30. Preparation, Structure, and Reactivity of Thioxo and Imino Derivatives of the Triolide (and Pentolide) from (*R*)-3-Hydroxybutanoic Acid

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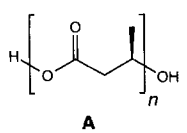
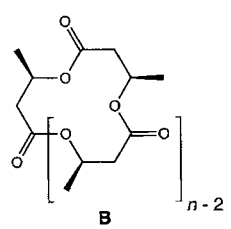
Reaction of the triolide **1** from (*R*)-3-hydroxybutanoic acid with *Lawesson*'s reagent **5** leads to the mono-, di-, and trithio derivatives **6–8** which can be isolated in pure form (20–40% yields), and which have crystal structures very similar to the parent triolide **1** (*Fig. 1*). Similarly, pentolide **3** is converted to mixtures of various thio derivatives, three of which are separated (**10–12**) by HPLC and fully characterized. The X-ray structures of the mono- and of one of the dithiopentolides (**10, 12**) differ remarkably from each other (*Fig. 3*). Reduction of the thiotriolides **6–8** ($NaBH_4$, R_3SnH, Cl_3SiH, *Raney*-Ni) gives 12-membered rings containing up to three ether groups (chiral crown ethers, **15, 17–19**) in poor yields. The thiotriolides react spontaneously and in yields of up to 96% with ammonia, certain primary amines, and hydroxylamine to give imine and oxime derivatives with intact 12-membered-ring backbones (**20, 22–24, 30**, see crystal structures in *Figs. 4–7*). The rigid structure of all the derivatives of triolide **1** puts the C=O, C=S, and C=NR O-, S-, and N-atoms in juxtaposition (a feature reminiscent of the side chains in the iron-binder enterobactin, *Fig. 6*). Imines containing PPh_2 groups are prepared (**30, 33, 35**) from the thiotriolides and tested as chiral ligands for Pd^{II}-catalyzed 1,3-diphenylallylations (→**37**, enantiomer ratio up to 77:23). The reactions described demonstrate that multiple reactions of the triolide **1** from (*R*)-3-hydroxybutanoic acid which proceed through tetrahedral intermediates are possible without ring opening – the skeleton is remarkably stable, and this might be exploited as a template for bringing up to three pendent substituents into close proximity to allow a study of their interactions and cooperative properties. Also, the di- and trithio derivatives **7** and **8** could be used for cross-linking in molecules containing primary NH_2 groups.

1. Introduction. – Poly((*R*)-3-hydroxybutanoate) (P(3-HB)) **A** is a stereoregular polyester produced, as a storage material, by prokaryotic microorganisms under growth-limiting conditions [1–3]. P(3-HB) and the copolymer poly((*R*)-3-hydroxybutanoate/(*R*)-3-hydroxyvalerate) (P(3-HB/3-HV)) have acquired some economic importance due to the



A

$n \approx 10000$



B

1 $n = 3$ (triolide)
2 $n = 4$ (tetrolide)
3 $n = 5$ (pentolide)
4 $n = 6$ (hexolide)

[1]) Part of the Ph. D. Thesis of *A. B.*, dissertation No. 11239, ETH Zürich, 1995.
[2]) Part of the projected Ph. D. Thesis of *F.N.M.K.*

fact that they are biodegradable. This allows them to be used as substitutes for conventional plastics, and they are thus produced on an industrial scale [4]. A decade ago, the fact that microbially synthesized polyesters show an impressive stereoregularity brought our research group into contact with P(3-HB) for the first time. To exploit the synthetic potential of P(3-HB), suitable procedures for the preparative degradation to its monomeric unit were developed [5] [6] (using procedures elaborated in our group, it is possible to replace any of the H-atoms in (*R*)-3-hydroxybutanoic acid by other substituents [2] [7]).

Suitable chemical degradation procedures yield the cyclic oligomers **B**, so-called oligolides, which can also be obtained from monomeric (3-HB) derivatives using a variety of macrolactonization conditions[3]) [9–12]. Initially, possible antibiotic activity of such oligolides was a motivation for their synthesis[4]). In the meantime, the main interest shifted towards structural characteristics of these oligolides: the crystal structures of a number of such oligolides were determined which led to the construction of models for the structure of the open-chain polymer[5]) [11] [12] [17].

The cyclic 3-HB trimer **1** is the prevailing component in the reaction mixture, when macrolactonization conditions are applied to P(3-HB) under thermodynamic control. Thus, by simply heating the polymer in a mixture of toluene and dichloroethane in the presence of an acid catalyst with concomitant removal of H_2O from the reaction mixture, the triolide **1** is formed as the major product[6]). In this way, pure triolide can be obtained in 40–50% yield directly from P(3-HB) on a multiple-gram scale[7]) [12] [19]. Hence, the triolide can be used as a new enantiomerically pure starting material for diastereoselective reactions[8]).

One interesting feature of the triolide, which is revealed by X-ray diffraction, is its rather rigid structure where all three carbonyl O-atoms point in the same direction. The triolide is also found as the basic skeleton of naturally occurring macrolides such as the siderophore enterobactin[9]) [24].

It was our goal to synthesize derivatives of the trimer **1** whilst maintaining the rigid 12-membered-ring backbone. Particularly, the synthesis of derivatives which are able to coordinate to transition-metal centers was of interest to us.

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[3]) Recently, the synthesis of the cyclic dimer of 3-HB (**B**, $n = 2$) was also reported [8].

[4]) Antibiotic fungal metabolites such as pyrenophorin, elaiophylin, and vermiculin [13] have a 16-membered ring backbone that is reminiscent of the cyclic tetramer **2** of 3-HB.

[5]) The structure of open-chain oligo(3-HB) is of special interest due to its possible role as part of a non-proteinaceous integral membrane channel [14] [15]. Furthermore, channel-forming activity of 3-HB oligomers in planar lipid bilayers was detected [16].

[6]) The higher oligolides **2–4** appear as side products.

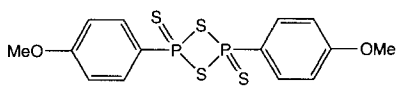
[7]) The synthesis of triolide **1** from 3-HB derivatives by macrolactonization methods was first described in communications by *Müller et al.* [11] and shortly afterwards by *Kimura et al.* [18]. For complete analytical data, see [19]. The synthesis by enzymatic esterification from the corresponding monomer of the CF_3 analog of **1** was reported in a patent [20]. We were not able to prepare oligolides from 4,4,4-trifluoro-3-hydroxybutanoic acid [12] [21].

[8]) Triolide **1** was also reported as a starting material for ring-opening polymerizations leading to isotactic P(3-HB) [18] [22].

[9]) The all-(*S*)-triolide *ent*-**1** was reported as an active antibiotic metabolite of the red algae *Laurencia pinnatifida* [23]. There are several discrepancies between the data reported in [23] and in [11] [12] [19].

2. Results and Discussion. – 2.1. *Thioxo Derivatives of Triolide* **1**. Because initial attempts to alkylate the triolide at the position α to the carbonyl moiety had failed[10]), we focused our attention on the modification of the ester functionality of triolide **1**. First, the transformation of the ester into a thio *O*-ester functionality was investigated. For this purpose, triolide **1** was treated with *Lawesson*'s reagent **5** [25] which led to a mixture of mono-, di-, and trithiotriolide derivatives **6**–**8** (*Scheme 1*). The products were separable by flash chromatography (silica gel), and their ratio depended on the amount of *Lawesson*'s reagent added and on the reaction time (see *Table 1*). Under appropriate conditions, a total of *ca.* 60% thio products were isolated. The di- and trithiotriolides were formed preferentially by reaction of **1** with a 3.3-fold excess of *Lawesson*'s reagent, and after a reaction time of 17 h (*Table 1, Entry 3*); the products formed decomposed when

Scheme 1



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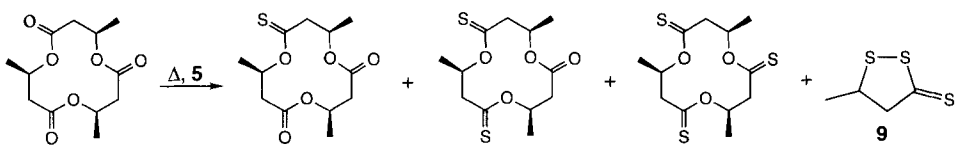

1 **6** **7** **8** **9**

Table 1. *Reaction of Triolide* **1** *with* Lawesson's *Reagent* **5** *to Give the Thio-*O*-Ester Derivatives* **6**–**8**

Entry	**1** [g]	**5** [equiv.]	Solvent	Reaction time [h]	Yield [%]		
					6	**7**	**8**
1	0.5	3.6	*o*-xylene (6 ml)	6	[a])	28	7
2	0.5	3.6	*o*-xylene (6 ml)	11	25	27	18
3	5	3.3	*o*-xylene (60 ml)	17	–	32	29
4	0.5	3.6	*o*-xylene (6 ml)	23	–	–	2
5	0.5	3.6	mesitylene (6 ml)	5	–	22	16
6	5	2.5	*o*-xylene (60 ml)	18	–	21	8
7	0.5	1	*o*-xylene (2.5 ml)	6	34	29	9
8	5	1	*o*-xylene (60 ml)	7	42	17	2
9	0.5	0.5	*o*-xylene (2.5 ml)	6	40	13	2
10	0.5	0.5	*o*-xylene (2.5 ml)	14	38	14	2

[a]) Not isolated.

[10]) The triolide was treated with base at low temperature to generate the enolate and quench it with electrophiles. Under a variety of reaction conditions, no alkylation could be observed; after workup, unreacted starting material or ring-opened products were isolated [21]. Apparently, the triolide is not stable under the conditions applied; either β-elimination is favored over enolate formation at −78°, or the enolate is unstable and decomposes by ring opening.

longer reaction times are applied. For the synthesis of the monothiotriolide **6**, it was sufficient to use 0.5–1 equiv. of *Lawesson*'s reagent to obtain a *ca.* 40% yield (*Table 1, Entries 8–10*).

In most experiments, compound **9** was formed as a by-product in 1–4% yield. The three triolides **6–8** were found to contain only O-atoms as heteroatoms within the ring; products containig an S-atom within the ring were not observed[11]).

Crystals suitable for X-ray crystal-structure analysis were obtained from all thiotriolides **6–8** (*Fig. 1*). The mono- and dithiotriolides **6** and **7** crystallize in the same space group as triolide **1** itself ($P2_12_12_1$), whereas trithiotriolide **8** crystallizes in the monoclinic space group $P2_1$[12]) (see *Fig. 2*). In the crystal structure, the average distances between the carbonyl O- or S-atoms is successively enlarged moving from triolide **1** to the thio derivatives with increasing number of S-atoms (*Table 2*). The characteristic backbone of triolide **1** is still present in all of the thio derivatives (*Fig. 1*).

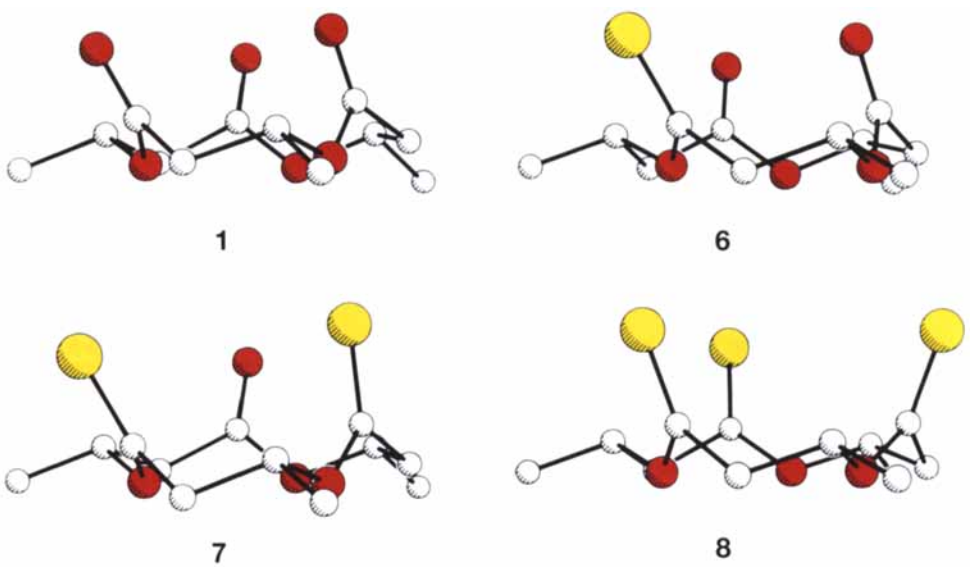

Fig. 1. *X-Ray crystal structure of triolide* **1** [12] *and of its thio analogs* **6–8**. S-Atoms in yellow, O-atoms in red. H-Atoms are omitted for clarity.

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[11]) It is proposed that after ring opening of the triolide backbone and a second thioxoation of a previously thioxoated ester, the monomeric 3-HB derivative **9** and not the corresponding 12-membered-ring derivative is formed. For 3-HB, the 12-membered-ring derivative **1** is the thermodynamically most stable oligolide under acid-catalyzed conditions [12] [19].

[12]) As this symmetry point group is lacking a center of inversion, a nonlinear effect of *second harmonic generation* should be observed in crystalline **8** [26]. By a so-called 'powder test' for the qualitative evaluation of this effect, it was shown, that **8** is able to double a frequency from the near-IR into the VIS. As the effect is only of the order of that observed for urea, no further investigations into nonlinear effects of **8** were undertaken.

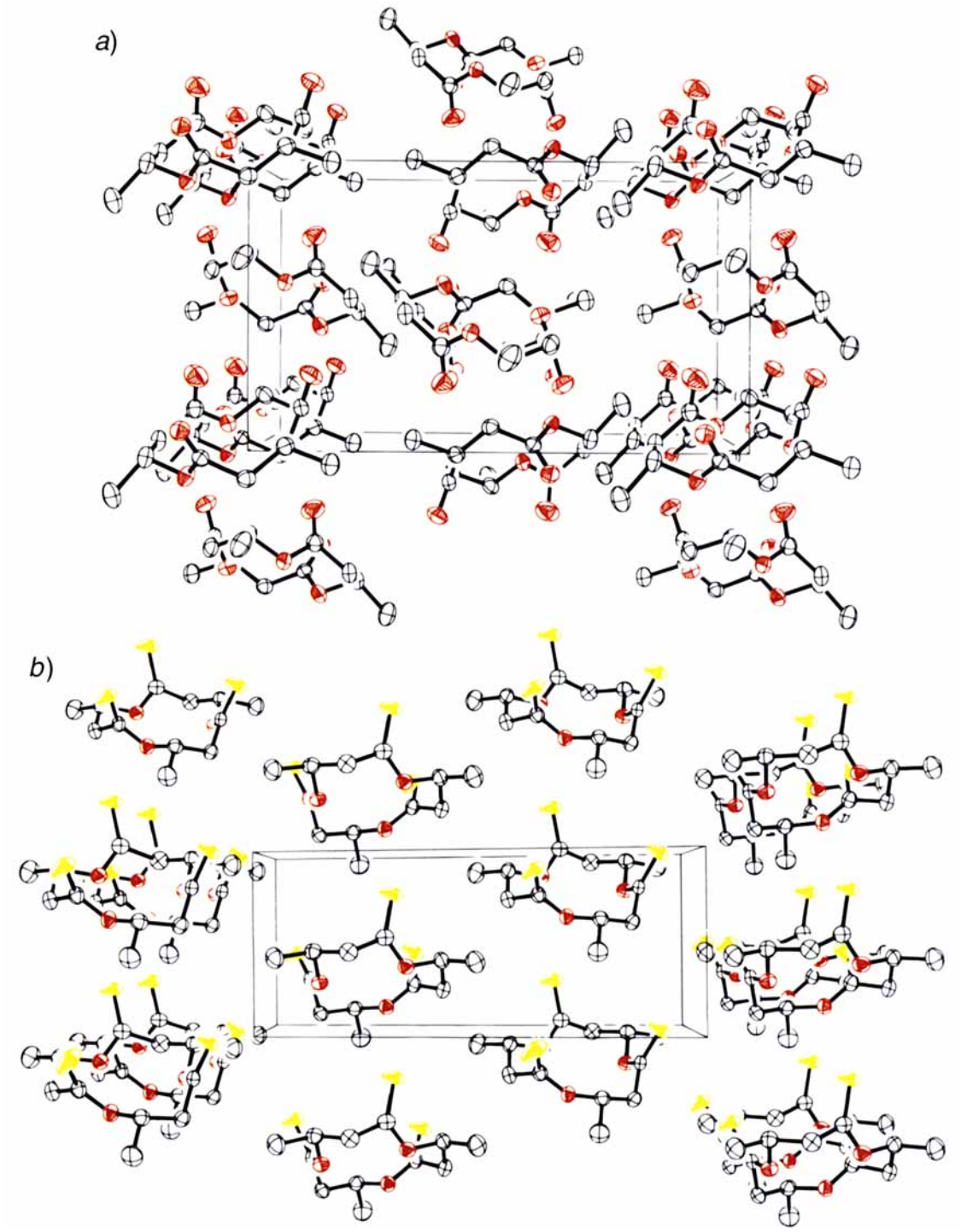


Fig. 2. *Packing plot* a) *of the triolide molecules* **1** [12] *and* b) *of the trithiotriolide* **8**. Projection down the *b*-axis. S-Atoms in yellow, O-atoms in red. H-Atoms are omitted for clarity. Vibrational elipsoids are drawn at the 25% probability level.

