Preparation of Polystyrene Beads with Dendritically Embedded TADDOL and Use in Enantioselective Lewis Acid Catalysis 1)

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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. 1–5). 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 Et2Zn 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 (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 Cl2 and (TsO)2Ti-TADDOLate as chiral Lewis acid to preferentially prepare one enantiomer of the exo and the endo (3 + 2) cycloadduct, respectively, of diphenyl nitroso 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].

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]). 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 Sc(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
copolymerized with styrene and DVB as cross-linker to give, after loading with metal salts, polymer-bound TADDOLate complexes of high catalytic activity [20]. In 1997, we reported for the first time on the copolymerization with styrene of styryl-functionalized TADDOL dendrimers according to Scheme 1. Besides our own work, TADDOL has also been immobilized by other groups [21].

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.
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 K$_2$CO$_3$ (4 equiv.) in acetone at 65°C were the best conditions to reduce the amount of C$_1$-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].
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)\(^5\)\(^6\).

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\(_2\)O, the desired bromide 19 was obtained in pure form without formation of by-products, even though 18 was insoluble in Et\(_2\)O.
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 \(\alpha,\alpha'\)-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
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
polymer-bound TADDOLs p-26 (‘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

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\(^7\) 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/I\textsubscript{2}/H\textsubscript{2}OCl.

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 Et\textsubscript{2}Zn and Bu\textsubscript{2}Zn to PhCHO. – The addition of Et\textsubscript{2}Zn to PhCHO catalyzed by (\textit{iPrO})\textsubscript{2}Ti-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 Et\textsubscript{2}Zn 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 H\textsubscript{2}O. The beads were resuspended in toluene, and an equimolar amount of Ti(O\textit{iPr})\textsubscript{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 \textit{iPrOH}. The polymer-bound Ti-TADDOLates p-5·Ti(O\textit{iPr})\textsubscript{4}, p-7·Ti(O\textit{iPr})\textsubscript{4}, p-20·Ti(O\textit{iPr})\textsubscript{4}, p-21·Ti(O\textit{iPr})\textsubscript{4}, p-26·Ti(O\textit{iPr})\textsubscript{4}, or p-28·Ti(O\textit{iPr})\textsubscript{4} were resuspended in toluene, Ti(O\textit{iPr})\textsubscript{4} (1 equiv.) as well as PhCHO (1 equiv.) were added, and the reaction mixture was cooled to –20\degree C, followed by addition of a 2\textit{m} solution of Et\textsubscript{2}Zn (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 1\textit{m} aqueous H\textsubscript{2}OCl, 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 Et\textsubscript{2}Zn-to-PhCHO addition with polymer-bound Ti-TADDOLates
Scheme 6. a) Multiple Use of Polymer-Bound Ti-TADDOLates in the Addition of Et₂Zn 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).

\[ \text{p-5} \cdot \text{Ti(O} \text{Pr})_2, \text{ p-6} \cdot \text{Ti(O} \text{Pr})_2, \text{ p-7} \cdot \text{Ti(O} \text{Pr})_2, \text{ p-20} \cdot \text{Ti(O} \text{Pr})_2, \text{ p-21} \cdot \text{Ti(O} \text{Pr})_2, \text{ p-26} \cdot \text{Ti(O} \text{Pr})_2 \text{ or p-28} \cdot \text{Ti(O} \text{Pr})_2 \]

0.2 equiv.

1.0 equiv. Ti(OPr)₄, toluene, -20°C

- Filtration of the reaction mixture
- Washing of the polymer-beads with toluene
- Workup of the reaction solution and GC analysis
- Re-use of the catalyst

major enantiomer

p-5 · Ti(O’Pr) ₂, p-7 · Ti(O’Pr) ₂, p-20 · Ti(O’Pr) ₂, p-21 · Ti(O’Pr) ₂, p-26 · Ti(O’Pr) ₂, or p-28 · Ti(O’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.
under homogeneous conditions (thus, with Ti-TADDOLate \( \text{28} \cdot \text{Ti(OiPr)}_2 \) 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 \cdot \text{Ti(OiPr)}_2, p-7 \cdot \text{Ti(OiPr)}_2, p-20 \cdot \text{Ti(OiPr)}_2, p-21 \cdot \text{Ti(OiPr)}_2, and p-26 \cdot \text{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 \cdot \text{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 \cdot \text{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 \cdot \text{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 \cdot \text{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 \cdot \text{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 Et\(_2\)Zn to PhCHO, according to the protocol outlined in Scheme 6. As can be seen from Fig. 4, a, the polymer with a

