1** [**1**][**24**] (286 mg, 0.49 mmol), **19** (765 mg, 1.95 mmol), and K_2CO_3 (270 mg, 1.95 mmol) in acetone (15 ml) was heated at 50° for 12 h, then at 65° for 28 h. Workup according to *GP 1* and purification of the crude product by FC ($\text{CH}_2\text{Cl}_2 \rightarrow \text{CH}_2\text{Cl}_2/\text{acetone}$ 99:1) yielded **21** (579 mg, 76%). Colorless foam. R_f (hexane/acetone 1:1) 0.49. $[\alpha]_D^{25} = -42.4$ ($c = 1.00$, CHCl_3). IR (CHCl_3): 3584w, 3341w, 3042w, 3008s, 2860s, 1910w, 1608m, 1582w, 1508s, 1461w, 1402w, 1380m, 1298m, 1248s, 1082s, 1006s, 911m, 884m, 831m. $^1\text{H-NMR}$ (500 MHz, CDCl_3): 1.09 (s, 2 CH_3); 4.04 (s, 2 OH); 4.53 (s, H–C(4), H–C(5)); 4.59–4.60 (m, 8 PhCH_2O); 5.06 (s, 2 PhCH_2O); 5.13 (s, 2 PhCH_2O); 5.26 (dd, $J = 11.8, 0.9$, 4 vinyl H); 5.75 (dd, $J = 16.7, 1.0$, 4 vinyl H); 6.71–6.77 (m, 4 CH_2CH); 6.89, 6.98 (2d, $J = 9.0$, 8 arom. H (TADDOL)); 7.27–7.64 (m, 48 arom. H, 8 arom. H (TADDOL)). $^{13}\text{C-NMR}$ (125 MHz, CDCl_3): 27.25; 69.69; 69.77; 71.75; 71.90; 71.91; 77.62; 81.15; 109.25; 113.56; 113.82; 114.30; 126.29; 127.15; 127.16; 127.29; 127.96; 128.02; 128.11; 128.27; 128.29; 128.93; 129.76; 135.41; 136.02; 136.06; 136.56; 137.06; 137.45; 137.47; 137.85; 138.69; 140.17; 140.20; 140.65; 140.67; 157.92; 158.02. MALDI-TOF-MS (HABA): 1803.0 ($[M + \text{Na}]^+$). Anal. calc. for $\text{C}_{123}\text{H}_{110}\text{O}_{12}$ (1780.18): C 82.99, H 6.23; found: C 83.09, H 6.29.

5. Preparation of TADDOL **26**. Bis(4-ethenylphenyl)methanol (**22**). At r.t., a soln. of 4-ethenylbenzaldehyde [**20a**] (4.80 g, 36.4 mmol) in THF (10 ml) was slowly added to a soln. of the Grignard reagent prepared from 4-chlorostyrene (5.04 g, 36.4 mmol) and Mg (1.06 g, 43.7 mmol) in THF (10 ml). After heating at 70° for 1 h, the soln. was cooled to 0°, 2M HCl (90 ml) was added, and the mixture was stirred for 5 min. The resulting suspension was extracted with Et_2O (3×100 ml), the combined org. phases were dried (MgSO_4), and the solvents were evaporated to give a yellow solid as crude product. FC (CH_2Cl_2) afforded **22** (6.86 g, 80%). Colorless solid. R_f (CH_2Cl_2) 0.32. $^1\text{H-NMR}$ (300 MHz, CDCl_3): 2.20 (d, $J = 3.7$, OH); 5.23 (d, $J = 11.2$, 2 vinyl H); 5.72 (d, $J = 17.4$, 2 vinyl H); 5.81 (d, $J = 3.3$, CHOH); 6.69 (dd, $J = 17.4, 11.2$, 2 CH_2CH); 7.30–7.40 (m, 8 arom. H).