Table 2. *Distances* [Å] *between the Carbonyl O-Atoms and the Thiocarbonyl S-Atoms in Triolide* **1** *and Its Thio Derivates* **6–8** *in the Crystal*

Triolide **1**		Monothiotriolide **6**		Dithiotriolide **7**		Trithiotriolid **8**	
O–O	3.62	O–O	3.61	O–S	3.79	S–S	4.80
O–O	3.69	O–S	4.05	S–S	4.30	S–S	4.90
O–O	4.65	O–S	5.15	O–S	4.99	S–S	4.92
Average	3.99		4.27		4.36		4.87

The unidirectional arrangement of the thiocarbonyl S-atoms should favor the multidentate complexation of transition-metal ions by trithiotriolide **8**. Unfortunately, it proved impossible to obtain crystals suitable for X-ray crystal-structure analysis of transition-metal complexes of **8**: either the metal salt and **8** crystallized separately, or an amorphous precipitate was formed (the experiments were done with the following salts: $Mn(NO_3)_2$, [Fe(acac)$_3$], [Ni(SCN)$_2$], CuCl, CuCN, $CuCl_2$, $[Cu(MeCN)_4]BF_4$, $[Cu(MeCN)_4]PF_6$, $Cu(NO_3)_2 \cdot 3H_2O$, [Cu(acac)$_2$], [Cu(py)$_2$(NCS)$_2$], [Pd(SCN)$_2$], $Cd(NO_3)_2 \cdot 4H_2O$, $Cd(NO_3)_2$, $Cd(TosO)_2$).

2.2. *Thioxo Derivatives of Pentolide* **3**. Thioxoation of pentolide **3** (also accessible in g-quantities directly from (3-HB) when acid-catalyzed macrolactonization conditions were applied [12]) with *Lawesson*'s reagent led to a mixture of thiopentolide derivatives (*Scheme 2*). The mono-, di-, and trithio compounds **10–14** were isolated by flash chromatography (*Table 3*). Again, the monomeric 3-HB derivative **9** was formed in minor amounts. The pairs of constitutional isomers **11**/**12** and **13**/**14** were obtained as 1:1 mixtures (according to ^{1}H-NMR), the components of which were inseparable by conventional flash chromatography.

Scheme 2

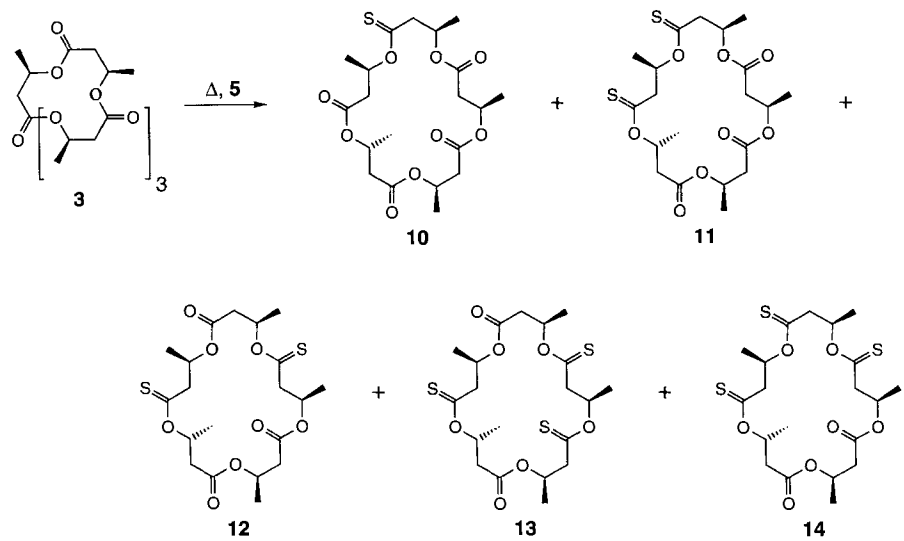


Table 3. *Reaction of the Pentolide* **3** *with* Lawesson's *Reagent* **5** *in Refluxing Solvents to Give the Thio-O-Ester Derivatives* **10**–**14**. The boiling points of *o*-xylene and mesitylene are 144° and 165°.

5 [equiv.]	Solvent	Reaction time [h]	Yield [%]				
			10	**11/12**	**13/14**	**9**	**3**
1	*o*-xylene (2.5 ml)	7	26	2	–	–	62
2	*o*-xylene (2.5 ml)	20	18	7	2	6	18
5	*o*-xylene (5 ml)	7	26	19	5	2	–
5	*o*-xylene (5 ml)	8	23	23	*ca.* 7[a])	[b])	*ca.* 10[a])
5	*o*-xylene (5 ml)	17	21	7	*ca.* 2[a])	6	–
5	mesitylene (5 ml)	7	–	–	–	–	*ca.* 5[a])

[a]) As component of mixtures in chromatography fractions, as analyzed by ^{1}H-NMR.
[b]) Not isolated.

The dithiopentolides **11** and **12** were separated by HPLC on a preparative scale (*LiChrosorb 60*; hexan/i-PrOH 99.7:0.3), yielding first **12** as a solid and then **11** which solidified only after a second HPLC purification step. A separation of the rather small amounts of the trithiopentolides **13** and **14** present in the reaction mixtures was not considered worthwhile.

Crystals suitable for X-ray structure analysis were obtained from the thiopentolides **10** and **12** (*Fig. 3*) and revealed the following characteristics. Monothiopentolide **10** crystallizes like precursor **3** in the orthorhombic space group $P2_12_12_1$. The conformation of **10**, however, deviates significantly from that of **3**: all the carbonyl O-atoms and the thiocarbonyl S-atom are located in the same half space, while the Me groups adopt quasi-equatorial positions. The dithiopentolide **12** crystallizes in the monoclinic space group $P2_1$. A superposition of the structures of **12** and **3** reveals only slight differences in the conformation of these two molecules. A least-square fit of all atoms (except H) gives a root mean square deviation of only 0.07 Å. All of the carbonyl O- and one of the thiocarbonyl S-atoms of **12** are pointing in the same direction, while the second thiocarbonyl S-atom is pointing in the opposite direction. All the ester bonds of the thiopentolides **10** and **12** have s-*trans*-conformation.

2.3. *Reduction of Triolide* **1** *and Its Thio Derivatives.* Since the pioneering work of *Pedersen, Lehn,* and *Cram* [27], the chemistry and complexation ability of macrocyclic ethers are of ever growing interest. The role of chiral crown ethers as catalysts in enantioselective reactions was discussed [28–30]. Macrocyclic chiral ethers should be accessible in two steps from the readily available triolide **1**[13]) by desulfurization of the tioxo derivatives described in *Sect. 2.1.*

The desulfurization of thio *O*-esters of primary and secondary alcohols is usually carried out by reduction with *Raney*-Ni; the corresponding ethers can be obtained in good yields [32] [33]. However, reaction of trithiotriolide **8** with an excess of *Raney*-Ni led predominantly to mixtures of ring-opened products, even at reaction temperatures as low as −20°. Reaction of dithiotriolide **7** gave the corresponding dioxamonolactone in a yield of 10% (after flash chromatography). Desulfurization of the monothiotriolide **6** by

[13]) For the synthesis and complexing properties of [12]crown-3 and derivatives, see [31].

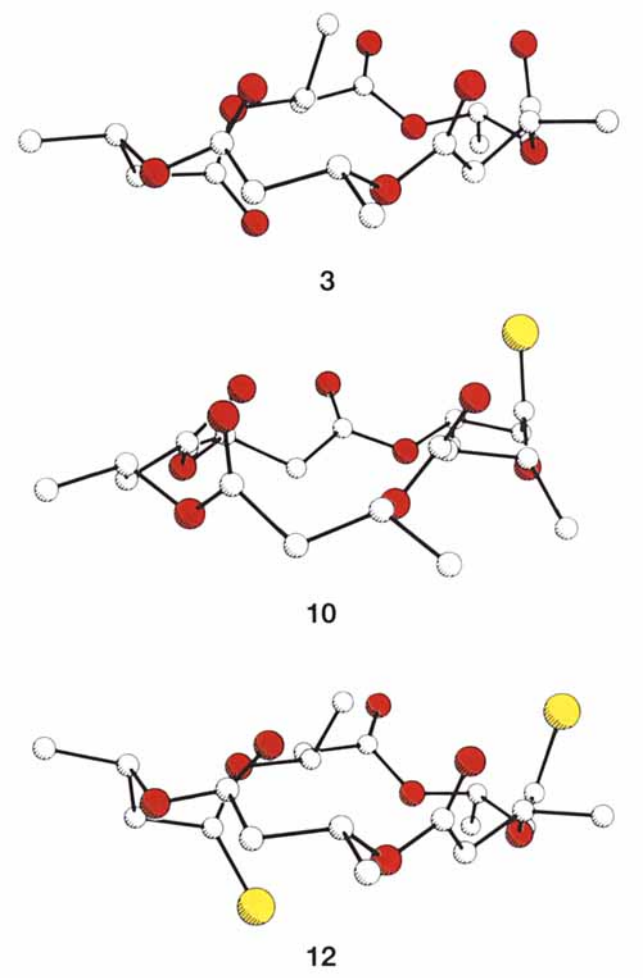


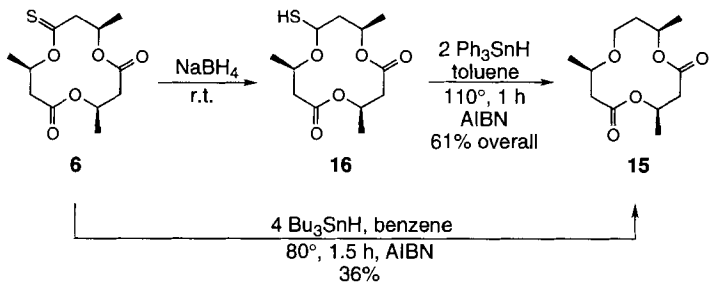
Fig. 3. *X-Ray crystal structure of pentolide* **3** [10] *and of its thio analogs* **10** *and* **12**. S-Atoms in yellow, O-atoms in red. H-Atoms are omitted for clarity.

reaction with Bu_3SnH[14]) gave oxadilactone **15** in *ca.* 35% yield (*Scheme 3*). This method failed for the reduction of the thio derivatives **7** and **8**.

The yield of oxadilactone **15** could be increased by reduction of **6** with $NaBH_4$ prior to treatment with tin hydride. The mercapto-diolide **16** was obtained in quantitative yield as a single diastereoisomer and then reduced without purification with Ph_3SnH to give

[14]) Tin hydrides are usually used for the desulfurization of sulfides and dithianes to the corresponding alkanes [34] [35].

Scheme 3



oxadilactone **15** in an overall yield of 61% (*Scheme 3*)[15]). Again, this method of desulfurization failed with the di- and trithiotriolides **7** and **8**.

Thus, the reduction of triolide **1** to the corresponding ethers *via* its thio-*O*-ester derivatives is only useful for the synthesis of oxadilactone **15**. To prepare the dioxamonolactone **17** or the cyclic triether **18**, triolide **1** was subjected directly to deoxygenating conditions.

Reaction of an ester with $SiHCl_3$ is a common way for the synthesis of the corresponding ether [36], with the highest yields being reported when the reaction is performed without a solvent [37]. The reduction of triolide **1** to **17–19** was carried out according to the procedure reported [37] (*Scheme 4*); the crude product mixture could be separated chromatographically, revealing the product distributions indicated in *Table 4*. When the

Scheme 4

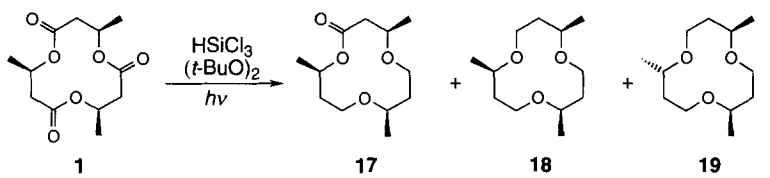


Table 4. *Product Distribution for the Deoxygenation Reaction of Triolide* **1** *with Trichlorosilane* (see *Scheme 4*)

1 [g]	$SiHCl_3$ [equiv.]	Solvent [equiv.]	Reaction time [h]	Yield [%]		
				17[a])	**18**[a])	**19**
2.0	10	–	22	9	7	14
1.0	25	THF (7)	5	13	6	–
2.0	25	Et_2O (40)	3	6 (7)	13 (9)	–

[a]) According to ^{1}H-NMR spectra of the mixed fractions; yields of actually isolated products in parentheses.

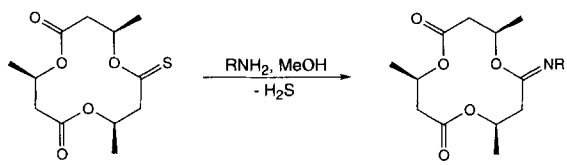
[15]) We assume that the hydride is transferred to the *Si*-face of the thiocarbonyl group, producing the diastereoisomer **16** with (*R*)-configuration at the newly formed stereogenic center. – Reaction of **7** with $NaBH_4$ led to the corresponding dimercaptomonolactone as an impure crude product in high yields (no suitable purification method was found); reduction of the crude material with Ph_3SnH gave dioxamonolactone **17** in 9% yield. Reaction of **8** with $NaBH_4$ led to an inseparable product mixture.

reaction was carried out without any solvent added, partial isomerization to the (*R,R,S*)-isomer **19** occurred. The formation of **19** was suppressed in THF or Et_2O, the highest yields of **18** being obtained in Et_2O. None of the desired ether compounds were formed on reaction of **1** with $SiHCl_3$ in toluene or CCl_4 (solvents common for reactions under free-radical conditions).

Although the synthesis of the chiral crown ether **18** can be achieved in one step from the readily available triolide **1**, the yields obtained are too low[16]) for a practical access to amounts of product necessary for further experiments.

2.4. *Imidate Derivatives of Triolide* **1**. Thio *O*-esters can be converted to imidates by reaction with amines in alcohol [40]. Between 0° and room temperature, the imidates **20** were usually formed from monothiotriolide **6** in good-to-excellent yields (see *Table 5*) after purification (see *Exper. Part*). However, only primary amines without branching in the α-position to N reacted with **6**; sterically more demanding amines such as (i-Pr)NH_2 or aniline did not form the desired imidates even when higher reaction temperatures were used.

Table 5. *Imidates* **20** *from Monothiotriolide* **6** *and Primary Amines.* In each run, 10 equiv. of the indicated amine were used; the yields refer to purified products.



6 **20**

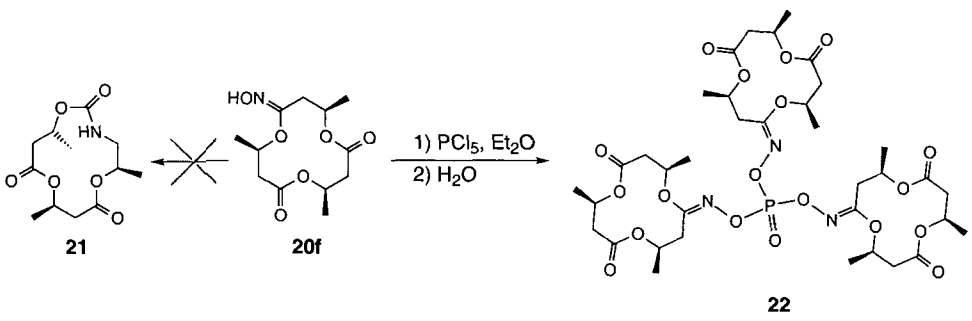
6 [mg]	RNH_2	Conditions		Product	Yield [%]
		t [min]	Temp.		
50	$MeNH_2$	60	r.t.	**20a**	68
50	$BuNH_2$	30	r.t.	**20b**[a])	90
50	i-$PrNH_2$	45	r.t.	**20c**	–
500	$BnNH_2$	60	0°	**20d**	96
50	Aniline	60	r.t.	**20e**	–
200	H_2NOH	30	r.t.	**20f**	88
100	NH_3	45	0°	**20g**[a])[b])	quant.

[a]) No purification method was found.
[b]) For analytical purposes, **20g** was converted to the stable acetyl derivative **20h** (R = Ac).

Stirring hydroximate **20f** in Et_2O over PCl_5 followed by aqueous workup led to a single product in high yield, the ^{1}H-NMR and EI mass spectra of which indicated that the urethane **21** might have been formed (*Beckmann* rearrangement of the lactone oxime **20f**). However, a crystal-structure analysis revealed that the product was actually a phosphate (*Scheme 5* and *Fig. 4*): three hydroximate molecules **20f** had reacted with PCl_5 to give an intermediate which was converted to **22** during aqueous workup. It is assumed

[16]) Direct deoxygenation of **1** using other common reducing reagents gave no improvement: with $LiAlH_4$/$BF_3 \cdot Et_2O$ [38], **18** was formed in rather poor yields (*ca.* 10%), reaction with $NaBH_4$/$BF_3 \cdot Et_2O$ [39] led to inseparable product mixtures.