<table>
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<tr>
<th>Polymer</th>
<th>Loading [mmol g(^{-1})]</th>
<th>Conversion [%]</th>
<th>(S)/(R)</th>
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<tr>
<td>p-5 \cdot \text{Ti(OiPr)}_2</td>
<td>0.25</td>
<td>84</td>
<td>97:3</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>97</td>
<td>98:2</td>
</tr>
<tr>
<td>p-6 \cdot \text{Ti(OiPr)}_2</td>
<td>0.10</td>
<td>54</td>
<td>91:9</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>71</td>
<td>95:5</td>
</tr>
<tr>
<td>p-7 \cdot \text{Ti(OiPr)}_2</td>
<td>0.14</td>
<td>78</td>
<td>99:1</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>quant.</td>
<td>93:7</td>
</tr>
<tr>
<td>p-20 \cdot \text{Ti(OiPr)}_2</td>
<td>0.25</td>
<td>76</td>
<td>98:2</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>76</td>
<td>99:2</td>
</tr>
<tr>
<td>p-21 \cdot \text{Ti(OiPr)}_2</td>
<td>0.25</td>
<td>60</td>
<td>94:6</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>70</td>
<td>99:1</td>
</tr>
<tr>
<td>p-26 \cdot \text{Ti(OiPr)}_2</td>
<td>0.21</td>
<td>quant.</td>
<td>97:3</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>99</td>
<td>98:2</td>
</tr>
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\(\text{a) 2 mol }\% \text{ of catalyst are used. b) 5 mol }\% \text{ of catalyst are used. c) Reaction time 14 h. d) }[^{[\text{PhCHO}]} = 0.05\text{M.}]

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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 (→ 0.14 mmol g\(^{-1}\) → 0.25 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 p-5·Ti(OiPr)\(_2\), p-20·Ti(OiPr)\(_2\), p-21·Ti(OiPr)\(_2\), and p-28·Ti(OiPr)\(_2\) with a degree of loading of 0.10 mmol g\(^{-1}\) are presented in Fig. 4a. Whereas p-5·Ti(OiPr)\(_2\) and p-28·Ti(OiPr)\(_2\) gave rise to stable enantioselectivities during recycling, comparable to p-6·Ti(OiPr)\(_2\), polymers p-20·Ti(OiPr)\(_2\) (containing TADDOL cross-linker 20 with flexible alkyl spacers) and p-21·Ti(OiPr)\(_2\) (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 p-6·Ti(OiPr)\(_2\) with different degrees of loading and of b) polymers p-5·Ti(OiPr)\(_2\), p-20·Ti(OiPr)\(_2\), p-21·Ti(OiPr)\(_2\), and p-28·Ti(OiPr)\(_2\) with degrees of loading of 0.10 mmol g\(^{-1}\)](image-url)
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 Et₂Zn 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·Ti(PrO)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·Ti(PrO)₂, p-20·Ti(PrO)₂, and p-21·Ti(PrO)₂, prepared with nondendritic TADDOL cross-linkers, showed a decline in reaction kinetics during multiple use. The reaction rates measured with p-20·Ti(PrO)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·Ti(PrO)₂ had given rise to a constant performance with respect to enantioselectivity during recycling (cf. Fig. 4, b), like p-6·Ti(PrO)₂. In contrast, however, the reaction rates gradually dropped (Fig. 5, c), in pronounced contrast to polymer p-6·Ti(PrO)₂ (Fig. 5, a). This means that only with dendritically cross-linked polymer p-6·Ti(PrO)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·Ti(PrO)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·Ti(PrO)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-Ti(OiPr)$_2$, b) p-20-Ti(OiPr)$_2$, and c) p-28-Ti(OiPr)$_2$ with degrees of loading of 0.10 mmol g$^{-1}$
very persistent and stable morphology, which explains its superior catalytic performance.

To learn more about the factors that influence the reaction kinetics observed with p-6-Ti(OiPr)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 p-6-Ti(OiPr)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\(^6\)-Ti(OiPr)\(_2\) 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-28·Ti(OiPr)2 with those observed when we used the corresponding monomer 28·Ti(OiPr)2 under homogeneous conditions (Fig. 8, a). However, when comparing the kinetics of the dendrimer complex 6·Ti(OiPr)2 in solution and the dendritically cross-linked polymer p-6·Ti(OiPr)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) 28·Ti(OiPr)2 and p-28·Ti(OiPr)2; b) 6·Ti(OiPr)2 and p-6·Ti(OiPr)2.
One interpretation of this phenomenon might be that, in solution, the dendritic arms of complex 6·Ti(OiPr)_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 6 is chiral (C₂ 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 p-6·Ti(OiPr)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, Et₂Zn, and Ti(OiPr)₄) in these regions, leading to higher local concentrations and, therefore, a higher reaction rate. This is not the case with polymer p-28·Ti(OiPr)₂; and may serve as a third rationale supporting a higher reaction rate with polymer p-6·Ti(OiPr)₂ (under heterogeneous conditions), as compared to the monomer 6·Ti(OiPr)₂ (under homogeneous conditions). Elemental analysis of a sample of p-6·Ti(OiPr)₂ indicated that 85% of the TADDOL sites are complexed with Ti. In contrast, all dendritic TADDOL ligands 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 (1).

As already mentioned, one aim of our work was to check whether catalytically active TADDOL ligands could be generated by copolymerization of diester 25 followed by Grignard addition (cf. Scheme 5,b). The Ti-TADDOLate-mediated addition of Bu₂Zn to PhCHO was chosen as test reaction for polymers p-26·Ti(OiPr)₂ and p-27·Ti(OiPr)₂ [34] (Table 2). The reactions were performed in analogy to the addition of Et₂Zn to PhCHO. The Bu₂Zn was prepared in situ by mixing BuLi (solution in hexane) with ZnCl₂ (solution in Et₂O) in toluene and removing LiCl with a syringe filter, prior to addition to the reaction mixture. For comparison, p-26·Ti(OiPr)₂, prepared by copolymerization of TADDOL 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 p-26·Ti(OiPr)₂ was only 2% lower, the reaction was markedly slower. It was not possible, as in the case of the addition of Et₂Zn to PhCHO, to simply recycle the polymers by washing and reloading with substrates. The polymer-bound Ti-TADDOLate complexes had to be hydrolyzed with THF/10% HCl, followed by reloading with titanate, prior to each catalytic run. Probably, the reaction of BuLi with ZnCl₂ was not complete, and these reagents caused inactivation of the polymer-bound Ti complex. Polymer p-26·Ti(OiPr)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 \( p-27 \cdot \text{Ti(OiPr)}_2 \), bearing naphthalen-2-y1 groups at the TADDOL units, 1-phenylpentan-1-ol was obtained with a lower enantiomer purity in comparison to \( p-26 \cdot \text{Ti(OiPr)}_2 \), whereas, in solution, the analogous tetra(naphthalene-2-y1)-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 \( \text{Bu}_2\text{Zn} \) 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).