Bis(4-ethenylphenyl)methanone (**23**). A soln. of $\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$ (3.65 g, 12.2 mmol) and conc. H_2SO_4 (3.3 ml) in H_2O (20 ml) was slowly added to a soln. of **22** (6.86 g, 29.1 mmol) in Et_2O (25 ml). After stirring at r.t. for 2 h (TLC control), Et_2O (100 ml) was added, and the Cr salts were filtered off over *Celite*. After evaporation of the solvent, Et_2O (100 ml) was added to the residue, and the org. phase was washed with H_2O (100 ml) and sat. NaHCO_3 soln. (2×100 ml). Drying of the org. phase (MgSO_4) and evaporation of the solvent, followed by FC (hexane/ CH_2Cl_2 1:2), afforded **23** (4.90 g, 72%). White solid. M.p. 118.0–120.0°. R_f (hexane/ CH_2Cl_2 1:1) 0.31. IR (CHCl_3): 3008w, 1653s, 1605s, 1556w, 1402m, 1310m, 1281s, 1178m, 1150w, 1116w, 1016w, 999m, 930s, 861m. $^1\text{H-NMR}$ (400 MHz, CDCl_3): 5.40 (dd, $J = 10.9, 0.7$, 2 vinyl H); 5.89 (dd, $J = 17.6, 0.7$; 2 vinyl H); 6.78 (dd, $J = 17.6, 10.9$; 2 CH_2CH); 7.49–7.50 (m, 4 arom. H); 7.76–7.79 (m, 4 arom. H). $^{13}\text{C-NMR}$ (100 MHz, CDCl_3): 116.55; 126.04; 130.44; 136.03; 136.85; 141.49; 195.61. EI-MS: 235.2 (6), 234.2 (40 M^+), 206.2

(5), 132.1 (10), 131.1 (100), 103.1 (47), 102.1 (11), 77.1 (54), 76.1 (6), 75.1 (5), 51.1 (12), 28.1 (7). Anal. calc. for $C_{17}H_{14}O$ (234.29): C 87.15, H 6.02; found: C 87.04, H 6.18.

Bis(4-ethenylphenyl)dimethoxymethane (24). A soln. of **23** (1.50 g, 6.4 mmol), TsOH (5 mg), HC(OMe)₃ (1.43 ml, 12.8 mmol), and MeOH (40 ml) was heated at 80°. After 3 h, the mixture was cooled to r.t., and 1*N* NaOH (50 ml) was added. Extraction of the aq. phase with Et₂O (3 × 100 ml), drying of the combined org. phases (MgSO₄), and evaporation of the solvents, followed by FC (hexane/CH₂Cl₂ 1:1), afforded **24** (1.70 g, 95%). Colorless oil. *R*_f (hexane/CH₂Cl₂ 1:2) 0.51. IR (CHCl₃): 3088*w*, 3008*m*, 2941*m*, 2832*m*, 1630*m*, 1507*m*, 1402*m*, 1177*m*, 1092*s*, 1059*s*, 1018*m*, 991*s*, 912*s*, 848*s*. ¹H-NMR (400 MHz, CDCl₃): 3.13 (*s*, 2 Me); 5.21 (*dd*, *J* = 10.9, 1.0, 2 vinyl H); 5.71 (*dd*, *J* = 17.6, 1.0, 2 vinyl H); 6.67 (*dd*, *J* = 17.6, 10.9, 2 CH₂CH); 7.32–7.35 (*m*, 4 arom. H); 7.43–7.46 (*m*, 4 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 49.32; 102.76; 113.91; 125.93; 127.07; 136.50; 136.76; 141.92. EI-MS: 280.1 (6, *M*⁺), 250.1 (19), 249.1 (100), 234.0 (13), 206.0 (6), 177.0 (13), 131.0 (36), 103.0 (12), 77.0 (8). Anal. calc. for C₁₉H₂₀O₂ (280.36): C 81.40, H 7.19; found: C 81.35, H 7.24.