Scheme 5



that the C=N bond in the hydroximate **20f**, like those in **22**, has the (*E*)-configuration[17]) (which is the thermodynamically favored one in acyclic oxime esters[18]) [45]). The single crystals of **22** suitable for crystal structure analysis were obtained by recrystallization from CH_2Cl_2. The crystals (space group $P2_1$) include one solvent molecule (CH_2Cl_2) per phosphate **22**. All of the C=N bonds are in the (*E*)-configuration with all the triolide subunits situated in the same half space around the tetracoordinated P-atom. The 'crown-ester' geometry with the C=N and the two C=O groups being approximately parallel is still present in all three 12-membered rings of phosphate **22**; however, in two of them, the crown is somewhat expanded: While the average distance between the carbonyl O-atoms in triolide **1** is 3.99 Å, the values for the average distances between the carbonyl O- and the imidate N-atoms in the 12-membered rings of phosphate **22** are 3.94, 4.23, and 4.64 Å.

Single crystals suitable for crystal-structure analysis were also obtained from the *N*-benzylimidate **20d**. As in most imidates[19]) [48], the C=N bond of **20d** has (*E*)-configuration (*Fig. 5*).

By reaction of the dithio- and trithiotriolides **7** and **8** with primary amines of the general formula RCH_2NH_2 at 0°, the corresponding imidates **23** and **24** were formed in high yields. Some of the rather unstable *N*-alkylimidates were isolated in higher purity by an aqueous workup rather than by filtration through silica gel (see *Exper. Part*). In each case, only one configurational isomer was obtained.

We thought that the isolated imidates might be of interest as chiral catalysts: Imidates of type **25** or **26** were used by *Pfaltz* and coworkers as ligands in various enantioselective reactions [49] [50]. The Pd-catalyzed allylic alkylation often serves as a standard test

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[17]) Already *Werner* reported that one isomer of ethyl benzohydroximate rearranged to the corresponding urethane by treatment with PCl_5, while the other isomer formed a phosphate (analogous to **22**) [41]. For the formation of the phosphate from (*E*)-isopropyl benzohydroximate, see also [42]. For examples of *Beckmann* rearrangements of hydroximo-lactones, see [43].

[18]) Five- and six-membered hydroximo-lactones were reported to exist preferentially as the (*Z*)-isomers [43] [44]. The $n_N \rightarrow \sigma^*_{C-O}$ stereoelectronic effect should favor the (*Z*)-configuration of hydroximino esters.

[19]) Based on ^{1}H-NMR studies, the (*Z*)-configuration was originally assigned as the thermodynamically more stable one by *Moriarty et al.* [46]. *Meese et al.* proved that the (*E*)-configuration is, in fact, the more stable one, which was assumed to be a consequence of its lower dipole moment [47]. Again (*cf.*[18])), the stereoelectronic $n_N \rightarrow \sigma^*_{C-O}$ effect should favor the (*Z*)-configuration.

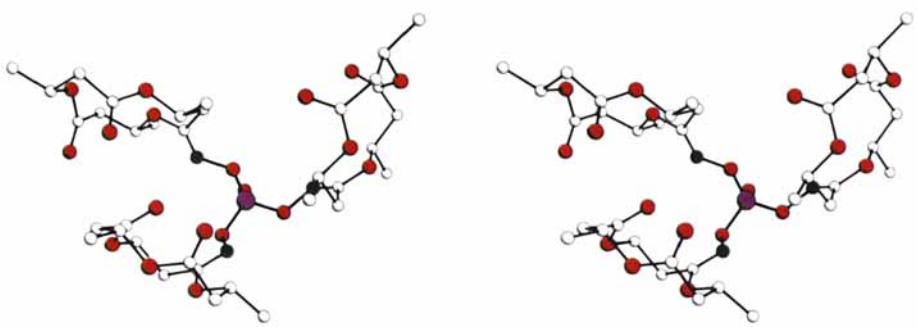


Fig. 4. *X-Ray crystal structure of phosphate* **22**. P-Atom in purple, O-atoms in red, N-atoms in green. H-Atoms and the cocrystallized solvent molecule (CH_2Cl_2) are omitted for clarity.

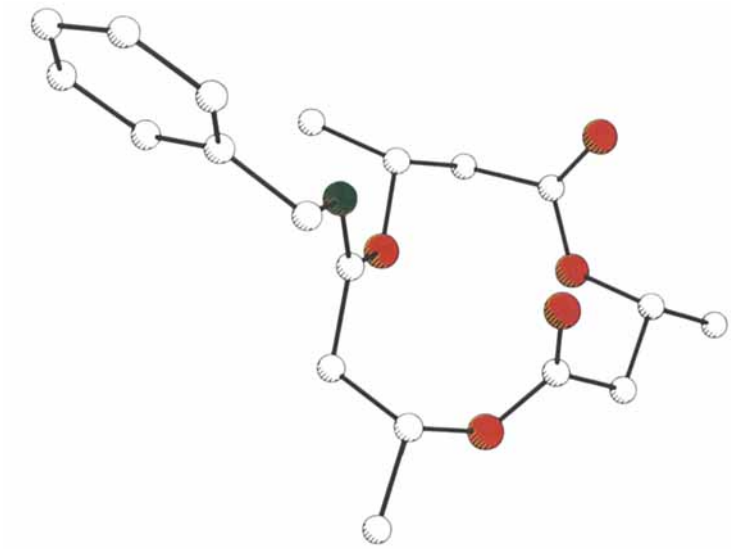
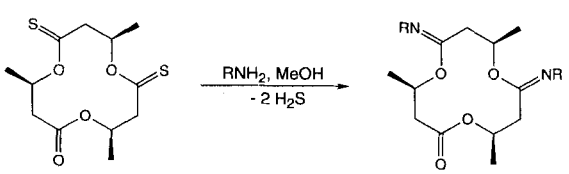


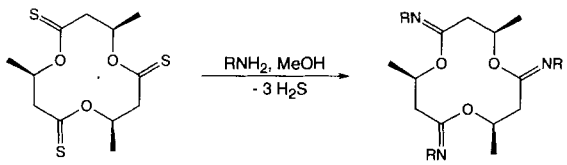
Fig. 5. *X-Ray crystal structure of the* N-*benzylimidate* **20d**. O-Atoms in red, N-atom in green. H-Atoms are omitted for clarity.

Table 6. *Imidates* **23** *from Dithiotriolide* **7** *and Primary Amines.* In each run, 20 equiv. of the amine were used; reaction temperature 0°.



7 **23**

7 [mg]	Amine	Reaction time [min]	Product	Yield [%]
200	$MeNH_2$	5	**23a**	77
50	$BuNH_2$	5	**23b**	88
200	$BnNH_2$	60	**23c**	83



8 24

Table 7. *Imidates* **24** *from Trithiotriolide* **8** *and Primary Amines.* In each run, 30 equiv. of the amine were used; reaction temperature 0°.

8 [mg]	RNH_2	Reaction time [min]	Product	Yield [%]
50	$MeNH_2$	40	**24a**	> 99
100	$BuNH_2$	45	**24b**	90
250	$BnNH_2$	30	**24c**	70
50	H_2NOH	90	**24e**	–

reaction for N- or P-based ligands. Unfortunately, the imidates **23** and **24** were not catalytically active in this reaction. This result was not surprising after a consideration of the crystal structure of **24c** (*Fig. 6*): the C=N bonds all possess the (*E*)-configuration, even when the N-atom bears sterically demanding benzyl substituents. A chelating effect of the lone pairs on the N-atoms, as in the ligands of type **25** and **26**, is thus impossible.

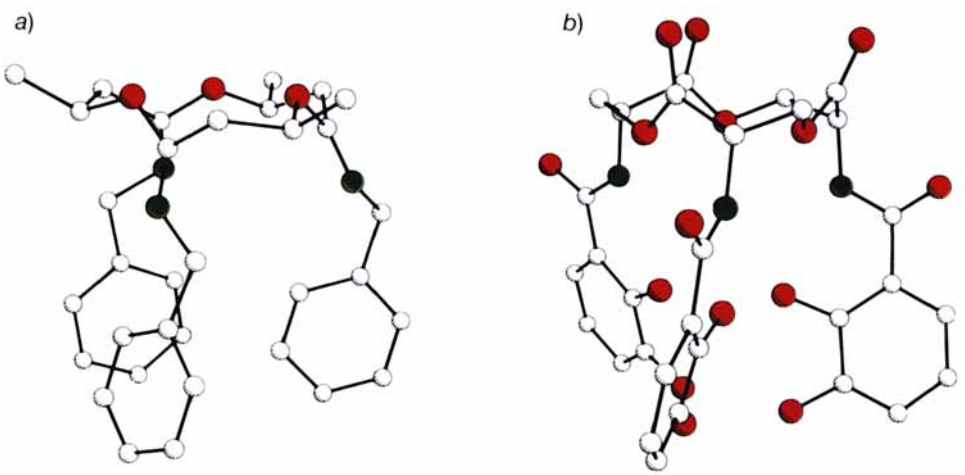
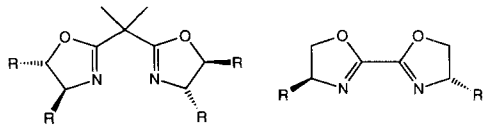
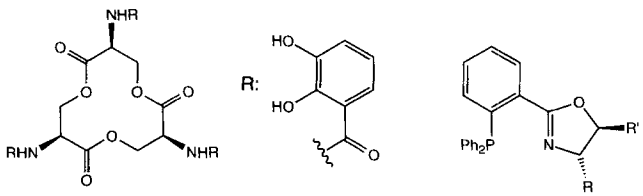


Fig. 6. *Comparison of* a) *the crystal structure of tri*-N-*benzylimidate* **24c** *and* b) *the structure of enterobactin* **27** (in the crystal structure of $[K_2[V(enterobactin)] \cdot 3\ DMF]$ [24]). O-Atoms in red, N-atoms in green. H-Atoms are omitted for clarity.

Nevertheless, introducing appropriate moieties on the benzylic residues might lead to compounds with the ability to complex metal centers, as shown by the structural similarity between **24c** and the natural siderophore enterobactin **27**, a serine-derived triolide with 2,3-dihydroxybenzoyl groups on the N-atoms [24] (*Fig. 6*).



25 26

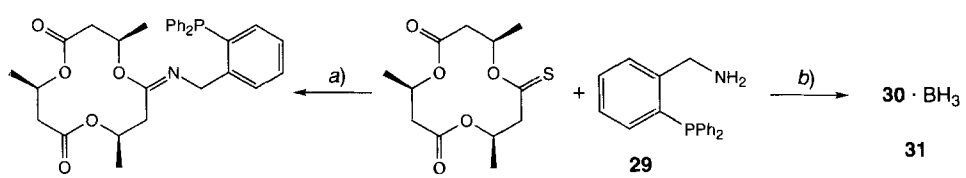


27 28

2.5. *Phosphinoimidate Derivatives of Triolide* **1** *as Ligands in the Pd-Catalyzed Allylation.* N-Based ligands of type **25** and **26** and P-containing dihydrooxazole ligands of type **28** were shown to give high asymmetric induction in the Pd- and W-catalyzed allylic substitution reaction [51]. To obtain phosphinoimidates with similar complexing properties, monothiotriolide **6** was converted to the phosphinoimidates **30** and **33**.

Phosphinoimidate **30** was obtained in moderate yields by reaction of **6** with amine **29**. The reaction was not complete after several hours at room temperature, even not when a twofold excess of **29** was employed. Since the remaining thiotriolide **6** could not be separated from **30** by chromatography, NH_3 was bubbled through the reaction mixture before workup. The imidate **20g** thus formed was then separated from imine **30** by

Scheme 6



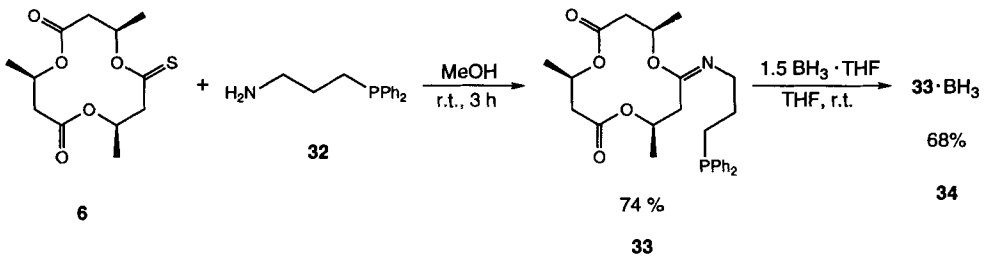
30 6 29 31

a) MeOH, 15 h, r.t.; NH_3, 5 min; FC; 48%. *b*) MeOH, r.t., 18 h; NH_3, 10 min, filtration (SiO_2); THF, 3 BH_3·THF; FC; 40%

chromatography. Although the reaction and workup were carried out with degassed solvents, the crude product **30** contained 5–8% of the corresponding phosphine oxide as a by-product. Since we were not able to purify **30**, it was used as such for further experiments. For characterization by elemental analysis, the crystalline borane adduct **31** was used.

The phosphinoimidate **33** was obtained in a similar way in good yield (*Scheme 7*). After filtration over SiO_2, **33** was used without further purification (it contained traces of

Scheme 7

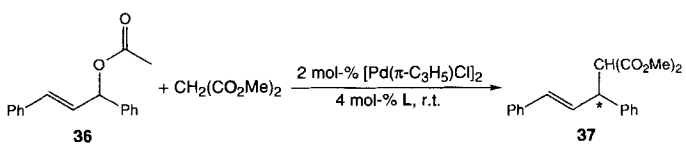


the corresponding phosphine oxide). For analysis, again the more stable crystalline borane adduct **34** was used. Single crystals of **34** suitable for X-ray analysis were obtained. As in the other imidate derivatives of the triolide investigated, the C=N bond turned out to have (*E*)-configuration (*Fig. 7*). Although a sterically demanding diphenylphosphino moiety is connected to the 12-membered-ring backbone, only a small deviation between the cyclic backbones of imidate derivative **34** and triolide **1** is observed (root mean square deviation of 0.11 Å with a maximum value of 0.39 Å between two carbonyl O-atoms).

The phosphinoimidates **30** and **33** gave moderate values of induction when used as ligands in the Pd^{II}-catalyzed 1,3-diphenylallylation reaction (*Table 8*). The best result, a selectivity of 46% ee, was obtained when **30** was used as ligand. When a mixture of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ and the phosphinoimidate **30** was stirred at 50° for 1 h before the reactants were added (to enforce the formation of a bidentate complex), no selectivity was observed for the allylation; **30** appears to be unstable under these conditions.

In an attempt to obtain a catalytically active bidentate ligand, the bisphosphine **35** was prepared in moderate yield by reaction of dithiotriolide **7** with an excess of

Table 8. *Allylation Catalyzed by Palladium(II) Complexes with the Imidates* **30**, **33**, *and* **35** *as Ligands*



Ligand L	Solvent	Base	Time [h]	Yield[a]) [%]	Enantioselectivity ee[b]) [%][c])
33	THF	NaH	15	82	14 (*R*)
30	THF	NaH	12	74	18 (*R*)
35	THF	NaH	13	91	31 (*S*)
33	CH_2Cl_2	BSA[d])	18	92	7 (*R*)
30	CH_2Cl_2	BSA	43[e])	61	46 (*S*)
35	CH_2Cl_2	BSA	18	68	55 (*S*)
30	CH_2Cl_2	BSA	46[f])	65	0

[a]) Yield of pure product after chromatography.
[b]) Determined by ^{1}H-NMR spectroscopy in the presence of $[Eu(hfc)_3]$.
[c]) The absolute configuration of the enantiomer **37** formed in excess is given in brackets.
[d]) BSA = *N,O*-bis[trimethylsilyl]acetamide.
[e]) Compound **30** was stirred with $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ for 1 h at 40° prior to the addition of the reactants.
[f]) Compound **30** was stirred with $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ for 1 h at 50° prior to addition of the reactants.

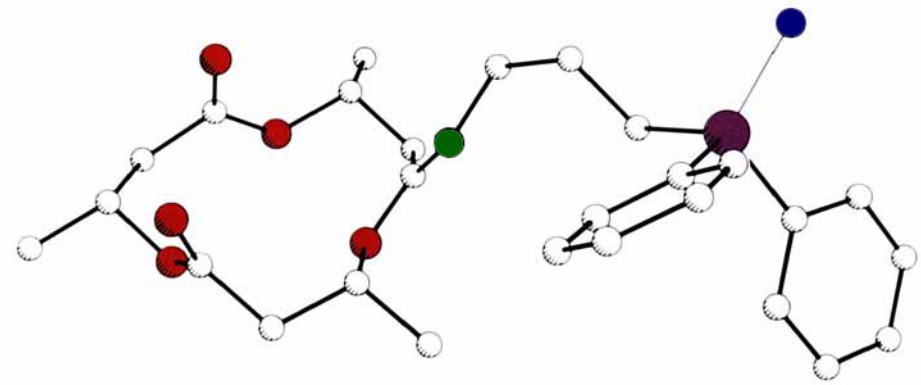
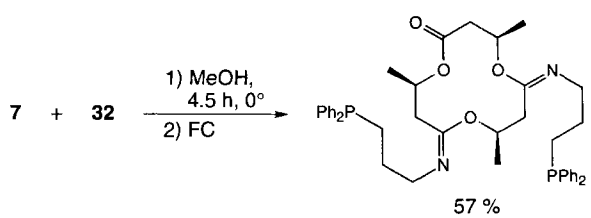


Fig. 7. *X-Ray crystal structure of the phosphine borane adduct* **34**. P-Atom in purple, B-atom in blue, O-atoms in red, N-atoms in green. H-Atoms are omitted for clarity.

phosphinoamine **32** (*Scheme 8*). After chromatography, **35** was used without further purification (traces of the phosphine oxides were present) as a ligand in the Pd^{II}-catalyzed allylation; again a modest selectivity of 55% ee was observed (*Table 8*).