5. Application of Polymer-Bound Ti-TADDOLate Complexes in Enantioselective 1,3-Dipolar Cycloadditions of Diphenyl Nitrone to \([ (E)\text{-But-2-enoyl}]\text{-oxazolidinone.} \)

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 \( \text{Et}_2\text{Zn} \) 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 \( p-28 \cdot \text{Ti(OiPr)}_2 \) can be used for the catalysis of the addition of diphenyl nitrone to \([ (E)\text{-but-2-enoyl}]\text{-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-6-TiCl$_2$ or b) p-6-Ti(OTs)$_2$ in the 1,3-dipolar cycloaddition of diphenyl nitrene to [\((E)\text{-but-2-enoyl}]$\text{-oxazolidinone}$
Polymer p-6 was loaded with titanate by the addition of a solution of TiCl$_2$(OiPr)$_2$ in toluene [36] to the polymer beads suspended in toluene. A solution of diphenyl nitronate and [(E)-but-2-enoxy]-oxazolidinone in toluene was added, and the mixture was worked up after a reaction time of 40 h at 0°C. The cycloadducts were isolated, and the conversion, the exo/endo selectivity, as well as the enantiomer ratio ofexo-29 were determined as described in [35a]. It turned out that high conversions could only be achieved when 50 mol-% of polymer p-6·TiCl$_2$ 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·TiCl$_2$, the exo/endo selectivity (82:18), the enantiomer purity ofexo-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 Et$_2$Zn 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/1M HCl, followed by reloading with titanate. With this protocol, p-6·TiCl$_2$ 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. 9a).

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. 9a, the exo 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·TiCl$_2$, 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 Cl$_2$Ti-TADDOLates. However, the formation of the corresponding endo-cycloadducts is favored, when (TsO)$_2$-Ti-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·TiCl$_2$, 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-exo-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. 9b. Within experimental error, the diastereomeric (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 conditions\(^8\).

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-6·Ti(OiPr)\(_2\). The dendritic cross-linkers 30, 31, and 32 of zeroth, first, and second generation were prepared by etherification of 1,1,1-tris(4-hydroxyphenyl)ethane with 4-vinylbenzyl chloride (→ 30) or branches 3 (→ 31) and 4

\(^8\) In 1999, Jørgensen and co-workers reported on the 1,3-dipolar cycloaddition of diphenyl nitrore 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 nitrore to tert-butyl vinyl ether were obtained, when 20 mol-% of tetra(naphthalen-2-yl)-TADDOL 1 (exo/endo 87:13, ex(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 AlMe\(_3\), giving rise to a stable performance. However, due to the rather modest enantioselectivities, no further investigations were carried out with this reaction.
(→32) in the presence of K$_2$CO$_3$ 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 TADDOLS 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·Ti(OiPr)$_2$, p-31·Ti(OiPr)$_2$, and p-32·Ti(OPr)$_2$ by the addition of Ti(OiPr)$_4$, and employed for the catalysis of the addition of Et$_2$Zn 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·Ti(OiPr)$_2$ and p-32·Ti(OiPr)$_2$, containing first- and second-generation dendrimers 31 and 32, respectively, as cross-linkers, are quite stable and reproducible, recycling p-30·Ti(OPr)$_2$ 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·Ti(OPr)$_2$.

In summary, it was not possible by this approach to obtain polymer-bound TADDOLates with a comparable performance as p-6·Ti(OPr)$_2$. 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·Ti(OPr)$_2$ gives rise to a faster reaction rate in the Et$_2$Zn addition to PhCHO than its soluble precursor 6·Ti(OPr)$_2$. 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)
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.

We gratefully acknowledge financial support by the Swiss National Science Foundation (project No. 2027-048157 and 20-50674.97, and Chiral2, project No. 20-48157-96). The following companies provided chemicals: Witco GmbH (Et2Zn), Chemische Fabrik Uetikon (diethyl tartrate). We thank Novartis Pharma AG, Basel, for continuing financial support.