*Diethyl (4*R*,5*R*)-2,2-Bis(4-ethenylphenyl)-1,3-dioxolane-4,5-dicarboxylate (25)*. BF₃ · OEt₂ (4.7 ml, 15.6 mmol, 48% in Et₂O) was slowly added to a soln. of (*R,R*)-diethyl tartrate (1.33 ml, 7.8 mmol) and **24** (2.18 g, 7.8 mmol) in AcOEt (30 ml) at 0°. After stirring at this temp. for 1 h, AcOEt (30 ml) and 1*N* NaOH (50 ml) were added, the org. phase was separated, and the aq. layer was extracted with AcOEt (2 × 50 ml). Drying of the combined org. phases (MgSO₄), evaporation of the solvent, and FC (pentane/Et₂O 4:1) afforded **25** (2.60 g, 79%). Colorless oil. *R*_f (pentane/Et₂O 3:1) 0.41. $[\alpha]_D^{25} = +60.4$ (*c* = 1.00, CHCl₃). IR (CHCl₃): 3090*w*, 2985*m*, 1745*s*, 1630*w*, 1566*w*, 1509*w*, 1466*w*, 1402*m*, 1373*m*, 1265*s*, 1106*s*, 1024*s*, 990*m*, 960*w*, 915*m*, 846*m*. ¹H-NMR (400 MHz, CDCl₃): 1.21 (*t*, *J* = 7.1, 2 Me); 4.09–4.19 (*m*, 2 CH₂O); 4.93 (*s*, H–C(4), H–C(5)); 5.24 (*dd*, *J* = 10.9, 0.9, 2 vinyl H); 5.73 (*dd*, *J* = 17.6, 0.9, 2 vinyl H); 6.68 (*dd*, *J* = 17.6, 10.9, 2 CH₂CH); 7.34–7.37 (*m*, 4 arom. H); 7.47–7.50 (*m*, 4 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 13.98; 61.89; 113.05; 114.54; 125.87; 126.92; 136.33; 137.96; 139.98; 168.89. HR-MALDI-MS: 445.1609 (7, [*M* + Na]⁺), 423.1791 (9, [*M* + 1]⁺, calc. 423.1808), 319.1173 (100), 285.0607 (5), 159.5587 (6), 137.0237 (6), 106.3756 (9). Anal. calc. for C₂₅H₂₆O₆ (422.47): C 71.07, H 6.20; found: C 71.11, H 6.09.

*(4*R*,5*R*)-2,2-Bis(4-ethenylphenyl)- $\alpha,\alpha,\alpha',\alpha'$ -tetraphenyl-1,3-dioxolane-4,5-dimethanol (26)*. At r.t., a soln. of **25** (1.28 g, 3.0 mmol) in THF (10 ml) was added to a soln. of the Grignard reagent prepared from bromobenzene (2.38 g, 15.1 mmol) and Mg (0.37 g, 15.1 mmol) in THF (10 ml). After stirring at r.t. for 3 h, the mixture was hydrolyzed by the addition of sat. NH₄Cl soln. (30 ml) and H₂O (30 ml). The aq. phase was extracted with Et₂O (3 × 100 ml), and the combined org. phases were washed with brine (100 ml) and dried (MgSO₄). After evaporation of the solvents, the crude product was subjected to FC (pentane/Et₂O 5:1) to give **26** (1.35 g, 69%). Colorless foam. *R*_f (CH₂Cl₂) 0.56. $[\alpha]_D^{25} = +184.2$ (*c* = 0.99, CHCl₃). IR (CHCl₃): 3549*s*, 3008*m*, 1630*m*, 1600*m*, 1494*s*, 1448*s*, 1403*m*, 1178*w*, 1104*s*, 1048*m*, 1016*m*, 999*m*, 914*s*, 851*s*, 634*w*, 616*s*. ¹H-NMR (400 MHz, CDCl₃): 2.07 (*s*, 2 OH); 5.20 (*dd*, *J* = 10.9, 0.9, 2 vinyl H); 5.53 (*s*, H–C(4), H–C(5)); 5.66 (*dd*, *J* = 17.6, 0.9, 2 vinyl H); 6.61 (*dd*, *J* = 17.6, 10.9, 2 CH₂CH); 6.87–6.97 (*m*, 6 arom. H); 7.01–7.04 (*m*, 4 arom. H); 7.18–7.27 (*m*, 14 arom. H); 7.47–7.49 (*m*, 4 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 79.54; 83.70; 112.04; 114.38; 125.16; 125.73; 126.45; 126.47; 126.80; 127.15; 127.80; 128.06; 136.22; 137.26; 142.37; 143.92; 145.73. ESI-MS: pos. mode: 681.4 ([*M* + K]⁺), 665.4 ([*M* + Na]⁺), 660.4 ([*M* + NH₄]⁺). Anal. calc. for C₄₅H₃₈O₄ (642.78): C 84.09, H 5.96; found: C 83.89, H 6.12.