On reaction of dithiotriolide **7** with an excess of phosphinoamine **29**, product mixtures were obtained from which the desired bisphosphine could not be isolated in pure form. We also failed in our attempts to synthesize a tripodal phosphine ligand by reaction of trithiotriolide **8** with phosphinoamine **32**.

Scheme 8



57 %

35

3. Conclusion. – It was shown that several transformations of the ester group of the cyclic 3-HB trimer **1** can be carried out whilst leaving the 12-membered-ring system intact. Thus, the thio *O*-esters **6**–**8** can be obtained in reasonable yields, despite the fact that the rigid ring system of triolide **1** is undergoing up to three substitutions through tetracoordinated intermediates without ring opening!

Reaction of the thio *O*-esters thus obtained with primary amines, which have no branching in the α-position to N, leads to the corresponding imidates in good-to-excellent yields. Unfortunately, no complexation of such imidates with transition metals could be demonstrated. Phosphinoimidates are accessible from the thio derivatives by reaction with phosphinoamines. When used as ligands in the Pd^{II}-catalyzed allylation, these

phosphinoimidates lead to products which are formed in moderate to good yields, albeit with only low to moderate enantioselectivities.

The characteristic 'crown ester' conformation of the 12-membered-ring backbone of triolide **1** is essentially preserved in the thio-*O*-ester and imidate derivatives as proved by several X-ray structure analyses.

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Experimental Part

1. *General.* All solvents were either *puriss p.a.* quality or distilled over appropriate drying reagents. Triolide **1** and pentolide **3** were obtained by acid-catalyzed macrolactonization from P(3-HB) as described in [12]. TLC: *Merck* silica gel *60* F_{254} anal. plates; detection either with UV or by dipping into a soln. of I_2 (30 g) and KI (2 g) in EtOH/H_2O 1:1 (400 ml) and drying in the air. Flash chromatography (FC): *Merck* silica gel *60* (40–63 μm). Prep. HPLC: *Knauer* HPLC system; UV detector, programmer *50*; *Li-Chrosorb SI 60* (*Knauer*). M.p.: open capillaries; uncorrected. Optical rotations: 10-cm 1-ml cell, at r.t.; *Perkin-Elmer-241* polarimeter. IR Spectra: *Perkin-Elmer-983* or *-1600-FT* spectrophotometer. ^{1}H-NMR: *Bruker-AMX-II-500* (500 MHz), *Bruker-AMX-400* (400 MHz), *Bruker-ARX-300* (300 MHz), or *Varian-Gem-200* (200 MHz) spectrometer. ^{13}C-NMR: *Bruker-AMX-II-500* (125 MHz), *Bruker-AMX-400* (100 MHz), *Bruker-ARX-300* (75 MHz), or *Varian-Gem-200* (50 MHz) spectrometer. ^{31}P-NMR: *Bruker-AMX-II-500* (203 MHz), *Bruker-AMX-400* (162 MHz), or *Varian-Gem-300* (121 MHz) spectrometer. MS: *Hitachi Perkin-Elmer RMU-6M* (electron ionization (EI)); *VG ZAB2-SEQ* (fast-atom bombardment (FAB)) with 3-nitrobenzyl alcohol as matrix. High vacuum: h.v.

2. *Thiotriolide Derivatives* **6–8**. A mixture of **1** (5.0 g, 19 mmol), **5** (25.1 g, 62 mmol), and *o*-xylene (60 ml) was heated to reflux for 17 h. After cooling to r.t., chromatography of the mixture (column 5 × 20 cm, pentane (100 ml), Et_2O/pentane 1:20 (1000 ml), Et_2O/pentane 1:5 (1000 ml), Et_2O/pentane 1:2 (150 ml)) gave pure **7** (1.76 g, 32%) and slightly impure **8** (1.85 g, 32%) as orange solids. Crystallization from hexane gave pure **8** (1.43 g, 25%).

An analogous run with **1** (5.0 g, 19 mmol), **5** (8.1 g, 20 mmol), and a reaction time of 7 h (for the chromatography, an additional 800 ml of Et_2O/pentane 1:2 and 1:1 were used) gave **6** (2.18 g, 42%), **7** (956 mg, 17%), and **8** (119 mg, 2%) as yellow solids. For analysis, a sample of each compound was recrystallized from hexane (**8**), CH_2Cl_2/hexane (**7**), or Et_2O/hexane (**6**).

(4R,8R,12R)-4,8,12-Trimethyl-10-thioxo-1,5,9-trioxacyclododecane-2,6-dione (**6**): M.p. 128.8–129.2° (Et_2O/hexane). Single crystals were obtained from Et_2O/hexane. $[\alpha]_D = -57.0$ ($c = 1.1$, $CHCl_3$). IR (KBr): 2984*m*, 2936*w*, 1733*s*, 1448*w*, 1424*w*, 1373*m*, 1299*s*, 1214*s*, 1187*s*, 1170*s*, 1126*s*, 1094*m*, 1035*m*, 977*m*, 815*w*, 633*w*, 486*w*. ^{1}H-NMR (300 MHz): 1.318 (*d*, $J = 6.3$, Me); 1.323 (*d*, $J = 6.4$, Me); 1.38 (*d*, $J = 6.3$, Me); 2.40–3.01 (*m*, 3 CH_2); 5.29–5.43 (*m*, 2 CH); 5.91–6.02 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 19.19 (Me); 20.81 (Me); 20.94 (Me); 41.73 (CH_2); 42.45 (CH_2); 54.12 (CH_2); 68.92 (CH); 72.03 (CH); 76.10 (CH); 169.69 (CO); 170.04 (CO); 218.73 (CS). EI-MS: 274.1 (10, M^+), 204.0 (4), 173.1 (28), 155.1 (18), 131.1 (4), 103.0 (4), 87.0 (45), 69.0 (100), 42.0 (27). Anal. calc. for $C_{12}H_{18}O_5S$ (274.34): C 52.54, H 6.61; found: C 52.63, H 6.85.

(4R,8R,12R)-4,8,12-Trimethyl-6,10-dithioxo-1,5,9-trioxacyclododecan-2-one (**7**): M.p. 99.2–99.6° (hexane). Single crystals were obtained from CH_2Cl_2/hexane. $[\alpha]_D = -39.2$ ($c = 1.05$, CH_2Cl_2). IR (KBr): 2980*w*, 1730*s*, 1450*w*, 1360*m*, 1305*s*, 1250*m*, 1210*s*, 1170*s*, 1125*s*, 1090*s*, 1040*s*, 970*m*, 945*m*, 835*w*, 810*w*, 630*w*. ^{1}H-NMR (300 MHz): 1.33 (*d*, $J = 6.4$, Me); 1.38 (*d*, $J = 6.3$, Me); 1.39 (*d*, $J = 6.3$, Me); 2.56, 2.75 (*AB* of *ABX*, $J_{AX} = 2.2$, $J_{BX} = 11.2$, $J_{AB} = 13.6$, CH_2); 2.91–3.19 (*m*, 2 CH_2); 5.31–5.41 (*m*, 1 CH); 5.91–6.01 (*m*, 1 CH); 6.02–6.12 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 19.26 (Me); 19.36 (Me); 20.88 (Me); 41.88 (CH_2); 53.64 (CH_2); 54.38 (CH_2); 71.97 (CH); 75.95 (CH); 79.08 (CH); 169.66 (CO); 218.03 (CS); 218.86 (CS). EI-MS: 290.2 (14, M^+), 189.1 (12), 155.1 (7), 119.1 (3), 103.1 (24), 87.1 (26), 85.0 (23), 69.0 (100), 60.0 (8), 42.0 (59), 28.0 (16), 18.0 (5). Anal. calc. for $C_{12}H_{18}O_4S_2$ (290.40): C 49.63, H 6.25, S 22.08; found: C 50.10, H 6.24, S 22.53.

(4R,8R,12R)-4,8,12-Trimethyl-1,5,9-trioxacyclododecane-2,6,10-trithione (**8**): M.p. 137.4–138.0° (hexane). $[\alpha]_D = -17.8$ ($c = 0.96$, $CHCl_3$). IR (KBr): 2980*w*, 1450*m*, 1420*m*, 1360*s*, 1305*vs*, 1280*s*, 1210*vs*, 1170*s*, 1120*s*,

1090*s*, 1040*s*, 945*m*, 845*w*, 825*w*, 725*w*, 650*w*, 475*w*. ^{1}H-NMR (300 MHz): 1.39 (*d*, J = 6.3, Me); 3.08, 3.13 (*AB* of *ABX*, J_{AX} = 1.8, J_{BX} = 10.8, J_{AB} = 12.8, CH_2); 6.01–6.12 (*m*, 3 CH). ^{13}C-NMR (75 MHz): 19.39 (Me); 53.90 (CH_2); 78.89 (CH); 218.18 (CS). EI-MS: 306.1 (30, M^+), 242.1 (8), 204.1 (86), 171.1 (7), 155.1 (5), 140.1 (8), 129.1 (5), 119.1 (5), 103.1 (85), 85.1 (43), 74.1 (20), 71.0 (21), 69.1 (100), 60.1 (20), 42.1 (88), 27.1 (13), 18.0 (5). Anal. calc. for $C_{12}H_{18}O_3S_3$ (306.47): C 47.03, H 5.92; found: C 47.13, H 5.89.

5-Methyl-1,2-dithiolane-3-thione (**9**). An analogous run with **1** (10.0 g, 39 mmol) and **5** (50.0 g, 120 mmol) in *o*-xylene (100 ml) and a reaction time of 17 h gave, after FC (pentane → pentane/Et_2O 1:1), **8** (1.19 g, 16%), **7** (2.42 g, 21%), and **8**/**9** which could be separated by an additional FC (CH_2Cl_2/pentane 1:20 (500 ml), then Et_2O/pentane 1:1): **8** (236 mg, 2%) and **9** (230 mg, 1.3%; orange, clear oil). A sample of **9** was bulb-to-bulb distilled (100°/0.4 Torr) for analysis. $[\alpha]_D$ = +8.0 (c = 1.2, $CHCl_3$). IR (film): 2950*m*, 2910*m*, 2850*w*, 1440*m*, 1400*m*, 1370*m*, 1280*s*, 1275*s*, 1200*m*, 1170*s*, 1130*s*, 1080*m*, 1030*s*, 1020*s*, 970*s*, 960*s*, 900*m*, 850*w*, 830*m*, 660*w*, 630*m*, 620*w*. ^{1}H-NMR (300 MHz): 1.55 (*d*, J = 6.7, Me); 3.16, 3.49 (*AB* of *ABX*, J_{AX} = 5.2, J_{BX} = 7.9, J_{AB} = 17.2, CH_2); 4.10–4.21 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 18.42 (Me); 50.92 (CH); 65.88 (CH_2); 240.76 (CS). EI-MS: 150.0 (75, M^+), 108.0 (4), 92.0 (4), 87.1 (5), 86.1 (6), 85.1 (100), 71.0 (12), 64.0 (19), 59.0 (11), 58.0 (11), 45.0 (15). Anal. calc. for $C_{14}H_{16}S_3$ (150.29): C 31.97, H 4.02, S 64.01; found: C 32.25, H 4.00, S 63.64.

3. *Thiopentolides* **10**–**14**. A mixture of **3** (0.5 g, 1.2 mmol), **5** (2.35 g, 5.8 mmol), and *o*-xylene (5 ml) was heated to reflux for 8 h. After cooling to r.t., the solvent was evaporated. The residue was mixed with CH_2Cl_2 and filtered. FC of the filtrate (CH_2Cl_2 (400 ml), then Et_2O/pentane 1:10 → 1:2) gave a crude 1:1 mixture **13**/**14** (80 mg; content *ca.* 50%, yield *ca.* 7%), a 1:1 mixture **11**/**12** (128 mg, 23%), and crude **10** (150 mg). The crude **10** was mixed with CH_2Cl_2 and filtered (SiO_2, first CH_2Cl_2, then Et_2O); the Et_2O fraction was evaporated, yielding pure **10** (124 mg, 23%). The mixture **11**/**12** was separated by prep. HPLC (*LiChrosorb Si 60* (*Knauer*), i-PrOH/hexane 0.3:99.7, 20 ml/min, UV detection at 250 nm) yielding **12** (46 mg) as a white solid and **11** (45 mg) as a yellow oil. For analysis, a sample of **10** and **12** was recrystallized from hexane, **11** was separated from minor impurities by a further prep. HPLC step giving pure **11** as a slightly yellow, oily substance, which solidified after storage for several h under h.v.

*(4*R*,8*R*,12*R*,16*R*,20*R*)-4,8,12,16,20-Pentamethyl-18-thioxo-1,5,9,13,17-pentaoxacycloicosane-2,6,10,14-tetrone* (**10**): M.p. 86.8–87.5° (hexane). Single crystals were obtained from pentane. $[\alpha]_D$ = +10.1 (c = 1.0, $CHCl_3$). IR (KBr): 2985*m*, 2937*m*, 1740*s*, 1458*w*, 1382*m*, 1308*s*, 1258*m*, 1188*s*, 1141*m*, 1103*m*, 1082*m*, 1057*s*, 962*w*, 888*w*, 819*w*. ^{1}H-NMR (400 MHz): 1.26–1.31 (4*d*, 4 Me); 1.40 (*d*, J = 6.3, Me); 2.41–2.99 (*m*, 5 CH_2); 5.22–5.33 (*m*, 3 CH); 5.36–5.44 (*m*, 1 CH); 5.80–5.88 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 18.61 (Me); 19.61 (Me); 19.85 (3 Me); 40.40 (CH_2); 40.80 (CH_2); 40.87 (CH_2); 40.95 (CH_2); 53.14 (CH_2); 67.51 (CH); 67.59 (CH); 67.88 (CH); 69.91 (CH); 74.78 (CH); 169.07 (CO); 169.30 (CO); 169.37 (CO); 169.44 (CO); 217.32 (CS). EI-MS: 446.2 (2, M^+), 386.2 (3), 345.1 (9), 259.0 (10), 241.0 (8), 191.0 (1), 173.0 (16), 171.0 (10), 155.0 (65), 131.0 (4), 87.0 (22), 84.9 (8), 69.0 (100), 43.0 (12), 42.0 (13), 41.0 (12). Anal. calc. for $C_{20}H_{30}O_9S$ (446.52): C 53.80, H 6.77, S 7.18; found: C 53.98, H 6.78, S 7.15.

*(4*R*,8*R*,12*R*,16*R*,20*R*)-4,8,12,16,20-Pentamethyl-14,18-dithioxo-1,5,9,13,17-pentaoxacycloicosane-2,6,10-trione* (**11**): M.p. 42–60°. $[\alpha]_D$ = +25.1 (c = 0.59, $CHCl_3$). IR (KBr): 2985*w*, 2960*w*, 1737*s*, 1384*m*, 1303*s*, 1190*s*, 1132*m*, 1049*m*, 968*w*, 752*w*. ^{1}H-NMR (400 MHz): 1.26 (*d*, J = 6.5, Me); 1.28 (*d*, J = 6.5, Me); 1.30 (*d*, J = 6.3, Me); 1.39 (*d*, J = 6.3, Me); 1.40 (*d*, J = 6.3, Me); 2.39–3.20 (*m*, 5 CH_2); 5.21–5.31 (*m*, 2 CH); 5.32–5.44 (*m*, 1 CH); 5.79–5.87 (*m*, 1 CH); 5.96–6.04 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 18.27 (Me); 18.67 (Me); 19.67 (Me); 19.88 (2 Me); 40.29 (CH_2); 40.78 (CH_2); 40.84 (CH_2); 52.33 (CH_2); 53.20 (CH_2); 67.46 (CH); 67.71 (CH); 69.52 (CH); 74.87 (CH); 76.87 (CH); 169.15 (CO); 169.31 (CO); 169.41 (CO); 216.62 (CS); 217.29 (CS). EI-MS: 462.2 (2, M^+), 434.1 (1), 361.1 (5), 345.1 (1), 301.2 (1), 275.1 (1), 259.1 (5), 241.1 (6), 189.1 (2), 173.1 (11), 171.1 (9), 155.1 (55), 103.1 (6), 87.1 (21), 85.1 (11), 69.1 (100), 43.1 (13), 42.1 (14), 41.1 (16), 28.1 (6). Anal. calc. for $C_{20}H_{30}O_8S_2$ (462.59): C 51.93, H 6.54, S 13.86; found: C 51.80, H 6.41, S 13.90.