Experimental Part

1. General. Reagents: (i-PrO)2TiCl2 [35a] and 2 m stock soln. of Et2Zn [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. PhCHO was distilled prior to use. All other commercially available chemicals were as received from Fluka, Aldrich, or Acros. TLC: precoated silica gel 254 plates (Macherey-Nagel); visualization by UV 254 light or by development with phosphomolybdic acid solution (phosphomolybdic acid (25 g), Ce(SO4)2 ¥H2O (10 g), H2SO4 (conc., 60 ml), and H2O (940 ml)), followed by heating with a heat gun. Flash column chromatography (FC): silica gel 60 (Fluka, 0.040±0.063 mm); N2-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 Chiral OD (Daicel Chemical Industries, Ltd.; 4.6 ¥ 250 mm, 10 µm); eluent: hexane/i-PrOH 400:1 to 9:1; UV detection at 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°C; detector temp. 225°C (FID); carrier gas: H2. M.p.: Büchi-510 apparatus with open capillaries, uncorrected. Optical rotation [α]D: Perkin-Elmer 241 polarimeter (10 cm, 1 ml cell) at r.t.; p.a. solvents. IR Spectra: Perkin-Elmer 1600 FTIR; solns. in CHCl3; ν in cm-1. NMR Spectra: Bruker AMX-500 (H: 500 MHz, 13C: 125 MHz), AMX-400 (H: 400 MHz, 13C: 100 MHz), AMX-300 (H: 300 MHz, 13C: 75 MHz), Varian XL-300 (H: 300 MHz, 13C: 75 MHz), Gemini-300 (H: 300 MHz, 13C: 75 MHz), or Gemini-200 (H: 200 MHz, 13C: 50 MHz); chemical shifts (δ) in ppm downfield from TMS (δ = 0 ppm); J values in Hz; spectra were recorded in CDCl3. MS: Hitachi-Perkin-Elmer RMU-6M spectrometer (EI), VG ZAB-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). K$_2$CO$_3$ (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 PhCH$_2$Br (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 CH$_2$Cl$_2$. After evaporation of the solvent, the residue was redissolved in CH$_2$Cl$_2$, and H$_2$O was added. The org. layer was separated, and the aq. phase was extracted with CH$_2$Cl$_2$, followed by drying of the combined org. phases (MgSO$_4$), evaporation of the solvent, and isolation of the product by FC.

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° C. 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 (in THF at 0° C). The mixture was heated at 60–70°. For workup, H$_2$O was carefully added at 0°. After extraction (×3 Et$_2$O), drying of the combined org. phases (MgSO$_4$), and evaporation of the solvent, the resulting crude product was purified by FC.

Preparation of TADDOL Cross-Linkers 5 and 20. (4R,5R,6aS,7aS-Tetrakis[4-[3-(4-ethylbenzoxyl)benzoxyl][phenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (5). A suspension of hexol 1 [1,24] (366 mg, 0.60 mmol), benzyl bromide 2 [22] (755 mg, 2.5 mmol), and K$_2$CO$_3$ (344 mg, 2.5 mmol) in acetone (25 ml) was heated at 50° for 20 h, according to GP 1. Workup and FC (CH$_2$Cl$_2$ → CH$_2$Cl$_2$/acetone 99.5:0.5) afforded 5 (580 mg, 66 %). Colorless foam. R$_f$ (hexane/acetonitrile 1:1) 0.55. [α]$_D$ = 32.4 (c = 1.00, CHCl$_3$). IR (CHCl$_3$): 3411, 3078, 2928, 1710, 1606, 1586, 1509, 1490, 1450, 1400, 1372, 1295, 1264, 1248, 1087, 1016, 992, 913, 884, 831. 1H-NMR (500 MHz, CDCl$_3$): 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 CH$_2$O); 5.24 (dd, J = 10.8, 0.9, 4 vinyl H); 5.74 (dd, J = 17.3, 0.9, 2 vinyl H); 6.86 – 6.74 (m, 4 CH$_2$OH); 6.82 (d, J = 9.0, 4 arom. H (TADDOL)); 6.91 (d, J = 8.9, 4 arom. H (TADDOL)). 13C-NMR (125 MHz, CDCl$_3$): 67.68 – 7.44 (m, 24 arom. H, 8 arom. H (TADDOL)). 19F-NMR (272 MHz, CDCl$_3$): 2279, 69.76, 69.84, 77.60, 81.12, 109.23, 113.34, 113.82, 113.95, 114.10, 114.11, 114.34, 114.40, 119.87, 120.02, 126.42, 126.44, 127.72, 128.89, 129.64, 129.73, 135.26, 136.44, 137.35, 137.36, 138.68, 138.70, 175.87, 157.96, 150.92, 159.03. MALDI-TOF-MS (HABA): 1443.0 ([M + Na]‘). Anal. Calc. for C$_{95}$H$_{86}$O$_{12}$ (1419.69): C 80.37, H 5.95. Found: C 80.36, H 6.10.

(4R,5R,a,S,a’,S’,a”-Tetrakis[4-[3,5,5-tris(4-ethylbenzoxyl)benzoxyl][phenyl]-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (6). According to GP 1, K$_2$CO$_3$ (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 (CH$_2$Cl$_2$ → CH$_2$Cl$_2$/acetone 99.5:0.5) to give 6 (0.72 g, 64%). Colorless foam. R$_f$ (hexane/acetonitrile 1:1) 0.36. [α]$_D$ = 24.0 (c = 1.00, CHCl$_3$). IR (CHCl$_3$): 3374, 3086, 1598, 1509, 1450, 1372, 1294, 1185, 1060, 1057, 913, 811, 1H-NMR (500 MHz, CDCl$_3$): 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 CH$_2$O); 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 (2s, 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 CH$_2$CH$_2$); 6.80, 6.90 (2d, J = 9.0, 4 arom. H (TADDOL)); 7.23 (d, J = 7.0, 4 arom. H (TADDOL)); 7.30 – 7.55 (m, 32 arom. H, 4 arom. H (TADDOL)). 1H-NMR (125 MHz, CDCl$_3$): 27.26; 69.87, 69.89; 81.15; 101.56; 101.61; 106.36; 106.49; 109.27; 113.57; 111.43; 113.34; 126.42; 126.44; 127.55; 128.77; 129.7; 133.45; 134.33; 136.37; 137.37; 137.69; 139.49; 139.55; 157.82; 159.2; 160.12; 160.13. MALDI-TOF-MS (dithiolane): 1971.72 [M + Na]‘. Anal. Calc. for C$_{39}$H$_{33}$O$_{16}$ (1948.4): C 80.76, H 6.16. Found: C 80.75, H 6.11.