6. Preparation of Dendrimers **30–32**. *1,1,1-Tris[4-(4-ethenylbenzyloxy)phenyl]ethane (30)*. 18-Crown-6 (0.30 g, 1.1 mmol) and K₂CO₃ (1.49 g, 10.8 mmol) were added to a soln. of 1,1,1-tris(4-hydroxyphenyl)ethane (1.00 g, 3.3 mmol) in acetone (50 ml), followed by 4-ethenylbenzyl chloride (1.83 g, 10.8 mmol), according to *GP I*. After heating under reflux for 48 h the reaction was worked up and purified by FC (hexane/CH₂Cl₂ 1:1) to give **30** (1.88 g, 86%). Colorless powder. M.p. 126.0–128.0°; *R*_f (hexane/acetone 1:1) 0.67. IR (CHCl₃): 3007*m*, 1606*s*, 1579*w*, 1506*s*, 1463*w*, 1406*m*, 1376*m*, 1292*m*, 1178*s*, 1117*w*, 1021*s*, 990*m*, 913*m*, 831*s*. ¹H-NMR (400 MHz, CDCl₃): 2.10 (*s*, Me); 5.01 (*s*, 3 PhCH₂O); 5.25 (*dd*, *J* = 10.9, 0.9, 3 vinyl H); 5.74 (*dd*, *J* = 17.6, 0.9, 3 vinyl H); 6.71 (*dd*, *J* = 17.6, 10.9, 3 CH₂CH); 6.85, 6.98 (2*d*, *J* = 9.0, 12 arom. H); 7.36–7.43 (*m*, 12 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 30.75; 50.63; 69.72; 113.96; 114.05; 126.39; 127.72; 129.63; 136.44; 136.67; 137.28; 142.03; 156.79. FAB-MS: 654 (26, *M*⁺), 639 (53), 523 (8), 445 (100), 329 (20), 233 (7), 117 (17), 116 (95). Anal. calc. for C₄₇H₄₂O₃ (654.85): C 86.21, H 6.46; found: C 86.11, H 6.46.

1,1,1-Tris[4-[3,5-bis(4-ethenylbenzyloxy)benzyloxy]phenyl]ethane (31). 18-Crown-6 (0.24 g, 0.9 mmol), K₂CO₃ (1.40 g, 10.1 mmol), and dendritic branch **3** [22] (4.00 g, 9.2 mmol) were consecutively added to a soln. of 1,1,1-tris(4-hydroxyphenyl)ethane (0.94 g, 3.1 mmol) in acetone (80 ml), according to *GP I*. The resulting suspension was heated under reflux for 48 h. Workup and FC (hexane/CH₂Cl₂ 1:1 → CH₂Cl₂) gave **31** (3.85 g, 92%). Colorless foam. *R*_f (hexane/acetone 1:1) 0.65. IR (CHCl₃): 3008*m*, 1597*s*, 1508*s*, 1458*m*, 1407*w*, 1373*m*, 1293*m*, 1248*m*, 1156*s*, 1017*m*, 990*m*, 913*m*, 832*s*. ¹H-NMR (400 MHz, CDCl₃): 2.10 (*s*, Me); 4.95, 5.00 (2*s*,