*(4*R*,8*R*,12*R*,16*R*,20*R*)-4,8,12,16,20-Pentamethyl-10,18-dithioxo-1,5,9,13,17-pentaoxacycloicosane-2,6,14-trione* (**12**): M.p. 116.5–117.5° (hexane). Single crystals were obtained from AcOEt/hexane. $[\alpha]_D$ = +11.4 (c = 0.78, $CHCl_3$). IR (KBr): 2982*w*, 2936*w*, 1744*s*, 1450*m*, 1386*m*, 1363*m*, 1305*m*, 1256*m*, 1193*s*, 1139*m*, 1102*m*, 1086*m*, 1055*s*, 963*m*, 860*w*, 821*w*, 760*w*, 703*w*. ^{1}H-NMR (400 MHz): 1.28 (*d*, J = 6.3, Me); 1.29 (*d*, J = 6.3, Me); 1.30 (*d*, J = 6.3, Me); 1.37 (*d*, J = 6.3, Me); 1.39 (*d*, J = 6.3, Me); 2.40–2.98 (*m*, 5 CH_2); 5.23–5.31 (*m*, 1 CH); 5.39–5.47 (*m*, 2 CH); 5.81–5.89 (*m*, 2 CH). ^{13}C-NMR (100 MHz): 18.65 (Me); 18.71 (Me); 19.66 (Me); 19.68 (Me); 19.86 (Me); 40.376 (CH_2); 40.385 (CH_2); 40.81 (CH_2); 52.76 (CH_2); 52.95 (CH_2); 67.73 (CH); 69.97 (CH); 70.34 (CH); 74.58 (CH); 74.63 (CH); 169.04 (CO); 169.06 (CO); 169.36 (CO); 217.36 (CS); 217.43 (CS). EI-MS: 462.2 (8, M^+), 360.1 (2), 345.2 (1), 289.1 (1), 275.1 (7), 259.1 (2), 241.1 (2), 230.1 (1), 215.1 (4), 189.1 (12), 173.1 (26), 171.0 (16), 155.1 (39), 103.0 (11), 87.0 (32), 85.0 (16), 69.0 (100), 43.0 (11), 42.0 (15), 41.0 (13). Anal. calc. for $C_{20}H_{30}O_8S_2$ (462.59): C 51.93, H 6.54, S 13.86; found: C 52.22, H 6.43, S 13.76.

Trithiopentolides **13/14**: ^{1}H-NMR (200 MHz): 1.25–1.40 (*m*, 30 H, Me); 2.40–3.35 (*m*, 20 H, CH_2); 5.15–5.30 (*m*, 1 CH); 5.3–5.5 (*m*, 3 CH); 5.7–5.9 (*m*, 3 CH); 5.9–6.1 (*m*, 3 CH).

4. *Reductions of Triolide* **1** *or of Its Thio Derivatives.* 4.1. *Reduction of* **7** *with* Raney-*Ni.* To a mixture of pulverized NiAl alloy (10 g, 50% Ni) in H_2O (100 ml), NaOH pellets were added until the evolution of gas ceased. The suspension was stirred for 30 min at 70°, decanted, and washed with H_2O (5×), EtOH (7×), and Et_2O (7×). This suspension in Et_2O was stirred over 4-Å molecular sieves for 30 min and then cooled to −10°. A soln. of **7** (0.5 g, 1.7 mmol) in Et_2O (4 ml) and CH_2Cl_2 (2 ml) was added over 20 min. After 40 min (temp. ≤ −5°) the reaction was complete according to TLC. The mixture was centrifuged, decanted, and filtered (*Celite*) and the residue washed with Et_2O (3×). Evaporation gave a colorless oil (180 mg). FC (Et_2O/pentane 1:2) yielded crude **17** (71 mg, 18%). A second FC (Et_2O/pentane 1:4) gave pure **17** (39 mg, 10%).

4.2. *Reduction of* **6** *with* Bu_3SnH. A mixture of **6** (50 mg, 0.18 mmol), Bu_3SnH (0.2 ml, 0.75 mmol), AIBN (2,2′-azobis[2-methylpropanenitrile]; 5 mg) and benzene (degassed with Ar; 2 ml) was heated to reflux for 1.5 h. After cooling to r.t., the solvent was removed under h.v. FC (pentane (300 ml), then Et_2O/pentane 1:2 → 1:1) gave **15** (16 mg, 36%) as a colorless oil.

4.3. *Reduction of* **6** *with* $NaBH_4$ *and* Ph_3SnH. A mixture of **6** (250 mg, 0.91 mmol), $NaBH_4$ (50 mg, 1.3 mmol), and i-PrOH (25 ml) was stirred for 18 h at r.t. under Ar. The mixture was quenched with 1N HCl (5 ml) and stirred for *ca.* 1 min. After the addition of brine, the soln. was extracted with Et_2O and the org. phase dried ($MgSO_4$). Evaporation gave crude **16** (259 mg) as a white solid. FC (Et_2O/pentane 1:2) yielded pure **16** (155 mg, 62%). A sample was recrystallized from CH_2Cl_2/hexane for analysis.

In a run analogous to *Exper. 4.3* (reaction time 12 h), crude **16** was mixed with Ph_3SnH (640 mg, 1.82 mmol), AIBN (5 mg), and toluene (degassed with Ar; 10 ml) and heated to reflux for 1 h. FC (pentane (100 ml), then Et_2O/pentane 1:3) of the mixture gave **15** (136 mg, 61%) as a colorless oil. For analysis, a sample was chromatographed twice (1. Et_2O/pentane 1:3; 2. CH_2Cl_2/Et_2O/pentane 1:1:2) and bulb-to-bulb distilled (125°/0.2 Torr).

4.4. *Reduction of* **1** *with* $SiHCl_3$. 4.4.1. *Without Solvent.* A suspension of **1** (2.0 g, 7.7 mmol), $SiHCl_3$ (distilled over quinoline; 8 ml, 76 mmol) and di(*tert*-butyl) peroxide (0.2 ml, 1.2 mmol) was irradiated with a Hg-lamp in a *Pyrex* tube at 0° for 22 h. The mixture was dissolved in CH_2Cl_2 (200 ml), and to this soln., H_2O (80 ml) and 15% NaOH soln. (15 ml) were added under cooling with ice and vigorous stirring (the use of a large beaker is recommended, foaming!) The suspension obtained was filtered (*Celite*), the aq. phase extracted twice with CH_2Cl_2, and the combined org. phase washed with brine, dried ($MgSO_4$), and evaporated: colorless oil (1.37 g). FC (Et_2O/pentane) yielded **19** (240 mg, 14%) and **17**/**18** (*ca.* 10:7 according to ^{1}H-NMR; 280 mg).

4.4.2. *With* Et_2O *as Solvent.* A soln. of **1** (2.0 g, 7.6 mmol) in Et_2O (30 ml) was mixed with di(*tert*-butyl) peroxide (0.2 ml, 1.2 mmol) and $SiHCl_3$ (20 ml, 0.19 mol) and irradiated for 3 h. Workup as in *4.4.1* gave a colorless oil (1.13 g). FC (Et_2O/pentane 1:2) yielded **17**/**18** (*ca.* 1:2 according to ^{1}H-NMR; 316 mg). A second FC (Et_2O/CH_2Cl_2/pentane 1:2:3) yielded pure **17** (127 mg, 7.2%) and **18** (145 mg, 8.8%) as colorless oils. For analysis, a separate sample of **17** and **18** was each chromatographed and subsequently bulb-to-bulb distilled (80°/0.2 Torr).

4.5. *Data of* **15**–**19**. *(4*R*,8*R*,12*R*)-4,8,12-Trimethyl-1,5,9-trioxacyclododecane-2,6-dione* (**15**): $[\alpha]_D = -46.4$ (*c* = 1.10, $CHCl_3$). IR (film): 2977*m*, 2935*m*, 2878*w*, 1738*s*, 1451*w*, 1427*w*, 1374*s*, 1302*s*, 1259*m*, 1188*s*, 1136*s*, 1105*s*, 1053*m*, 976*m*, 924*w*, 871*w*, 831*w*, 782*w*, 736*w*, 647*w*. ^{1}H-NMR (400 MHz): 1.19 (*d*, *J* = 6.1, Me); 1.23 (*d*, *J* = 6.4, Me); 1.30 (*d*, *J* = 6.5, Me); 1.65–1.72 (*m*, 1 H, CH_2); 1.90–1.99 (*m*, 1 H, CH_2); 2.30–2.62 (*m*, 4 H, CH_2); 3.28–3.33 (*m*, 1 H, OCH_2); 3.77–3.87 (*m*, 2 H, OCH_2, CH); 5.07–5.15 (*m*, 1 CH); 5.56–5.65 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 18.78 (Me); 20.84 (Me); 21.26 (Me); 35.87 (CH_2); 42.88 (CH_2); 43.04 (CH_2); 66.53 (CH_2); 68.02 (CH); 71.70 (CH); 73.37 (CH); 170.79 (CO); 171.20 (CO). EI-MS: 245.1 (2, $[M + H]^+$), 244.1 (1), 229.1 (1), 216.1 (1), 200.1 (2), 189.1 (1), 185.1 (2), 174.1 (63), 155.1 (19), 141.1 (27), 131.1 (19), 114.1 (13), 105.1 (14), 103.1 (19), 101.1 (13), 99.1 (8), 87.1 (95), 71.1 (29), 69.0 (100), 55.1 (25), 45.0 (15), 43.0 (37), 42.0 (23), 41.0 (20). Anal. calc. for $C_{12}H_{20}O_5$ (244.29): C 59.00, H 8.25; found: C 58.82, H 8.34.

*(4*R*,8*R*,12*R*)-10-Mercapto-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione* (**16**): M.p. 113.0–114.5° (CH_2Cl_2/hexane). $[\alpha]_D = -135.8$ (*c* = 0.93, $CHCl_3$). IR (KBr): 3400*w* (br.), 3229*w* (br.), 2985*m*, 2933*w*, 2559*w*, 1739*s*, 1710*m*, 1449*w*, 1379*m*, 1309*s*, 1245*m*, 1191*s*, 1132*m*, 1090*s*, 699*w*. ^{1}H-NMR (300 MHz): 1.17 (*d*, *J* = 6.1, Me); 1.27 (*d*, *J* = 6.2, Me); 1.29 (*d*, *J* = 6.2, Me); 1.91 (*ddd*, *J* = 1.4, 4.2, 15.2, 1 H, CH_2); 2.36–2.62 (*m*, 6 H); 4.43–4.54 (*m*, H–C(10)); 4.91–4.96 (*m*, SH); 5.57–5.71 (*m*, 2 CH). ^{13}C-NMR (75 MHz): 17.58 (Me); 20.78 (Me); 21.49 (Me); 42.79 (CH_2); 42.95 (CH_2); 44.87 (CH_2); 66.30 (CH); 68.04 (CH); 68.46 (CH); 75.50 (CH); 170.37 (CO); 170.66 (CO). EI-MS: 276.1 (0.05, M^+), 274.1 (0.06), 261.1 (0.2), 243.1 (45), 189.1 (8), 173.1 (41), 155.1 (22), 131.1 (9), 115.1 (4), 113.1 (4), 105.1 (7), 103.0 (8), 87.1 (91), 71.1 (42), 69.0 (100), 60.0 (5), 45.0 (32), 43.0 (58), 42.0 (20), 41.0 (29), 28.0 (12). FAB-MS: 553.2 (3, $[2M + H]^+$), 519.2 (10), 415.1 (3), 299.1 (3), 289.1 (3), 277.1 (5), 244.1 (25),

243.1 (100), 191.1 (10), 173.1 (28), 86.9 (36), 68.9 (32). Anal. calc. for $C_{12}H_{20}O_5S$ (276.35): C 52.15, H 7.29, S 11.60; found: C 52.38, H 7.09, S 11.43.

(4R,8R,12R)-4,8,12-Trimethyl-1,5,9-trioxacyclododecan-2-one (**17**): $[\alpha]_D = -55.2$ ($c = 1.14$, $CHCl_3$). IR ($CHCl_3$): 2960*w*, 1710*s*, 1450*w*, 1370*m*, 1340*w*, 1290*m*, 1140*s*, 1130*s*, 1090*s*. ^{1}H-NMR (300 MHz): 1.11 (*d*, $J = 6.1$, Me); 1.22 (*d*, $J = 6.4$, Me); 1.23 (*d*, $J = 6.4$, Me); 1.55–1.78 (*m*, 3 H); 1.84–1.97 (*m*, 1 H); 2.29, 2.62 (*AB* of *ABX*, $J_{AX} = 3.0$, $J_{BX} = 11.6$, $J_{AB} = 13.4$, CH_2); 3.23–3.32 (*m*, 2 H); 3.47–3.57 (*m*, 1 H); 3.75–3.87 (*m*, 2 H); 4.04–4.15 (*m*, 1 CH); 5.17–5.28 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 19.26 (Me); 19.52 (Me); 21.30 (Me); 36.32 (CH_2); 37.03 (CH_2); 42.18 (CH_2); 62.67 (CH_2); 65.84 (CH_2); 70.82 (CH); 72.68 (CH); 73.66 (CH); 172.18 (CO). EI-MS: 230.1 (1, M^+), 215.0 (1), 175.0 (5), 171.1 (5), 159.1 (9), 141.03 (11), 126.1 (9), 114.0 (16), 105.0 (11), 99.1 (16), 87.0 (73), 71.0 (55), 55.0 (90), 43.0 (100), 28.0 (43), 18.0 (16). Anal. calc. for $C_{12}H_{22}O_4$ (230.30): C 62.58, H 9.63; found: C 62.73, H 9.70.

(2R,6R,10R)-2,6,10-Trimethyl-1,5,9-trioxacyclododecane (**18**): $[\alpha]_D = -33.8$ ($c = 0.65$, $CHCl_3$). IR (film): 2940*s*, 2900*m*, 2840*m*, 1720*w*, 1460*w*, 1440*w*, 1360*m*, 1330*w*, 1140*s*, 1100*s*, 1010*w*, 905*w*, 745*w*. ^{1}H-NMR (300 MHz): 1.15 (*d*, $J = 6.3$, Me); 1.59–1.67 (*m*, 3 H); 1.72–1.81 (*m*, 3 H); 3.24–3.28 (*m*, 3 H); 3.58–3.66 (*m*, 3 H); 3.86–3.90 (*m*, 3 H). ^{13}C-NMR (75 MHz): 20.13 (Me); 36.80 (CH_2); 64.27 (CH_2); 74.32 (CH). EI-MS: 216.1 (2, M^+), 201.3 (0.5), 188.1 (1), 175.1 (1), 161.1 (8), 143.1 (8), 128.1 (15), 126.1 (12), 117.1 (22), 111.1 (15), 101.1 (31), 89.1 (47), 87.1 (16), 85.1 (19), 71.1 (64), 55.1 (100), 43.0 (63), 28.0 (18), 18.0 (58). Anal. calc. for $C_{12}H_{24}O_3$ (216.32): C 66.63, H 11.18; found: C 66.53, H 11.45.

(2R,6R,10S)-2,6,10-Trimethyl-1,5,9-trioxacyclododecane (**19**): $[\alpha]_D = +8.7$ ($c = 0.94$, $CHCl_3$); $[\alpha]_{365} = +25.5$ ($c = 0.94$, $CHCl_3$). IR (film): 2975*m*, 1730*w*, 1460*w*, 1375*m*, 1350*w*, 1280*s*, 1150*m*, 1110*m*, 1080*m*, 1005*w*, 910*w*, 750*w*. ^{1}H-NMR (300 MHz): 1.155 (*d*, $J = 6.6$, Me); 1.157 (*d*, $J = 6.2$, Me); 1.18 (*d*, $J = 6.5$, Me); 1.45–1.55 (*m*, 3 H); 1.78–1.94 (*m*, 3 H); 3.40–3.47 (*m*, 1 H); 3.50–3.75 (*m*, 5 H); 3.78–3.95 (*m*, 3 H). ^{13}C-NMR (75 MHz): 19.87 (Me); 20.10 (Me); 20.65 (Me); 35.35 (CH_2); 36.61 (CH_2); 37.16 (CH_2); 63.83 (CH_2); 63.97 (CH_2); 64.35 (CH_2); 69.14 (CH); 69.84 (CH); 74.71 (CH). EI-MS: 217.3 (2, $[M + H]^+$), 201.3 (1), 188.3 (1), 175.3 (1), 161.2 (10), 143.2 (10), 128.2 (22), 126.2 (15), 117.2 (28), 111.2 (17), 101.2 (37), 89.2 (62), 85.2 (25), 71.1 (75), 55.1 (100), 43.1 (69), 29.1 (17). Anal. calc. for $C_{12}H_{24}O_3$ (216.32): C 66.63, H 11.18; found: C 66.16, H 10.75.

5. *Imidate Derivatives of Triolide* **1**. 5.1. *Imidates* **20**: *General Procedure* (*GP*). A soln. of **6** in MeOH was mixed with the amine and stirred for 30–60 min at r.t. The solvent was removed under h.v. without heating. The residue was dissolved in CH_2Cl_2 and filtered with Et_2O through a short column of SiO_2 and the soln. evaporated ($\leq$ r.t.).