(4R,5R,a,S,a’,S’,a”-Tetrakis[4-[3,5,5-tris(4-ethylbenzoxyl)benzoxyl][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, 24 mmol), and K$_2$CO$_3$ (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 (CH$_2$Cl$_2$/hexane 3:1 → CH$_2$Cl$_2$/CH$_2$Cl$_2$/acetone 95:5:5). 7 (2.56 g, 70%) was obtained. Colorless foam. R$_f$ (hexane/acetonitrile 2:1) 0.06. [α]$_D$ = −10.2 (c = 1.00, CHCl$_3$). IR (CHCl$_3$): 3333, 3008, 2379w, 1594, 1512m, 1458m, 1407w, 1372m, 1295m, 1157w, 1056m.
117.1, 30.8; 116.1, 44.1; 115.1, 91.1 (12), 75.0 (11), 73.1 (6), 71.3 (3).

4-(4-ethylbenzoxazolyl)butan-1-ol (4). A soln. of 9 (19.2 g, 60 mmol) in THF (200 ml) was treated with Bu4NF·3 H2O (28.3 g, 90 mmol) at 0 °C. After stirring at r.t. for 12 h, H2O (50 ml) and Et2O (500 ml) were added, the org. layer was separated, and the aq. layer was treated with Et3O (2 x 500 ml). Drying of the combined org. phases (MgSO4), evaporation of the solvent, and purification of the crude product by FC gave 10 (6.4 g, 58.2 mmol) in THF (100 ml) at 0 °C, according to GP 2. After heating at 50 °C for 30 min, the mixture was recooled to 0 °C, and a soln. of 4-ethylbenzyl chloride (179 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60 °C for 30 min. After heating at the suspension at 50 °C for 30 min, the mixture was recooled to 0 °C, and a soln. of 4-ethylbenzyl chloride (179 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60 °C for 72 h. Workup and purification of the crude product by FC gave 9 (19.2 g, 68%). Yellow oil. Rf (hexane/Et2O 1:1) 0.20. IR (CHCl3): 3098, 3005, 2932, 2856, 1629, 1512, 1471, 1406, 1389, 1361, 1256, 1088, 1073, 1000, 990, 938, 591, 846, 3832. 1H-NMR (400 MHz, CDCl3): 0.04 (m, 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)butyoxymethyl)-4-ethylbenzene (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 °C, according to GP 2. After heating at the suspension at 50 °C for 30 min, the mixture was recooled to 0 °C, and a soln. of 4-ethylbenzyl chloride (179 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60 °C for 72 h. Workup and purification of the crude product by FC gave 9 (19.2 g, 68%). Yellow oil. Rf (hexane/Et2O 1:1) 0.20. IR (CHCl3): 3098, 3005, 2932, 2856, 1629, 1512, 1471, 1406, 1389, 1361, 1256, 1088, 1073, 1000, 990, 938, 591, 846, 3832. 1H-NMR (400 MHz, CDCl3): 0.04 (m, 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)butyoxymethyl)-4-ethylbenzene (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 °C, according to GP 2. After heating at the suspension at 50 °C for 30 min, the mixture was recooled to 0 °C, and a soln. of 4-ethylbenzyl chloride (179 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60 °C for 72 h. Workup and purification of the crude product by FC gave 9 (19.2 g, 68%). Yellow oil. Rf (hexane/Et2O 1:1) 0.20. IR (CHCl3): 3098, 3005, 2932, 2856, 1629, 1512, 1471, 1406, 1389, 1361, 1256, 1088, 1073, 1000, 990, 938, 591, 846, 3832. 1H-NMR (400 MHz, CDCl3): 0.04 (m, 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)butyoxymethyl)-4-ethylbenzene (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 °C, according to GP 2. After heating at the suspension at 50 °C for 30 min, the mixture was recooled to 0 °C, and a soln. of 4-ethylbenzyl chloride (179 g, 88 mmol) in THF (50 ml) was slowly added. Then, the mixture was heated at 60 °C for 72 h. Workup and purification of the crude product by FC gave 9 (19.2 g, 68%). Yellow oil. Rf (hexane/Et2O 1:1) 0.20. IR (CHCl3): 3098, 3005, 2932, 2856, 1629, 1512, 1471, 1406, 1389, 1361, 1256, 1088, 1073, 1000, 990, 938, 591, 846, 3832. 1H-NMR (400 MHz, CDCl3): 0.04 (m, 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).
resulting mixture was heated at 70\degree C according to GP2.

The 1H-NMR data corresponded to those in [31].