9 PhCH₂O); 5.24 (*dd*, *J* = 10.9, 0.9, 6 vinyl H); 5.74 (*dd*, *J* = 17.6, 0.9, 6 vinyl H); 6.54 (*t*, *J* = 2.2, 3 arom. H); 6.66 (*d*, *J* = 2.2, 6 arom. H); 6.71 (*dd*, *J* = 17.6, 10.9, 6 CH₂CH); 6.83, 6.98 (*d*, *J* = 9.0, 12 arom. H); 7.34–7.42 (*m*, 24 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 30.77; 50.65; 69.85; 69.91; 101.54; 106.43; 114.02; 114.12; 126.42; 127.75; 129.64; 136.30; 136.42; 137.36; 139.62; 142.08; 156.75; 160.09. FAB-MS: 1369 (3, *M*⁺), 1354 (28, [*M* – CH₃]⁺), 1239 (5), 922 (16), 921 (13), 805 (5), 567 (5), 353 (4), 233 (7), 118 (15), 117 (100). Anal. calc. for C₉₅H₈₄O₉ (1369.70): C 83.31, H 6.18; found: C 83.28, H 6.36.

1,1,1-Tris(4-[3,5-Bis[3,5-bis(4-ethenylbenzyloxy)benzyloxy]phenyl)ethane (32). According to *GP 1*, 18-crown-6 (0.06 g, 0.2 mmol), K₂CO₃ (0.32 g, 2.3 mmol) and branch **4** [22] (2.00 g, 2.2 mmol) were added to a soln. of 1,1,1-tris(4-hydroxyphenyl)ethane (0.22 g, 0.7 mmol) in acetone (20 ml), and the mixture was heated under reflux for 48 h. Workup and FC (CH₂Cl₂) afforded **32** (1.76 g, 89%). Colorless foam. *R_f* (hexane/acetone 1:1) 0.56. IR (CHCl₃): 3008*m*, 2870*w*, 1596*s*, 1511*m*, 1451*m*, 1407*w*, 1373*m*, 1295*m*, 1156*s*, 1056*m*, 1017*m*, 990*m*, 913*m*, 832*m*. ¹H-NMR (500 MHz, CDCl₃): 2.07 (*s*, Me); 4.92, 4.94, 4.98 (3*s*, 21 PhCH₂O); 5.23 (*dd*, *J* = 10.9, 0.9, 12 vinyl H); 5.72 (*dd*, *J* = 17.6, 0.9, 12 vinyl H); 6.51, 6.53 (2*t*, *J* = 2.2, 9 arom. H); 6.64 (*d*, *J* = 2.2, 18 arom. H); 6.68 (*dd*, *J* = 17.6, 10.9, 12 CH₂CH); 6.82, 6.96 (2*d*, *J* = 9.0, 12 arom. H); 7.33, 7.37 (2*d*, *J* = 8.2, 48 arom. H). ¹³C NMR (125 MHz, CDCl₃): 30.78; 50.67; 69.85; 69.91; 69.97; 101.56; 101.64; 106.40; 106.49; 114.03; 114.10; 126.41; 127.73; 129.65; 136.30; 137.34; 139.26; 139.58; 142.09; 156.77; 160.03; 160.11. MALDI-TOF-MS (DHB): 2823.7 ([*M* + Na]⁺), 2840.5 ([*M* + K]⁺). Anal. calc. for C₁₉₁H₁₆₈O₂₁ (2799.42): C 81.95, H 6.05; found: C 81.91, H 6.18.

7. Suspension Copolymerization of Cross-Linkers 5–7 and 20, 21, 25 and 26 with Styrene, of TADDOL 28 with Styrene/DVB, and of TADDOL 28 with Styrene and Dendrimers 30, 31, or 32. General Procedure 3 (GP 3) [1][20][29]. Example for the preparation of TADDOL/styrene-copolymer p-**6** with a loading of 0.10 mmol g⁻¹: In a three-necked flask, equipped with a condenser and an overhead stirrer, a warm soln. of poly(vinyl alcohol) (80 mg, degree of polymerization 100000, 86–89% hydrolyzed) in H₂O (25 ml), which was prepared by violent stirring at 40–50° and filtration of the insoluble parts, was added to a soln. of **6** (1.00 g, 0.51 mmol), styrene (4.27 g, 41.04 mmol, 80 equiv.), and AIBN (35 mg) in THF (2.5 ml) and benzene (8.3 ml). After stirring at r.t. for 5 min to homogenize the emulsion, the temp. was slowly raised to 75–80°. After stirring at this temp. for 40 h, the suspension was filtered through a glass filter (*G2*), and the resulting polymer beads were washed with hot H₂O (500 ml), MeOH/H₂O (200 ml), MeOH (200 ml), THF (200 ml), MeOH (200 ml), and pentane (200 ml), then collected and dried under high vacuum for several h to give polymer p-**6** (5.02 g, 95%, theoretical loading: 0.10 mmol g⁻¹). The beads were collected by size with a set of sieves (mesh width: 1000, 800, 630, 500, 400, 250, 160, 100) to give fractions of uniform size. Anal. calc. for C₁₃₁H₁₁₈O₁₆ + 80 C₈H₈ (10280.46): C 90.08 H 7.43; found: C 89.17 H 7.79.