(4R,8R,12R)-4,8,12-Trimethyl-10-(methylimino)-1,5,9-trioxacyclododecane-2,6-dione (**20a**). According to *GP*, from **6** (50 mg, 0.18 mmol) and $MeNH_2$ (225 µl, 8.03M in EtOH, 1.8 mmol): **20a** (33 mg, 68%). White solid. For analysis, a sample was recrystallized from CH_2Cl_2/pentane. M.p. 101.2–102.2° (CH_2Cl_2/pentane). $[\alpha]_D = -88.6$ ($c = 1.01$, $CHCl_3$). IR (KBr): 2986*m*, 2934*w*, 1734*s*, 1679*s*, 1449*m*, 1430*w*, 1375*m*, 1305*s*, 1290*m*, 1270*m*, 1190*s*, 1129*s*, 1106*m*, 1053*m*, 978*w*, 964*m*, 934*w*, 869*w*, 828*w*, 801*w*, 710*w*, 644*w*. ^{1}H-NMR (400 MHz): 1.24 (*d*, $J = 6.2$, Me); 1.30 (*d*, $J = 6.2$, Me); 1.32 (*d*, $J = 6.3$, Me); 2.22–2.68 (*m*, 3 CH_2); 3.02 (*s*, MeN); 5.13–5.21 (*m*, 1 CH); 5.28–5.35 (*m*, 1 CH); 5.35–5.44 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 20.22 (Me); 20.69 (Me); 21.30 (Me); 35.26 (CH_2); 35.53 (Me); 42.15 (CH_2); 42.39 (CH_2); 67.41 (CH); 68.21 (CH); 68.27 (CH); 160.30 (CN); 170.25 (CO); 170.67 (CO). EI-MS: 271.1 (1, M^+), 243.1 (7), 227.1 (1), 202.1 (1), 186.1 (2), 173.1 (4), 168.1 (8), 155.1 (12), 141.1 (4), 126.1 (5), 118.1 (11), 116.1 (24), 101.1 (13), 100.1 (34), 99.1 (11), 87.1 (12), 86.1 (8), 85.1 (6), 84.1 (7), 82.1 (10), 73.1 (10), 69.1 (100), 58.1 (19), 43.1 (6), 42.1 (8), 41.1 (9). Anal. calc. for $C_{13}H_{21}NO_5$ (271.31): C 57.55, H 7.80, N 5.16; found: C 57.31, H 7.94, N 4.86.

(4R,8R,12R)-10-(Butylimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione (**20b**). According to *GP*, from **6** (50 mg, 0.18 mmol) and butylamine (180 µl, 1.8 mmol): **20b** (51 mg, 90%). Colorless oil. The product decomposed after a few days standing at r.t. $[\alpha]_D = -68.7$ ($c = 0.96$, $CHCl_3$). IR (film): 2958*m*, 2933*m*, 2872*w*, 1742*s*, 1678*s*, 1449*w*, 1427*w*, 1378*m*, 1302*s*, 1265*m*, 1185*s*, 1133*s*, 1106*m*, 1054*m*, 977*w*, 916*w*, 734*w*, 648*w*. ^{1}H-NMR (400 MHz): 0.92 (*t*, $J = 7.3$, *Me*$(CH_2)_3$); 1.24 (*d*, $J = 6.2$, Me); 1.28 (*d*, $J = 6.3$, Me); 1.31 (*d*, $J = 6.4$, Me); 1.24–1.41 (*m*, 2 H); 1.48–1.55 (*m*, 2 H); 2.21–2.70 (*m*, 6 H); 3.07–3.18 (*m*, 1 H); 3.20–3.27 (*m*, 1 H); 5.09–5.17 (*m*, 1 CH); 5.29–5.34 (*m*, 1 CH); 5.34–5.44 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 14.00 (Me); 20.20 (Me); 20.50 (CH_2); 20.75 (Me); 21.35 (Me); 33.70 (CH_2); 35.43 (CH_2); 42.15 (CH_2); 42.45 (CH_2); 48.30 (CH_2); 67.39 (CH); 68.28 (CH); 68.80 (CH); 158.23 (CN); 170.28 (CO); 170.82 (CO). FAB-MS: 627.3 (6, $[2\ M + H]^+$), 314.1 (100, $[M + H]^+$), 210.1 (9), 142.1 (41), 68.9 (66).

(4R,8R,12R)-10-(Benzylimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione (**20d**). A soln. of **6** (500 mg, 1.8 mmol) and benzylamine (2 ml, 18 mmol) in MeOH (15 ml) was stirred at 0° for 60 min. The solvent was removed under h.v. without heating and the residue dissolved in Et_2O. FC (column 3 × 9 cm, Et_2O/pentane 1:3) gave **20d** (605 mg, 96%). Colorless solid. For analysis, a sample was recrystallized from Et_2O. M.p. 106.6–107.0° (Et_2O). $[\alpha]_D = -70.4$ ($c = 1.1$, $CHCl_3$). IR (KBr): 2972*m*, 2925*w*, 1735*s*, 1678*s*, 1497*w*, 1457*w*, 1420*w*, 1375*m*,

1305*s*, 1268*m*, 1238*w*, 1196*s*, 1134*s*, 1107*m*, 1054*m*, 967*m*, 907*w*, 877*w*, 826*w*, 801*w*, 761*w*, 746*w*, 711*m*, 698*w*, 643*w*. ^{1}H-NMR (400 MHz): 1.29 (*d*, *J* = 6.3, Me); 1.31 (*d*, *J* = 6.2, Me); 1.33 (*d*, *J* = 6.5, Me); 2.31–2.70 (*m*, 6 H); 4.43, 4.55 (*AB*, J_{AB} = 15.7, PhCH_2N); 5.12–5.19 (*m*, 1 CH); 5.39–5.53 (*m*, 2 CH); 7.20–7.34 (*m*, 5 arom. H). ^{13}C-NMR (100 MHz): 20.28 (Me); 20.73 (Me); 21.37 (Me); 35.82 (CH_2); 42.14 (CH_2); 42.44 (CH_2); 51.93 (CH_2); 68.04 (CH); 68.33 (CH); 68.58 (CH); 126.46 (CH); 126.99 (CH); 128.30 (CH); 140.68 (C); 160.02 (CN); 170.24 (CO); 170.78 (CO). FAB-MS: 695.3 (4, [2 *M* + H]$^+$), 370.1 (8, [*M* + Na]$^+$), 348.1 (100, [*M* + H]$^+$), 307.0 (12), 289.0 (7), 194.1 (11), 176.1 (20), 154.0 (59), 136.0 (46), 107.0 (23), 90.9 (60), 76.9 (23), 68.9 (45), 54.9 (18). Anal. calc. for $C_{19}H_{25}NO_5$ (347.41): C 65.69, H 7.25, N 4.03; found: C 65.80, H 7.30, N 4.09.

*(4*R*,8*R*,12*R*)-10-(Hydroxyimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione* (**20f**). According to *GP* (suspension) from **6** (200 mg, 0.73 mmol), $H_2NOH \cdot HCl$ (500 mg, 7.2 mmol), and NaOH (280 mg, 7.2 mmol): **20f** (175 mg, 88%). Colorless solid. For analysis, a sample was recrystallized from CH_2Cl_2/pentane. M.p. 157.5–158.5° (CH_2Cl_2/pentane). $[\alpha]_D = -103.4$ (*c* = 1.02, $CHCl_3$). IR (KBr): 3483*m*, 2983*m*, 2938*w*, 1731*s*, 1701*s*, 1658*m*, 1451*m*, 1430*m*, 1376*s*, 1311*s*, 1273*s*, 1249*m*, 1194*s*, 1134*s*, 1106*m*, 1044*m*, 999*s*, 979*m*, 967*m*, 876*w*, 833*w*, 801*w*, 749*w*, 645*w*, 619*w*. ^{1}H-NMR (400 MHz): 1.30 (*d*, *J* = 6.1, Me); 1.31 (*d*, *J* = 6.6, Me); 1.32 (*d*, *J* = 6.6, Me); 2.06–3.07 (*m*, 3 CH_2); 5.06–5.14 (*m*, 1 CH); 5.30–5.38 (*m*, 1 CH); 5.38–5.46 (*m*, 1 CH); 6.16 (*s*, NOH). ^{13}C-NMR (100 MHz): 19.90 (Me); 20.61 (Me); 21.23 (Me); 34.19 (CH_2); 42.34 (CH_2); 42.46 (CH_2); 68.70 (CH); 68.84 (CH); 70.22 (CH); 162.33 (CN); 170.26 (CO); 170.58 (CO). EI-MS: 273.1 (0.4, M^+), 258.1 (0.1), 187.1 (0.3), 173.1 (4), 170.1 (2), 155.1 (4), 131.1 (1), 112.1 (2), 101.1 (15), 87.1 (19), 69.1 (100), 43.0 (23), 42.1 (17), 41.1 (24), 28.0 (26). Anal. calc. for $C_{12}H_{19}NO_6$ (273.29): C 52.74, H 7.01, N 5.13; found: C 52.98, H 6.74, N 5.14.

*(4*R*,8*R*,12*R*)-10-Imino-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione* (**20g**). To a soln. of NH_3 in MeOH (10 ml), **6** (100 mg, 0.36 mmol) was added and stirred for 45 min at 0°. The solvent was evaporated under h.v. without heating to give crude **20g** (101 mg) as a slightly yellow oil. The product decomposed after a few days standing at r.t. $[\alpha]_D = -35.7$ (*c* = 0.99, $CHCl_3$). IR (film): 3320*w*, 2983*m*, 2937*w*, 2456*w*, 1732*s*, 1651*s*, 1449*m*, 1428*m*, 1379*m*, 1302*s*, 1263*m*, 1184*s*, 1134*s*, 1109*s*, 1049*m*, 977*m*, 951*w*, 882*w*, 829*w*, 756*s*, 666*w*, 643*w*. ^{1}H-NMR (300 MHz): 1.29 (*d*, *J* = 6.3, Me); 1.32 (*d*, *J* = 6.4, Me); 1.33 (*d*, *J* = 6.2, Me); 2.35–2.64 (*m*, 3 CH_2); 3.8–4.7 (br., NH); 5.19–5.30 (*m*, 1 CH); 5.30–5.45 (*m*, 2 CH). ^{13}C-NMR (75 MHz): 20.17 (Me); 20.85 (Me); 21.07 (Me); 42.28 (CH_2); 42.41 (CH_2); 43.41 (CH_2); 68.65 (CH); 68.91 (CH); 69.66 (CH); 168.83 (CN); 170.37 (CO); 170.47 (CO). EI-MS: 258.1 (1, [*M* + H]$^+$), 242.1 (0.6), 229.1 (4), 213.1 (1), 189.1 (2), 171.1 (17), 155.1 (13), 154.1 (27), 138.1 (6), 127.1 (8), 112.1 (5), 104.1 (8); 103.1 (7), 102.1 (9), 87.1 (20), 86.1 (29), 85.1 (19), 69.1 (100), 43.1 (11), 42.1 (9), 41.1 (9).

*(4*R*,8*R*,12*R*)-10-(Acetylimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione* (**20h**). A soln. of crude **20g** (101 mg, obtained by the reaction described above), Et_3N (56 µl, 0.4 mmol), and AcCl (28 µl, 0.4 mmol) in CH_2Cl_2 was stirred for 18 h at 0°. The mixture was poured onto ice, mixed with 1N NaOH, and extracted twice with CH_2Cl_2. The org. phases were washed (H_2O), dried ($MgSO_4$), and evaporated to give **20h** (96 mg, 89% rel. to **6**) as a slightly yellow oil. For analysis, a sample was purified by FC (AcOEt/hexane 1:2) and recrystallization (Et_2O/pentane): **20h** as a colorless solid. M.p. 98.5–99.0° (Et_2O/pentane). $[\alpha]_D = -12.4$ (*c* = 1.02, $CHCl_3$); $[\alpha]_{365} = +146.4$ (*c* = 1.02, $CHCl_3$). IR (KBr): 2991*m*, 2940*w*, 1747*s*, 1721*m*, 1691*m*, 1637*m*, 1458*m*, 1426*m*, 1371*m*, 1322*m*, 1300*s*, 1270*m*, 1236*s*, 1208*m*, 1179*s*, 1140*m*, 1118*m*, 1101*m*, 1051*m*, 975*s*, 957*m*, 926*w*, 866*w*, 842*w*, 764*w*, 688*w*, 657*w*, 609*w*. ^{1}H-NMR (300 MHz): 1.27 (*d*, *J* = 6.3, Me); 1.31 (*d*, *J* = 6.3, Me); 1.33 (*d*, *J* = 6.4, Me); 2.23 (*s*, Ac); 2.31–2.86 (*m*, 3 CH_2); 5.14–5.25 (*m*, 1 CH); 5.25–5.37 (*m*, 1 CH); 5.37–5.49 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 19.94 (Me); 20.64 (Me); 21.16 (Me); 26.71 (Me); 38.26 (CH_2); 41.89 (CH_2); 42.31 (CH_2); 68.64 (CH); 68.85 (CH); 70.90 (CH); 160.95 (C); 170.17 (C); 183.57 (C). EI-MS: 299.2 (2, M^+), 284.1 (1), 271.2 (0.4), 257.1 (2), 256.2 (2), 242.1 (1), 230.1 (2), 213.2 (1), 189.1 (15), 171.1 (25), 154.1 (15), 144.1 (5), 128.1 (21), 112.1 (8), 103.1 (13), 87.1 (16), 86.1 (13), 85.1 (14), 69.1 (100), 60.1 (5), 43.1 (22), 42.1 (8), 41.1 (9). Anal. calc. for $C_{14}H_{21}NO_6$ (299.32): C 56.18, H 7.07, N 4.68; found: C 56.30, H 7.05, N 4.44.

*Tris[(4*R*,8*R*,12*R*)-4,8,12-trimethyl-6,10-dioxo-1,5,9-trioxacyclododecane-2-ylideneamino] Phosphate* (**22**). A soln. of **20f** (184 mg, 0.67 mmol) in Et_2O (10 ml) was mixed with PCl_5 (*ca.* 50 mg) and stirred for 1.5 h at 0°. The mixture was poured onto ice and the aq. phase extracted with Et_2O. The combined org. phase was washed twice with brine, dried ($MgSO_4$), and evaporated to give crude **22** (200 mg, quant.) as slightly yellow solid. Recrystallization (CH_2Cl_2/hexane) yielded **22** (95 mg, 45%) as a clathrate, including one CH_2Cl_2 molecule per phosphate **22**. M.p. 108.0–112.0° (CH_2Cl_2/hexane). Single crystals were obtained from CH_2Cl_2/hexane. $[\alpha]_D = -113.8$ (*c* = 1.05, $CHCl_3$). IR (KBr): 2985*m*, 2937*w*, 1733*vs*, 1630*m*, 1426*m*, 1383*s*, 1301*s*, 1266*m*, 1188*s*, 1133*s*, 1149*m*, 967*s*, 825*w*, 606*m*, 539*m*. ^{1}H-NMR (400 MHz): 1.32 (*d*, *J* = 6.4, Me); 1.33 (*d*, *J* = 6.4, Me); 1.38 (*d*, *J* = 6.2, Me); 2.23–3.14 (*m*, 9 CH_2); 5.08–5.17 (*m*, 3 CH); 5.21–5.28 (*m*, 3 CH); 5.30 (*s*, CH_2Cl_2); 5.33–5.41 (*m*, 3 CH). ^{13}C-NMR (100 MHz): 19.59 (Me); 20.54 (Me); 21.08 (Me); 34.90 (CH_2); 42.05 (CH_2); 42.22 (CH_2); 68.74 (CH); 68.86 (CH); 72.29 (CH); 168.97 (*d*, *J*(C,P) = 15.4, CN); 169.89 (CO); 169.97 (CO). ^{31}P-NMR (121 MHz): +2.09. FAB-MS:

996.1 (2, $[M + Cs]^+$), 864.1 (34, M^+), 609.0 (4), 354.0 (5), 274.1 (9), 155.1 (26), 68.9 (100). EI-MS: 273.2 (0.6), 258.1 (0.4), 255.9 (0.4), 243.2 (0.1), 230.2 (0.2), 214.2 (0.4), 189.2 (6), 173.2 (11), 171.2 (5), 155.2 (12), 154.2 (8), 128.1 (4), 103.1 (7), 101.1 (7), 87.1 (19), 69.1 (100), 57.1 (9), 43.1 (22), 42.1 (19), 41.1 (20). Anal. calc. for $C_{37}H_{56}Cl_2N_3O_{19}P$ (948.74): C 46.84, H 5.95, N 4.43; found: C 46.87, H 5.88, N 4.41.