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; 133.30; 135.60; 136.56; 137.04; 137.15; 137.88; 139.52; 140.21; 140.51. EI-MS: 568.5 (5%); 136.8; 134.8; 132.5 (32); 131.4 (7), 131.3 (5), 131.2 (25), 130.3 (10), 129.2 (2), 128.5 (25), 120.2 (2), 119.9 (1), 118.1 (1), 117.1 (5), 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, 49.0 (4). Anal. calc. for C39H20Br (583.39): C 64.79, H 6.47; found: C 64.87, H 6.61.

4-[(4-Bromomethylene)oxacyclobutylmethyl]-1,1-biphenyl (17). A solution of 16 (5.00 g, 11.1 mmol) in THF (30 ml) was added to a suspension of NaH (0.800 g, 33.2 mmol) in THF (90 ml) at 0\degree C. After stirring at this temp. for 1 h, the sulfinate was recovered and dried under vacuum.

4-[(4-Ethylbenzoxycarbonyl)oxy]methyl]-1,1-biphenyl (18). A solution of 17 (3.10 g, 5.5 mmol) in THF (120 ml) at 0\degree C. After stirring at this temp. for 2 h, workup as described for the preparation of 10 and FC (CH2Cl2/acetone 1:1) gave 18 (1.60 g, 89%). White solid. M.p. 124.0–126.0\degree C. Rf (CH2Cl2/acetone 1:1) 0.37. IR (CHCl3): 3667, 1761, 1660, 1599, 1543, 1486, 1384, 1361, 1263, 1082, 1039, 906a, 816a. 1H-NMR (400 MHz, CDCl3): 0.91 (t, J = 6.8, 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, d J = 176.1, 1 vinyl H); 6.72 (dd, J = 176, 10.9, CH2CH); 7.34–7.61 (m, 12 aromatic H). 13C-NMR (100 MHz, CDCl3): 65.13; 71.76; 113.84; 126.29; 127.14; 127.29; 127.49; 128.03; 128.36; 136.57; 137.07; 137.48; 139.92; 140.23; 140.37. EI-MS: 331.2 (13), 330.2 (51, 14), 226.1 (6), 213.1 (25), 212.1 (6), 199.1 (63), 197.1 (100), 196.1 (15), 195.1 (15), 185.1 (10), 182.1 (5), 181.1 (11), 180.1 (21), 178.1 (6), 169.1 (11), 168.2 (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 C21H26O3 (326.4): C 77.27, H 8.03; found: C 77.28, H 8.16.

4-[(4-Bromomethylene)oxacyclobutylmethyl]-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\degree C and stirred at this temp. for 1 h. After workup, H2O (20 ml) was added, and the mixture was extracted with CH2Cl2 (3 x 50 ml). The combined org.
phases were washed with sat. NaHCO₃ soln. (100 ml) and dried (MgSO₄). FC (hexane/CH₂Cl₂, 1:1) gave 19 (155 mg, 65%). White solid. M.p. 104.0 – 106.0. Rₜ (hexane/acetonitrile 2:1) 0.42. IR (CHCl₃): 3088s, 2925m, 2857s, 1710v, 1629w, 1610s, 1505s, 1410m, 1360m, 1083s, 1006s, 990m, 913v, 826s. ¹H-NMR (400 MHz, CDCl₃): 4.55 (s, CH₂Br); 4.58, 4.59 (2s, 2 PhCH₂); 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, CH₂CH); 7.35, 7.59 (3m, 12 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 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), 260.2 (7), 260.0 (6), 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 (17), 119.1 (5), 118.1 (47), 117.1 (59), 115.1 (13), 105.1 (6), 91.1 (9). Anal. calc. for C₂₀H₂₀BrO (393.33): C 70.24, H 5.38; found: C 70.04, H 5.28.

(4R,5R)-a,a′,a″,a‴-Tetraakis-{4-[4-(4-ethenylbenzoxyl)butoxy]methyl}benzoyl-2,2-dimethyl-5,5-dioxo-4,4-dimethanolate (20). According to GP 1, a suspension of 1 [1][24] (578 mg, 0.98 mmol), 14 (1.53 g, 3.93 mmol), and K₂CO₃ (543 mg, 3.93 mmol) in acetone (40 ml) was heated at 55°C for 40 h. Workup and FC (hexane/CH₂Cl₂/acetonate 5:2:0.1 – 5:2:0.5) gave 20 (113 mg, 65%). Colorless foam. Rₜ (hexane/acetonate 2:1) 0.46. [α]D = −30.0 (c = 1.00, CHCl₃). IR (CHCl₃): 3348w, 3056w, 2908, 2840m, 2681s, 1607s, 1582s, 1509s, 1456w, 1405w, 1362s, 1295w, 1264w, 1090s, 1017m, 910m, 832m. ¹H-NMR (500 MHz, CDCl₃): 1.08 (s, 2 Me); 1.70 – 1.74 (m, 8 CH₂); 3.48 – 3.52 (m, 8 CH₂O); 4.00 (s, 2 OH); 4.50 – 4.51 (m, 8 PhCH₂O); 4.53 (s, H – C(3)); 5.03, 5.08 (2s, 2 PhCH₂O); 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 CH₂CH); 6.86, 6.95 (2d, J = 8.9, 8 arom. H (TADDOL)); 7.26 – 7.47 (m, 32 arom. H, 8 arom. H (TADDOL)). ¹³C-NMR (125 MHz, CDCl₃): 26.52; 26.54; 2723; 69.75; 69.83; 70.11; 70.18; 70.20; 72.56; 72.58; 77.60; 81.15; 109.21; 113.56; 114.29; 126.29; 127.15; 127.16; 127.29; 127.96; 128.02; 128.11; 128.27; 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; 146.65; 157.92; 158.02. MALDI-TOF-MS (HABA): 1878.1 ([M + Na]+). Anal. calc. for C₉₇H₇₇O₃₇ (1803.0) ([M + Na]+). ¹H-NMR (400 MHz, CDCl₃): 6.9; 6.9; 6.9; 6.9; 6.9; 7.0; 7.0; 7.0; 7.0; 7.0; 7.0; 7.0.