The loading of the polymers is calculated by the amount of TADDOL (mmol) divided by the amount of polymer (in g) (in the case of quant. conversion).

To determine the actual loading of the polymer with Ti, Ti(OⁱPr)₄ (22 μl, 0.074 mmol) was added to a suspension of p-**6** (762 mg, 0.074 mmol, loading 0.10 mmol g⁻¹) in toluene (4 ml). After stirring at r.t. for 14 h, the solvent was removed by syringe, and the beads were extensively washed with toluene (10 × 10 ml). Elemental analysis gave a loading of 0.0038 mg Ti/mg polymer, theoretical loading: 0.0046 mg Ti/mg polymer. This indicates that 83% of the theoretically available TADDOL centers are complexed with Ti.

According to *GP 3*, all polymers were prepared by stoichiometrically adjusting the amounts of solvents, AIBN, H₂O, and poly(vinyl alcohol) to the amounts of monomers used.

8. Generation of Polymer-Bound TADDOLs by Addition of Aryl Grignard Reagents to Polymer-Bound Diester p-25: Polymers p-26' and p-27. General Procedure 4 (GP 4). Example for the preparation of polymer p-**26'** with a loading of 0.21 mmol g⁻¹. A soln. of PhMgBr (1.4 ml, 1.2 mmol, 0.85*M*) in THF was added to a suspension of beads of p-**25** (916 mg, 0.20 mmol, loading 0.22 mmol g⁻¹) in THF (8 ml) and stirred at r.t. for 1 h. Then, THF (5 ml) was added, and the suspension was heated at 50° for 1 h. The polymer beads were washed with THF (5 × 30 ml), THF/1*N* HCl 10:1 (10 × 30 ml), THF/H₂O 10:1 (5 × 30 ml), THF (5 × 30 ml), MeOH (2 × 30 ml), and pentane (2 × 30 ml). After drying under high vacuum, p-**26'** (903 mg, 94%) was obtained as slightly yellow beads with a new theoretical loading of 0.21 mmol g⁻¹. IR (KBr): 3529*m*, 3059*w*, 3024*m*, 2923*s*, 1943*m*, 1870*m*, 1802*m*, 1734*m*, 1601*s*, 1491*s*, 1450*s*, 1364*m*, 1181*m*, 1068*s*, 1028*s*, 906*s*, 841*m*, 755*s*, 696*s*, 538*s*.

9. Addition of Et₂Zn to PhCHO Mediated by Polymer-Bound Ti-TADDOLates. General Procedure 5 (GP 5). Example for the catalysis with polymer p-**6** (20 mol-%) with a loading of 0.10 mmol g⁻¹: Beads of polymer p-**6** (1.85 g, 0.18 mmol, 0.2 equiv.) were suspended in toluene (9 ml) and stirred at r.t. for 2 h. After evaporation of the solvent under high vacuum (in order to remove traces of H₂O in the polymer), the dry beads were resuspended in toluene (9 ml). Ti(OⁱPr)₄ (54 μl, 0.18 mmol, 0.2 equiv.) was added, and the suspension was stirred at r.t. for 14 h, followed by evaporation of the solvent (azeotropic removal of *i*-PrOH). The dried beads