5.2. *Imidates* **23**. *(4*R*,8*R*,12*R*)-4,8,12-Trimethyl-6,10-bis(methylimino)-1,5,9-trioxacyclododecan-2-one* (**23a**). A soln. of **7** (200 mg, 0.69 mmol) and $MeNH_2$ (8.03M in EtOH; 1.72 ml, 14 mmol) in 10 ml MeOH was stirred for 5 min at 0°. The solvent was evaporated under h.v. without heating. The residue was dissolved in CH_2Cl_2 and the soln. washed with brine (3×) dried ($MgSO_4$), and evaporated to yield **23a** (151 mg, 77%) as a yellow oil which solidified upon standing. For analysis, a sample was recrystallized from Et_2O/pentane. M.p. 92.8–93.0° (CH_2Cl_2/pentane). $[\alpha]_D = -154.7$ ($c = 0.73$, $CHCl_3$). IR (KBr): 2989*m*, 2966*m*, 2938*m*, 2794*w*, 1727*s*, 1671*s*, 1447*m*, 1427*m*, 1409*w*, 1379*m*, 1360*m*, 1299*s*, 1272*m*, 1252*m*, 1197*s*, 1131*s*, 1105*m*, 1077*w*, 1056*m*, 1041*m*, 971*m*, 951*m*, 907*w*, 868*w*, 822*w*, 792*w*, 761*w*, 719*w*, 701*w*, 635*w*. ^{1}H-NMR (400 MHz): 1.23 (*d*, $J = 6.1$, Me); 1.25 (*d*, $J = 6.2$, Me); 1.31 (*d*, $J = 6.4$, Me); 2.21–2.70 (*m*, 3 CH_2); 2.99 (*s*, MeN); 3.02 (*s*, MeN); 5.07–5.15 (*m*, 1 CH); 5.23–5.31 (*m*, 1 CH); 5.31–5.39 (*m*, 1 CH). ^{13}C-NMR (100 MHz): 20.30 (Me); 20.84 (Me); 21.35 (Me); 35.24 (CH_2); 35.56 (Me); 35.94 (CH_2); 42.44 (CH_2); 66.87 (CH); 67.17 (CH); 67.31 (CH); 160.64 (CN); 161.49 (CN); 170.99 (CN). EI-MS: 284.1 (0.2, M^+), 269.1 (1), 202.1 (1), 186.1 (3), 185.1 (3), 167.1 (2), 157.1 (2), 155.1 (2), 141.1 (8), 116.1 (31), 100.1 (40), 99.1 (33), 87.1 (13), 84.1 (16), 69.1 (100), 58.1 (28), 41.1 (16). Anal. calc. for $C_{14}H_{24}N_2O_4$ (284.36): C 59.14, H 8.51, N 9.85; found: C 59.50, H 8.89, N 9.83.

*(4*R*,8*R*,12*R*)-6,10-Bis(butylimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecan-2-one* (**23b**). As described for **23a**, with **7** (50 mg, 0.17 mmol) and butylamine (340 µl, 3.4 mmol) in MeOH (5 ml): crude **23b** (56 mg, 88%). Yellow oil. $[\alpha]_D = -104.6$ ($c = 0.98$, $CHCl_3$). IR (film): 2957*m*, 2932*m*, 2872*m*, 1738*s*, 1678*s*, 1458*w*, 1377*m*, 1299*s*, 1194*s*, 1133*m*, 1043*w*, 972*w*, 954*w*, 916*w*, 733*w*. ^{1}H-NMR (300 MHz): 0.89–0.94 (*m*, 2 *Me*(CH_2)$_3$); 1.21 (*d*, $J = 6.1$, Me); 1.25 (*d*, $J = 6.2$, Me); 1.29 (*d*, $J = 6.4$, Me); 1.21–1.40 (*m*, 4 H); 1.45–1.55 (*m*, 4 H); 2.19–2.66 (*m*, 6 H); 3.08–3.30 (*m*, 4 H); 5.11–5.24 (*m*, 2 CH); 5.33–5.44 (*m*, 1 CH). ^{13}C-NMR (75 MHz): 14.03 (Me); 20.36 (Me); 20.52 (CH_2); 20.80 (Me); 21.36 (Me); 33.79 (CH_2); 35.58 (CH_2); 36.03 (CH_2); 42.44 (CH_2); 48.30 (CH_2); 66.94 (CH); 67.91 (CH); 158.55 (CN); 159.36 (CN); 171.08 (CO). FAB-MS: 737.4 (1, $[2\ M + H]^+$), 369.2 (100, $[M + H]^+$), 228.1 (29), 210.1 (11), 160.1 (26), 142.1 (75), 124.1 (34), 100.0 (18), 68.9 (48), 56.9 (39).

*(4*R*,8*R*,12*R*)-6,10-Bis(benzylimino)-4,8,12-trimethyl-1,5,9-trioxacyclododecan-2-one* (**23c**). A soln. of **7** (200 mg, 0.69 mmol) and benzylamine (1.5 ml, 13.7 mmol) in 5 ml MeOH was stirred at 0° for 60 min. The solvent was removed under h.v. without heating. FC (3 × 3 cm, Et_2O/pentane 1:5) gave **23c** (250 mg, 83%). Yellow oil. $[\alpha]_D = -74.0$ ($c = 1.14$, $CHCl_3$). IR (film): 3027*w*, 2980*m*, 2932*w*, 2873*w*, 2247*w*, 1733*s*, 1678*s*, 1604*w*, 1495*w*, 1452*m*, 1425*w*, 1372*m*, 1298*m*, 1266*m*, 1190*s*, 1132*m*, 1105*w*, 1054*w*, 954*w*, 911*w*, 733*m*, 696*m*, 647*w*. ^{1}H-NMR (300 MHz): 1.29 (*d*, $J = 5.9$, Me); 1.31 (*d*, $J = 6.1$, Me); 1.34 (*d*, $J = 6.2$, Me); 2.35–2.74 (*m*, 3 CH_2); 4.43, 4.55 (*AB*, $J_{AB} = 15.6$, PhCH_2N); 4.44, 4.54 (*A'B'*, $J_{A'B'} = 15.7$, PhCH_2N); 5.24–5.41 (*m*, 2 CH); 5.53–5.64 (*m*, 1 CH); 7.16–7.35 (*m*, 10 arom. H). ^{13}C-NMR (75 MHz): 20.36 (Me); 20.97 (Me); 21.33 (Me); 35.93 (CH_2); 36.49 (CH_2); 42.37 (CH_2); 51.86 (CH_2); 67.39 (CH); 67.67 (CH); 126.31 (CH); 126.44 (CH); 127.02 (CH); 128.23 (CH); 140.76 (C); 141.01 (C); 160.17 (CN); 161.01 (CN); 170.99 (CO). FAB-MS: 873.5 (0.6, $[2\ M + H]^+$), 437.2 (84, $[M + H]^+$), 262.1 (21), 244.1 (11), 194.1 (22), 176.1 (65), 132.0 (24), 106.0 (33), 91.0 (100), 68.9 (45).

5.3. *Imidates* **24**. *(4*R*,8*R*,12*R*)-*N,N',N''*-4,8,12-Hexamethyl-1,5,9-trioxacyclododecane-2,6,10-triimine* (**24a**). A soln. of **8** (50 mg, 0.16 mmol) and $MeNH_2$ (8.03M in EtOH; 0.5 ml, 4 mmol) in MeOH (10 ml) was stirred at 0° for 40 min. The solvent was evaporated under h.v. without heating to give crude **24a** (51 mg, quant.). Yellow oil. No method of purification could be found. $[\alpha]_D = -140.5$ ($c = 0.97$, $CHCl_3$). IR (film): 2975*m*, 2932*m*, 2873*w*, 2785*w*, 1684*s*, 1554*w*, 1446*w*, 1407*w*, 1375*m*, 1296*s*, 1201*s*, 1130*s*, 1077*m*, 1046*w*, 953*w*, 867*w*, 729*w*, 701*w*. ^{1}H-NMR (200 MHz): 1.30 (*d*, $J = 6.1$, Me); 2.29, 2.65 (*AB* of *ABX*, $J_{AX} = 11.4$, $J_{BX} = 1.9$, $J_{AB} = 13.9$, CH_2); 2.98 (*s*, MeN); 5.05–5.25 (*m*, 3 H). ^{13}C-NMR (50 MHz): 20.57 (Me); 35.24 (Me); 35.41 (CH_2); 66.02 (CH); 161.49 (CN). FAB-MS: 298.1 (24, $[M + H]^+$), 199.1 (82), 181.1 (12), 149.0 (28), 100.0 (100), 81.9 (56), 68.9 (25), 57.8 (27).

*(4*R*,8*R*,12*R*)-*N,N',N''*-Tributyl-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6,10-triimine* (**24b**). A soln. of **8** (100 mg, 0.33 mmol) and butylamine (1.0 ml, 10 mmol) in MeOH (10 ml) was stirred at 0° for 45 min. The solvent was evaporated under h.v. without heating. The residue was dissolved in CH_2Cl_2 and the soln. washed with brine (3×), dried ($MgSO_4$), and evaporated: **24b** (126 mg, 90%). Yellow oil. The product partially decomposed after a few days standing at −20°. $[\alpha]_D = -105.8$ ($c = 1.05$, $CHCl_3$). IR (film): 2957*m*, 2929*m*, 2872*m*, 1682*s*, 1557*w*, 1458*w*, 1374*m*, 1296*m*, 1198*s*, 1134*m*, 1046*w*, 951*w*. ^{1}H-NMR (200 MHz): 0.90 (*t*, $J = 7.1$, 3 *Me*(CH_2)$_3$); 1.20 (*d*, $J = 6.1$, Me); 1.20–1.51 (*m*, 12 H); 2.25, 2.57 (*AB* of *ABX*, $J_{AX} = 11.5$, $J_{BX} = 1.9$, $J_{AB} = 13.8$, CH_2); 3.08–3.30 (*m*, 6 H); 5.15–5.35 (*m*, 3 CH). ^{13}C-NMR (50 MHz): 13.72 (Me); 20.22 (CH_2); 20.55 (Me); 33.55 (CH_2); 35.72 (CH_2); 47.89 (CH_2); 65.84 (CH); 159.31 (CN). FAB-MS: 847.7 (0.3, $[2\ M + H]^+$), 424.3 (8, $[M + H]^+$), 283.2 (56), 265.2 (16), 210.2 (14), 142.1 (100), 124.1 (43), 100.0 (29), 67.9 (62), 56.9 (52).

(4R,8R,12R)-N,N',N''-Tribenzyl-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6,10-triimine (**24c**). A soln. of **8** (250 mg, 0.82 mmol) and benzylamine (2.65 ml, 24.3 mmol) in MeOH (25 ml) was stirred at 0° for 30 min. The solvent was removed under h.v. without heating. FC (3 × 7 cm, Et_2O/pentane 1:3) gave **24c** (300 mg, 70%). Slightly yellow solid. For analysis, a sample was recrystallized from Et_2O. M.p. 93.2–94.2° (Et_2O). Single crystals were obtained from Et_2O/hexane. $[\alpha]_D = -98.0$ ($c = 1.05$, $CHCl_3$). IR (KBr): 3056*w*, 3028*w*, 2975*m*, 2929*w*, 2894*w*, 1681*s*, 1603*w*, 1493*w*, 1451*m*, 1432*w*, 1370*m*, 1311*m*, 1296*m*, 1265*m*, 1195*s*, 1137*m*, 1088*w*, 1048*m*, 956*m*, 902*w*, 870*w*, 797*w*, 729*m*, 696*m*, 611*w*. ^{1}H-NMR (400 MHz): 1.31 (*d*, $J = 6.2$, Me); 2.44, 2.71 (*AB* of *ABX*, $J_{AX} = 11.4$, $J_{BX} = 2.1$, $J_{AB} = 13.9$, CH_2); 4.42, 4.50 (*AB*, $J_{AB} = 15.7$, $PhCH_2N$); 5.47–5.55 (*m*, 3 CH); 7.14–7.28 (*m*, 15 arom. H). ^{13}C-NMR (100 MHz): 21.04 (Me); 36.46 (CH_2); 51.82 (CH_2); 66.61 (CH); 126.27 (CH); 127.03 (CH); 128.18 (CH); 141.05 (C); 161.20 (CN). FAB-MS: 1052.1 (2, [2 *M* + H]$^+$), 526.4 (13, [*M* + H]$^+$), 351.3 (65), 244.2 (13), 176.2 (78), 158.1 (13), 154.1 (18), 132.1 (17), 106.0 (22), 91.0 (100), 76.9 (13), 68.9 (27), 54.9 (13). Anal. calc. for $C_{33}H_{39}N_3O_3$ (525.69): C 75.40, H 7.48, N 7.99; found: C 75.38, H 7.44, N 7.87.

6. *Allylations.* 6.1. *Phosphinoimidates. 2-(Diphenylphosphino)benzylamine* (**29**). A soln. of 2-(diphenylphosphino)benzonitrile [52] [53] (3.05 g, 10.6 mmol) and $LiAlH_4$ (0.81 g, 21.3 mmol) in Et_2O (65 ml, all solvents degassed with Ar), was heated to reflux for 1 h, poured onto ice, and hydrolyzed with conc. HCl soln. The aq. phase was made basic with NaOH and extracted with Et_2O (3×). These combined org. phases were dried ($MgSO_4$) and evaporated to give **29** (2.94 g) as an oil which partially solidified upon standing. The product contained *ca.* 7% of the corresponding phosphine oxide. ^{1}H-NMR (300 MHz): 1.40–1.75 (br., NH_2); 4.03 (*d*, $J = 1.6$, $PhCH_2N$); 6.87–7.7 (*m*, 14 arom. H). ^{31}P-NMR (121 MHz): −15.6 (phosphine); +34.2 (phosphine oxide).

3-(Diphenylphosphino)propylamine (**32**) was obtained from the corresponding nitrile [54] as described [55]. ^{1}H-NMR (300 MHz): 1.0–1.3 (br., NH_2); 1.54–1.62 (*m*, 2 H); 2.05–2.11 (*m*, 2 H); 2.78 (*t*, $J = 7.0$, 2 H); 7.27–7.46 (*m*, 10 arom. H). ^{13}C-NMR (75 MHz): 25.36 (*d*, J(C,P) = 11.4); 30.21 (*d*, J(C,P) = 15.6); 43.43 (*d*, J(C,P) = 13.5); 128.39–138.85 (arom. C). ^{31}P-NMR (121 MHz): −15.9.

(4R,8R,12R)-10-{[2-(Diphenylphosphino)benzyl]imino}-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione (**30**). A soln. of **6** (200 mg, 0.73 mmol) and **29** (420 mg, 1.46 mmol) in MeOH (5 ml; degassed with Ar) was stirred for 15 h at r.t. under Ar. After cooling to 0°, NH_3 was bubbled through the mixture for *ca.* 5 min. Workup as in *GP* (see *5.1*) gave **30** (307 mg) as a yellow solid, containing *ca.* 20% of **29**. FC (1.5 × 25 cm, AcOEt/hexane 1:1) yielded **30** (188 mg, 48%) as a yellow oil (a foam under h.v.). The product contained *ca.* 8% of the corresponding phosphine oxide, but no separation method could be found. $[\alpha]_D = -39.2$ ($c = 0.98$, $CHCl_3$). IR ($CHCl_3$): 3057*w*, 2983*m*, 2934*w*, 1737*s*, 1675*m*, 1587*w*, 1435*m*, 1380*m*, 1303*s*, 1263*m*, 1132*m*, 1051*m*, 976*w*, 930*w*, 881*w*, 632*w*. ^{1}H-NMR (400 MHz): 1.12 (*d*, $J = 6.3$, Me); 1.26 (*d*, $J = 6.2$, Me); 1.31 (*d*, $J = 6.4$, Me); 2.15–2.61 (*m*, 6 H); 4.48–4.63 (*m*, $PhCH_2N$); 4.88–4.95 (*m*, 1 CH); 5.38–5.47 (*m*, 2 CH); 6.8–7.7 (*m*, 14 arom. H). ^{13}C-NMR (100 MHz): 20.25 (Me); 20.72 (Me); 21.23 (Me); 35.99 (CH_2); 42.15 (CH_2); 42.42 (CH_2); 50.33 (*d*, J(C,P) = 26, CH_2); 68.04 (CH); 68.24 (CH); 68.73 (CH); 126.6–134.2 (arom. C); 136.11 (*d*, J(C,P) = 10, C); 136.24 (*d*, J(C,P) = 10, C); 144.55 (*d*, J(C,P) = 22, C); 160.23 (CN); 170.11 (CO); 170.78 (CO). ^{31}P-NMR (162 MHz): −14.71 (phosphine); +32.16 (phosphine oxide). FAB-MS: 548.2 (37, [*M*O + H]$^+$), 532.2 (100, [*M* + H]$^+$), 460.1 (35), 358.1 (17), 291.1 (79), 288.1 (57), 275.1 (41), 136.0 (27), 68.9 (77).