5. Preparation of TADDOL. Bis(4-ethenylphenyl)ethanol (22). At r.t., a soln. of 4-ethenylbenzaldehyde [20] (4.80 g, 36.4 mmol) in THF (10 ml) was slowly added to a soln. of the Grignard reagent prepared from 4-chlorotrioxane (0.54, 36.4 mmol) and Mg (1.06 g, 43.7 mmol) in THF (10 ml). After heating at 70°C for 1 h, the soln. was cooled to 0°C. 2m HCl (90 ml) was added, and the mixture was stirred for 5 min. The resulting suspension was extracted with Et₂O (3 × 100 ml), the combined org. phases were dried (MgSO₄), and the solvents were evaporated to give a yellow solid. FC (hexane/CH₂Cl₂, 1:2) afforded 22 (4.90 g, 72%). White solid. M.p. 118.0 – 120.0°C. Rₜ (hexane/CH₂Cl₂, 1:1) 0.31. IR (CHCl₃): 3008w, 1653s, 1650s, 1556w, 1402m, 1311m, 1281s, 1178m, 1150w, 1116w, 1016w, 999m, 930s, 861m. ¹H-NMR (400 MHz, CDCl₃): 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 CH₂CH); 7.49 – 7.50 (m, 4 arom. H). ¹³C-NMR (100 MHz, CDCl₃): 116.55; 126.04; 130.44; 136.03; 136.85; 141.49; 195.61. EI-MS: 235.2 (6), 234.2 (40 M⁺).
hydrolyzed by the addition of sat. NH₄Cl soln. (30 ml) and H₂O (30 ml). The aq. phase was extracted with Et₂O (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 evaporated of the solvents, the crude product was subjected to FC (pentane/Et₂O 5:1) to give 25 (1.28 g, 3.1 mmol) in THF (10 ml) at 0°C. After stirring at this temp. for 1 h, AcOEt (30 ml) and 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. Rₚ (pentane/Et₂O 3:1) 0.41. [α]²⁵ = +60.4 (c = 1.00, CHCl₃). IR (CHCl₃): 3549, 1766, 1739, 1710, 1176, 1170, 1021, 901, 855, 846, 775, 767, 757. [M+] = 226.12. Anal. calc. for C₁₃H₉O₄: C, 56.3; H, 3.16. Found: C, 56.1; H, 3.12. After stirring at this temp. for 1 h, AcOEt (30 ml) was added to a soln. of 1,1,1-tris(4-hydroxyphenyl)ethane (0.94 g, 3.1 mmol) in acetone (80 ml), according to the method of [22]. After stirring at r.t. for 3 h, the mixture was added to 50 mL of 0.1 M HCl. The crude product was subjected to FC (pentane/Et₂O 5:1) to give 26 (1.35 g, 69%). Colorless foam. Rₚ (CHCl₃): 0.35. [α]²⁵ = +184.2 (c = 0.99, CHCl₃). IR (CHCl₃): 1765, 1745, 1630, 1560, 1509, 1466, 1402, 1375, 1265, 1106, 1024, 990, 960, 915, 846, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400. NH₄Cl soln. (30 ml) and H₂O (30 ml). The aq. phase was extracted with Et₂O (3 x 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. Rₚ (CHCl₃): 0.35. [α]²⁵ = +184.2 (c = 0.99, CHCl₃). IR (CHCl₃): 1765, 1745, 1630, 1560, 1509, 1466, 1402, 1375, 1265, 1106, 1024, 990, 960, 915, 846, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400. NH₄Cl soln. (30 ml) and H₂O (30 ml). The aq. phase was extracted with Et₂O (3 x 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. Rₚ (CHCl₃): 0.35. [α]²⁵ = +184.2 (c = 0.99, CHCl₃). IR (CHCl₃): 1765, 1745, 1630, 1560, 1509, 1466, 1402, 1375, 1265, 1106, 1024, 990, 960, 915, 846, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400, 3549, 3458, 3089, 1509, 1494, 1448, 1403, 1178, 1104, 1048, 1016, 999, 914, 851, 634, 616, 504, 400
9 PhCH₂OH): 5.24 (dd, J = 10.9, 0.9, 6 vinyl H); 5.74 (dd, J = 176, 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 = 176, 10.9, 6 CH₂CH₂); 6.83, 6.98 (2 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; 129.63; 136.41; 137.36; 139.62; 142.08; 156.75; 160.09. TOF-MS (DHB): 2823.7 ([M + Na]+, 114.03; 114.10; 126.41; 127.75; 129.64; 136.30; 136.42; 137.36; 139.62; 142.08; 156.77; 160.03; 160.11. FAB-MS: 1369 ([M + K]+, 114.10; 114.12; 126.42; 127.75; 129.63; 136.30; 136.42; 137.36; 139.62; 142.08; 156.77; 160.09; 160.11. MALDI-TOF-MS (DHB): 2823.7 ([M + Na]+, 114.03; 114.10; 126.41; 127.75; 129.63; 136.30; 136.42; 137.36; 139.62; 142.08; 156.77; 160.09; 160.11. ANAL. calc. for C₁₃₁H₁₁₈O₁₆: C 83.31, H 6.18; found: C 83.28, H 6.36.