were resuspended in toluene (9 ml), and $\text{Ti}(\text{O}^i\text{Pr})_4$ (270 μl , 0.90 mmol, 1.0 equiv.) and PhCHO (92 μl , 0.90 mmol, 1.0 equiv.) were added. The mixture was cooled to -20° , and Et_2Zn (0.81 ml, 1.62 mmol, 1.8 equiv., 2M in toluene) was added. After 2 h, the soln. was withdrawn by syringe, and the polymer beads were washed with toluene (5×10 ml) under Ar. 1N HCl (50 ml) was added to the combined org. fractions, the org. phase was separated, and the aq. layer was extracted with Et_2O (2×50 ml). Drying of the combined org. phases (MgSO_4) and evaporation of the solvents afforded 1-phenylpropan-1-ol. The enantioselectivity and conversion of the reaction were determined by CGC analysis (column: *b*; heating rate $110^\circ/1.5^\circ$ per min; pressure: 1.3 bar; $t_{\text{R}}(\text{PhCHO})$ ca. 2.8 min, $t_{\text{R}}((R)\text{-1-phenylpropan-1-ol})$ ca. 9.9 min, $t_{\text{R}}((S)\text{-1-phenylpropan-1-ol})$ ca. 10.3 min) of the crude reaction product: (*R*)/(*S*)-1-phenylpropan-1-ol: 2:98, conversion: 99% after 2 h. For multiple use of the catalyst, the washed beads were resuspended in toluene (9 ml), and $\text{Ti}(\text{O}^i\text{Pr})_4$ (270 μl , 0.90 mmol, 1.0 equiv.) and PhCHO (92 μl , 0.90 mmol, 1.0 equiv.) were added, followed by Et_2Zn (0.81 ml, 1.62 mmol, 1.8 equiv., 2M in toluene) at -20° . After stirring at -20° for several h, a sample of the mixture was diluted with Et_2O , some drops of 1N HCl were added, and the enantioselectivity as well as the conversion were determined by analysis of the org. layer by CGC.

10. *Addition of Bu_2Zn to PhCHO Mediated by Polymer-Bound Ti-TADDOLates. General Procedure 6 (GP 6)*. Example for the catalysis with polymer p-**26** (20 mol-%) with a loading of 0.21 mmol g^{-1} : Beads of polymer p-**26** (529 mg, 0.11 mmol, 0.2 equiv.), after azeotropic drying, were suspended in toluene (4 ml), and $\text{Ti}(\text{O}^i\text{Pr})_4$ (33 μl , 0.11 mmol, 0.2 equiv.) was added. The suspension was stirred at r.t. for 14 h, followed by evaporation of the solvent. The beads were resuspended in toluene (4 ml), then $\text{Ti}(\text{O}^i\text{Pr})_4$ (198 μl , 0.66 mmol, 1.2 equiv.) and PhCHO (56 μl , 0.55 mmol, 1.0 equiv.) were added. The suspension was cooled to -20° , and a Bu_2Zn solution was added, which had been prepared by adding BuLi (1.4 ml, 2.23 mmol, 4.0 equiv., 1.6M in hexane) to a soln. of ZnCl_2 (1.12 ml, 1.12 mmol, 2.0 equiv., 1M in Et_2O) in toluene (1.1 ml) [34], stirring at r.t. for 2 h and filtering the suspension through a syringe filter (PTFE, 0.45 μm). After 4.5 h at -20° , the soln. was separated and worked up as described in GP 5. The enantioselectivity and conversion of the reaction were determined by CGC analysis (column: *a*; heating 105° /isothermal; pressure: 1.0 bar; $t_{\text{R}}(\text{PhCHO})$ ca. 3.9 min, $t_{\text{R}}((R)\text{-1-phenylpentan-1-ol})$ ca. 40.5 min, $t_{\text{R}}((S)\text{-1-phenylpentan-1-ol})$ ca. 42.1 min) of the crude reaction product: (*R*)/(*S*)-1-phenylpentanol: 4:96, conversion: 68% after 4.5 h. For multiple use, substrates were added as described above.