In a three-necked flask, equipped with a condenser and an overhead stirrer, a warm soln. of poly(vinyl alcohol) (916 mg, degree of polymerization 100000, 86±89% hydrolyzed) in H₂O (25 ml), which was prepared by violent addition of Et₂Zn to PhCHOME 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(OPr)₃ (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 (10 ml) and stirred at r.t. for 2 h. After evaporation of the solvent under high vacuum, the suspension was filtered through a glass filter (slightly yellow beads with a new theoretical loading of 0.21 mmol g⁻¹).

This indicates that 83% of the theoretically available TADDOL centers are complexed with Ti. Elementary analysis gave a loading of 0.0038 mg Ti/mg polymer, theoretical loading: 0.0046 mg Ti/mg polymer. 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.

To determine the actual loading of the polymer with Ti, Ti(OiPr)₄ (22 mg, degree of polymerization 100000, 86±89% hydrolyzed) in H₂O (25 ml), which was prepared by violent addition of Et₂Zn to PhCHOME 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, the suspension was filtered through a glass filter (slightly yellow beads with a new theoretical loading of 0.21 mmol g⁻¹).
were resuspended in toluene (9 ml), and Ti(O\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°C, and Et₂Zn (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. In HCl (50 ml) was added to the combined org. phases, the org. phase was separated, and the aq. layer was extracted with Et₂O (2 × 50 ml). Drying of the combined org. phases (MgSO₄) and evaporation of the solvents afforded 1-phenylpropan-1-ol. The enantiomeric purity and the conversion of the crude product was determined by HPLC analysis (column: a) with a chiral column (Daicel Chiralcel OD, hexane/i-PrOH 9:1, flow rate 1 ml min⁻¹, UV 254 nm). 1H-NMR analysis of the crude product [35a]. FC (pentane/Et₂O 1:1) of the crude product afforded pure 1-phenylpropan-1-ol. The enantiomeric ratio (75:25) of which was determined by 1H-NMR analysis of the crude 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 Ti(O\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 Et₂Zn (0.81 ml, 1.62 mmol, 1.8 equiv., 2m in toluene) at −20°C. After stirring at −20°C for several h, a sample of the mixture was diluted with Et₂O, some drops of HCl were added, and the enantiomeric purity as well as the conversion was determined by analysis of the org. layer by GC/MS.

10. Addition of Bu₂Zn to PhCHO Mediated by Polymer-Bound Ti-TADDOLates. General Procedure 6 (GP 6). Example for the catalyst with polymer p-26 (20 mol-%) with a loading of 0.21 mmol g⁻¹. Beads of polymer p-2-6 (529 mg, 0.11 mmol, 0.2 equiv.), after azeotropic drying, were suspended in toluene (4 ml), and Ti(O\text{Pr})₄ (35 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 Ti(O\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°C, and a Bu₂Zn 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 ZnCl₂ (1.12 ml, 11.2 mmol, 2.0 equiv., 3M in Et₂O) in toluene (1.1 ml) [34], stirring at r.t. for 2 h and filtering the suspension through a syringe filter (PTFE, 0.45µ). For 4.5 h at −20°C, the soln. was separated and worked up as described in GP 5. The enantiomeric purity and the conversion of the reaction were determined by GC/MS analysis (column: a) with heating 105°C/isothermal; pressure: 1.0 bar; tᵣ(S)-1-phenylpentan-1-ol ca. 3.9 min, tᵣ((R)-1-phenylpentan-1-ol ca. 40.5 min, tᵣ(S)-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 Nitronite 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 TiCl₂(O\text{Pr})₄ [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°C, and a soln. of diphenyl nitronite [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/exo selectivity (82:18) as well as the conversion (93%) were determined by H¹-NMR analysis of the crude product [35a]. FC (pentane/Et₂O 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 H¹-NMR analysis with [Eu(hfc)₃] as a shift reagent. The polymer beads were hydrolyzed with THF/1s HCl 10:1 (5 × 20 ml), followed by washing with THF/H₂O 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 Nitronite 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 Ti(O\text{Pr})₄(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°C, followed by addition of a soln. of nitronite [40] (119 mg, 0.66 mmol, 1.2 equiv.) and [((E)-but-2-enoyl]-oxazolidinone [41] (78 mg, 0.55 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 H¹-NMR spectroscopy [35b]. Pure endo-cycloadduct 29 (51 mg, 29%) was isolated by FC (pentane/Et₂O 1:1) and prep. TLC (CH₂Cl₂/MeOH 99:1) of the crude product, and the enantiomeric purity (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.
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$t_{R(minor)}$: ca. 54.5 min, $t_{R(major)}$: ca. 64.5 min. The polymer beads were washed and used for multiple applications as described above.


Received June 28, 2001