11. *1,3-Dipolar Cycloaddition of Diphenyl Nitronone to [(E)-But-2-enoyl]-oxazolidinone Mediated by p-6-TiCl₂. General Procedure 7 (GP 7)*. Example for the reaction with p-**6** with a loading of 0.10 mmol g^{-1} : After azeotropic drying, polymer beads of p-**6** (1.66 g, 0.16 mmol, 0.5 equiv.) were suspended in toluene (4 ml), and a solution of $\text{TiCl}_2(\text{O}^i\text{Pr})_2$ [35a] (1.6 ml, 0.16 mmol, 0.5 equiv., 0.1M in toluene) was added, whereupon the beads immediately adopted a brown color. After stirring at r.t. for 14 h, the solvent was removed under reduced pressure, and the beads were resuspended in toluene (4 ml). The suspension was cooled to 0° , and a soln. of diphenyl nitronone [40] (76 mg, 0.35 mmol, 1.1 equiv.) and [(*E*)-but-2-enoyl]oxazolidinone [41] (50 mg, 0.32 mmol, 1.0 equiv.) in toluene (1 ml) was added. The mixture was stirred at this temp. for 48 h. For workup, the soln. was withdrawn by syringe, and the polymer beads were washed with toluene (3×10 ml). After evaporation of the solvent, the *exo/endo* selectivity (82:18) as well as the conversion (93%) were determined by $^1\text{H-NMR}$ analysis of the crude product [35a]. FC (pentane/ Et_2O 1:1) of the crude product afforded pure *exo*-cycloadduct **29** as a colorless foam, the enantiomer ratio (75:25) of which was determined by $^1\text{H-NMR}$ analysis with $[\text{Eu}(\text{hfc})_3]$ as a shift reagent. The polymer beads were hydrolyzed with THF/1N HCl 10:1 (5×20 ml), followed by washing with THF/ H_2O 10:1 (5×20 ml), THF (5×20 ml), and MeOH (2×20 ml). After azeotropic drying with toluene the polymer beads were loaded with titanate and employed for a new catalytic run as described above.

12. *1,3-Dipolar Cycloaddition of Diphenyl Nitronone to [(E)-But-2-enoyl]-oxazolidinone Mediated by p-6-Ti(OTs)₂. General Procedure 8 (GP 8)*. Example for the reaction with p-**6** with a loading of 0.10 mmol g^{-1} : Azeotropically dried polymer beads of p-**6** (2.57 g, 0.25 mmol, 0.5 equiv.) were suspended in toluene (6 ml), and a soln. of $\text{Ti}(\text{O}^i\text{Pr})_2(\text{OTs})_2$ [35b] (2.5 ml, 0.25 mmol, 0.5 equiv., 0.1M in toluene) was added. The beads immediately adopted a brown color. After stirring at r.t. for 5 h, the solvent was removed under reduced pressure. The beads were resuspended in toluene (6 ml), and the suspension was cooled to 0° , followed by addition of a soln. of nitronone [40] (119 mg, 0.6 mmol, 1.2 equiv.) and [(*E*)-but-2-enoyl]oxazolidinone [41] (78 mg, 0.5 mmol, 1.0 equiv.) in toluene (1 ml). The mixture was allowed to warm to r.t. and stirred at this temp. for 48 h. Then, the soln. was filtered off, and the beads were washed with toluene (3×10 ml). After evaporation of the solvent, the conversion (72%) and the *endo/exo* selectivity (88:12) were determined by $^1\text{H-NMR}$ spectroscopy [35b]. Pure *endo*-cycloadduct **29** (51 mg, 29%) was isolated by FC (pentane/ Et_2O 1:1) and prep. TLC ($\text{CH}_2\text{Cl}_2/\text{MeOH}$ 99:1) of the crude product, and the enantioselectivity (7:93) of *endo*-**29** was determined by HPLC analysis [35b] with a chiral column (*Daicel Chiralcel OD*, hexane/*i*-PrOH 9:1, flow rate 1 ml min^{-1} ,

t_R (minor): ca. 54.5 min, t_R (major): ca. 64.5 min). The polymer beads were washed and used for multiple applications as described above.

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