(4R,8R,12R)-10-{[2-(Diphenylphosphino)benzyl]imino}-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione–Borane (1/1) (**31**). First, **30** was obtained as described above (FC was omitted). To a soln. of crude **30** (235 mg) in THF (5 ml), 0.9 ml and after 3 h further 0.45 ml of BH_3·THF (1M in THF) were added and stirred at 0°. After a total reaction time of 6 h, evaporation and FC (AcOEt/hexane 1:3) yielded **31** (159 mg, 40% rel. to **6**). Yellow solid. For analysis, a sample was recrystallized from CH_2Cl_2/pentane. M.p. 118.2–119.0° (CH_2Cl_2/pentane). $[\alpha]_D = -70.7$ ($c = 0.97$, $CHCl_3$). IR (KBr): 3450*m* (br.), 2980*w*, 2931*w*, 2384*w*, 1736*s*, 1671*m*, 1437*m*, 1378*m*, 1303*s*, 1263*m*, 1188*s*, 1133*m*, 1104*m*, 1059*m*, 972*w*, 743*w*, 698*m*. ^{1}H-NMR (400 MHz): 1.14 (*d*, $J = 6.3$, Me); 1.27 (*d*, $J = 6.2$, Me); 1.30 (*d*, $J = 6.4$, Me); 2.09–2.61 (*m*, 6 H); 4.36, 4.57 (*AB*, $J_{AB} = 17.4$, $PhCH_2N$); 4.72–4.80 (*m*, 1 CH); 5.36–5.50 (*m*, 2 CH); 6.87–7.86 (*m*, 14 arom. H). ^{13}C-NMR (100 MHz): 20.24 (Me); 20.66 (Me); 21.30 (Me); 36.34 (CH_2); 42.19 (CH_2); 42.37 (CH_2); 50.91 (*d*, J(C,P) = 6.0, CH_2); 68.03 (CH); 68.24 (CH); 68.40 (CH); 125.59 (*d*, J(C,P) = 54, C); 126.4–133.7 (arom. C); 145.65 (*d*, J(C,P) = 10, C); 160.32 (CN); 169.96 (CO); 170.81 (CO). ^{31}P-NMR (162 MHz): +19.1 (br.). FAB-MS: 1091.4 (3, [2 *M* + H]$^+$), 546.2 (90, [*M* + H]$^+$), 532.2 (100, [*M*H − BH_3]$^+$), 460.1 (10), 291.0 (27), 288.1 (26), 275.1 (39), 197.0 (25), 154.0 (48), 136.0 (45), 68.9 (74). Anal. calc. for $C_{31}H_{37}BNO_5P$ (545.42): C 68.27, H 6.84, N 2.57; found: C 68.34, H 7.04, N 2.43.

(4R,8R,12R)-10-{[3-(Diphenylphosphino)propyl]imino}-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione (**33**). A soln. of **6** (100 mg, 0.36 mmol) and **32** (177 mg, 0.73 mmol) in MeOH (5 ml; degassed with Ar) was stirred for 3 h at r.t. under Ar. Workup as in *GP* (see *5.1*) yielded **33** (129 mg, 74%). Yellow oil. Traces of the corresponding phosphine oxide were present. $[\alpha]_D = -44.1$ ($c = 0.92$, $CHCl_3$). IR (KBr): 3052*w*, 2981*m*, 2933*m*,

1738*s*, 1677*m*, 1585*w*, 1481*w*, 1433*m*, 1373*m*, 1301*s*, 1262*m*, 1188*s*, 1132*m*, 1103*m*, 1053*m*, 975*m*, 739*m*, 698*m*. ^{1}H-NMR (300 MHz): 1.23 (*d*, *J* = 6.2, Me); 1.26 (*d*, *J* = 6.3, Me); 1.31 (*d*, *J* = 6.4, Me); 1.64–1.76 (*m*, 2 H); 2.04–2.64 (*m*, 8 H); 3.17–3.36 (*m*, 2 H); 5.06–5.15 (*m*, 1 CH); 5.29–5.45 (*m*, 2 CH): 7.30–7.49 (*m*, 10 arom. H). ^{13}C-NMR (75 MHz): 20.23 (Me); 20.72 (Me); 21.33 (Me); 25.59 (*d*, *J*(C,P) = 11.7, CH_2); 27.88 (*d*, *J*(C,P) = 15.7, CH_2); 35.67 (CH_2); 42.12 (CH_2); 42.41 (CH_2); 49.13 (*d*, *J*(C,P) = 12.7, CH_2); 67.55 (CH); 68.30 (CH); 68.58 (CH); 128.37 (*d*, *J*(C,P) = 7.1, CH); 128.41 (CH); 132.75 (*d*, *J*(C,P) = 18.1, CH); 138.89 (*d*, *J*(C,P) = 7.1, C); 139.05 (*d*, *J*(C,P) = 7.6, C); 158.82 (CN); 170.21 (CO); 170.76 (CO). ^{31}P-NMR (162 MHz): −15.8. FAB-MS: 500.1 (37, [*M*O + H]$^+$), 484.1 (100, [*M* + H]$^+$), 412.1 (19), 326.0 (10), 310.0 (10), 243.0 (48), 68.9 (56).

*(4*R*,8*R*,12*R*)-10-{[3-(Diphenylphosphino)propyl]imino}-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2,6-dione–Borane (1/1)* (**34**). A soln. of **33** (236 mg, 0.49 mmol) and BH_3·THF (1M in THF; 1 ml) in THF (5 ml) was stirred for 2 h at r.t. Evaporation of the solvent and FC (AcOEt/hexane 1:4) yielded **34** (167 mg, 68%). Colorless solid. For analysis, a sample was recrystallized twice (1. Et_2O/CH_2Cl_2, 2. CH_2Cl_2/pentane). M.p. 115.8–116.2° (CH_2Cl_2/pentane). Single crystals were obtained from CH_2Cl_2/pentane. $[\alpha]_D = -49.5$ (*c* = 1.02, $CHCl_3$). IR (KBr): 3425*m* (br.), 2978*w*, 2934*w*, 2901*w*, 2379*m*, 2344*w*, 1732*s*, 1671*s*, 1486*w*, 1453*w*, 1437*m*, 1374*m*, 1304*s*, 1275*m*, 1185*s*, 1133*s*, 1108*m*, 1064*m*, 1028*w*, 978*w*, 868*w*, 784*w*, 738*m*, 703*m*, 692*m*. ^{1}H-NMR (400 MHz): 1.24 (*d*, *J* = 6.2, Me); 1.26 (*d*, *J* = 6.3, Me); 1.31 (*d*, *J* = 6.4, Me); 1.68–1.89 (*m*, 2 H); 2.18–2.63 (*m*, 8 H); 3.19–3.29 (*m*, 2 H); 5.07–5.14 (*m*, 1 CH); 5.33–5.44 (*m*, 2 CH); 7.40–7.49 (*m*, 6 arom. H); 7.67–7.75 (*m*, 4 arom. H). ^{13}C-NMR (100 MHz): 20.25 (Me); 20.73 (Me); 21.34 (Me); 22.98 (*d*, *J*(C,P) = 38.5, CH_2); 25.05 (CH_2); 35.93 (CH_2); 42.16 (CH_2); 42.43 (CH_2); 48.51 (*d*, *J*(C,P) = 14.2, CH_2); 67.52 (CH); 68.26 (CH); 68.39 (CH); 128.68–132.31 (arom. C); 159.22 (CN); 170.20 (CO); 170.78 (CO). ^{31}P-NMR (162 MHz): +16.1 (br.); +16.4 (br.). FAB-MS: 995.4 (2, [2 *M* + H]$^+$), 498.2 (84, [*M* + H]$^+$), 484.2 (100, [*M*H − BH_3]$^+$), 340.1 (15), 312.1 (14), 270.1 (14), 270.1 (14), 254.1 (18), 243.1 (28), 227.1 (32), 183.0 (25), 154.0 (20), 136.0 (19), 121.0 (17), 109.0 (24), 91.0 (20), 76.9 (14), 68.9 (84), 55.9 (10). Anal. calc. for $C_{27}H_{37}BNO_5P$ (497.38): C 65.20, H 7.50, N 2.82; found: C 64.84, H 7.32, N 2.65.

*(4*R*,8*R*,12*R*)-6,10-Bis-{[3-(diphenylphosphino)propyl]imino}-4,8,12-trimethyl-1,5,9-trioxacyclododecane-2-one* (**35**). A soln. of **7** (100 mg, 0.34 mmol) and **32** (335 mg, 1.38 mmol) in MeOH (5 ml; degassed with Ar) was stirred for 4.5 h at 0° under Ar. Workup as in *GP* (see *5.1*) yielded crude **35** (174 mg, 71%) as a yellow oil. FC (3 × 7 cm, Et_2O/pentane 1:2) gave **35** (132 mg, 57%) as slightly yellow oil. The product contained *ca.* 4% of the corresponding phosphine oxides, but no separation method could be found. Reaction with BH_3·THF gave inseparable product mixtures. $[\alpha]_D = -38.9$ (*c* = 1.03, $CHCl_3$). IR (film): 3052*w*, 2978*m*, 2933*m*, 2245*w*, 1732*s*, 1674*s*, 1585*w*, 1481*w*, 1433*m*, 1370*m*, 1299*m*, 1190*s*, 1131*m*, 1045*w*, 971*w*, 912*w*, 737*m*, 696*s*, 646*w*. ^{1}H-NMR (300 MHz): 1.19 (*d*, *J* = 6.1, Me); 1.24 (*d*, *J* = 5.8, Me); 1.26 (*d*, *J* = 6.3, Me); 1.61–1.71 (*m*, 4 H); 1.99–2.63 (*m*, 10 H); 3.11–3.31 (*m*, 4 H); 5.08–5.21 (*m*, 2 CH); 5.35–5.42 (*m*, 1 CH); 7.24–7.36 (*m*, 12 arom. H); 7.36–7.46 (*m*, 8 arom. H). ^{13}C-NMR (75 MHz): 20.33 (Me); 20.81 (Me); 21.30 (Me); 25.54 (*d*, *J*(C,P) = 9.5, CH_2); 25.65 (*d*, *J*(C,P) = 7.6, CH_2); 27.92 (*d*, *J*(C,P) = 16.5, CH_2); 35.71 (CH_2); 36.23 (CH_2); 42.37 (CH_2); 49.04 (*d*, *J*(C,P) = 14.3, CH_2); 66.94 (CH); 67.17 (CH); 67.65 (CH); 128.30–139.19 (arom. C); 159.04 (CN); 159.88 (CN); 170.98 (CO). ^{31}P-NMR (203 MHz): −15.66; −15.90. FAB-MS: 1417.5 (0.6, [2 *M* + H]$^+$), 725.3 (15, [*M*O + H]$^+$), 709.3 (27, [*M* + H]$^+$), 398.1 (35), 310.1 (100), 243.0 (91), 227.1 (31), 199.0 (29), 183.0 (32), 121.0 (21), 108.9 (20), 90.9 (19), 68.9 (47), 55.9 (15).

6.2. *Allylation Catalyzed by Palladium(II) Complexes* (*Table 8*). 6.2.1. *With THF as Solvent.* A soln. of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (7 mg, 0.02 mmol) and **30**, **33**, or **35** (0.04 mmol) was degassed with two freeze-pump-thaw cycles and stirred for 0.5 h at r.t. Dimethyl malonate (0.34 ml, 3 mmol; deprotonated with NaH, dissolved in THF) and acetate **36** (250 mg, 1 mmol; dissolved in THF) were added and after five additional freeze-pump-thaw cycles, the mixture was stirred as indicated in *Table 8*. The mixture was poured into Et_2O, washed with sat. NH_4Cl soln, (2×) and H_2O (2×), dried ($MgSO_4$), and evaporated. The product **37** was isolated by FC (AcOEt/hexane 1:6). For the yields and enantiomeric excess values (ee), see *Table 8*.

6.2.2. *With CH_2Cl_2 as Solvent.* As in *6.2.1* with a soln. of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ and the phosphine in CH_2Cl (2 ml). Dimethyl malonate and acetate **36** were added as a soln. in CH_2Cl_2; *N,O*-bis(trimethylsilyl)acetamide (0.73 ml, 3 mmol) and KOAc (0.03 mmol) were used as base, the final volume of the reaction mixture was *ca.* 5 ml. Workup as in *6.2.1*.

*Dimethyl 2-[(*E*)-1,3-Diphenylprop-2-enyl]propanedioate* (**37**): ^{1}H-NMR (200 MHz, C_6D_6): 3.09 (*s*, MeO); 3.27 (*s*, MeO); 4.12 (*d*, *J* = 10.8, H–C(2)); 4.54 (*dd*, *J* = 7.5, 10.8, H–C(1′)); 6.38 (*dd*, *J* = 7.6, 15.7, H–C(2′)); 6.51 (*d*, *J* = 15.7, H–C(3′)); 7.00–7.26 (*m*, 10 arom. H). Determination of ee: ^{1}H-NMR (200 MHz, C_6D_6, [Eu(hfc)$_3$]/**37** 7:6): MeO signal at 3.27 → 3.66 and 3.74. The abs. configuration was determined by comparison of the optical rotation with published data [50].

7. *X-Ray Structure Analyses.* 7.1. *Structure of* **6** ($C_{12}H_{18}O_5S$). Determination of the cell parameters and collection of the reflection intensities were performed on an *Enraf-Nonius-CAD4* four-circle diffractometer

(graphite monochromatized MoK_α radiation, $\lambda = 0.7107$ Å). Pale yellow crystal, 0.3 × 0.3 × 0.3 mm, orthorhombic, space group $P2_12_12_1$, $a = 8.773(4)$ Å, $b = 9.674(4)$ Å, $c = 15.738(4)$ Å, $V = 1335.7(9)$ Å^3, $Z = 4$, $\rho_{calc.} = 1.36$ gcm^{-3}, $\mu = 0.24$ mm^{-1}, $F(000) = 584$. Number of unique reflections 1372 (ω scan, $0 < 2\theta < 50°$, T 85 K), of which 1170 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXTL PLUS [57] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were located from differential *Fourier* syntheses and refined isotropically. The refinement converged at $R = 0.033$; min. and max. rest electron density −0.36, 0.30 eÅ^{-3}; number of variables 183.

7.2. *Structure of* **7** ($C_{12}H_{18}O_4S_2$). Determination of the cell parameters and collection of the reflection intensities were performed on a *Siemens-R3m/V* four-circle diffractometer (graphite monochromatized MoK_α radiation, $\lambda = 0.7107$ Å). Colorless platelet, 0.2 × 0.3 × 0.3 mm, orthorhombic, space group $P2_12_12_1$, $a = 9.287(6)$ Å, $b = 9.869(8)$ Å, $c = 16.093(10)$ Å, $V = 1475(2)$ Å^3, $Z = 4$, $\rho_{calc.} = 1.31$ gcm^{-3}, $\mu = 0.364$ mm^{-1}, $F(000) = 616$. Number of reflections measured 2157 (ω scan, $3 < 2\theta < 55°$, T 298 K); 1933 unique reflections, of which 1615 with $I > 2\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXTL PLUS [57] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). The refinement converged at $R = 0.045$ ($wR = 0.046$); min. and max. rest electron density −0.33, 0.27 eÅ^{-3}; number of variables 181.

7.3. *Structure of* **8** ($C_{12}H_{18}O_3S_3$). As described in *7.1*. Yellow cube, 0.3 × 0.4 × 0.4 mm, monoclinic, space group $P2_1$, $a = 8.187(5)$ Å, $b = 6.417(3)$ Å, $c = 15.497(9)$ Å, $\beta = 98.57(5)°$, $V = 805.1(8)$ Å^3, $Z = 2$, $\rho_{calc.} = 1.264$ gcm^{-3}, $\mu = 0.458$ mm^{-1}, $F(000) = 324$. Number of reflections measured 965 (ω scan, $3 < 2\theta < 45°$, T 298 K); 927 unique reflections, of which 927 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXL-93 [58] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were located from differential *Fourier* syntheses and refined isotropically. The refinement converged at $R = 0.041$ ($wR = 0.114$); min. and max. rest electron density −0.23, 0.41 eÅ^{-3}; number of variables 163.

7.4. *Structure of* **10** ($C_{20}H_{30}O_9S$). As described in *7.1*. Colorless platelet, 0.1 × 0.2 × 0.4 mm, orthorhombic, space group $P2_12_12_1$, $a = 9.857(4)$ Å, $b = 10.504(4)$ Å, $c = 22.827(4)$ Å, $V = 2363(13)$ Å^3, $Z = 4$, $\rho_{calc.} = 1.255$ gcm^{-3}, $\mu = 0.182$ mm^{-1}, $F(000) = 952$. Number of reflections measured 2414 (ω scan, $3 < 2\theta < 50°$, T 233 K); 2378 unique reflections, of which 1745 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXL-93 [58] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule on idealized positions and refined isotropically. The refinement converged at $R = 0.056$ ($wR^2 = 0.166$); min. and max. rest electron density −0.49, 0.52 eÅ^{-3}; number of variables 271.

7.5. *Structure of* **12** ($C_{20}H_{30}O_8S_2$). Determination of the cell parameters and collection of the reflection intensities were performed on a *Picker-Stoe* four-circle diffractometer (graphite monochromatized MoK_α radiation, $\lambda = 0.7107$ Å). Yellow needle, 0.4 × 0.4 × 1.4 mm, monoclinic, space group $P2_1$, $a = 10.397(13)$ Å, $b = 10.460(13)$ Å, $c = 11.89(2)$ Å, $\beta = 111.41(11)°$, $V = 1204(3)$ Å^3, $Z = 2$, $\rho_{calc.} = 1.276$ gcm^{-3}, $\mu = 0.261$ mm^{-1}, $F(000) = 492$. Number of reflections measured 1206 (ω scan, $3 < 2\theta < 40°$, T 293 K); 1206 unique reflections, of which 1143 with $I > 2\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXTL PLUS [57] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). The refinement converged at $R = 0.058$ ($wR = 0.068$); min. and max. rest electron density −0.23, 0.25 eÅ^{-3}; number of variables 270.

7.6. *Structure of* **22** ($C_{37}H_{56}Cl_2N_3O_{19}P$). As described in *7.2*. Colorless cube, 0.8 × 0.8 × 0.8 mm, monoclinic, space group $P2_1$, $a = 9.81(2)$ Å, $b = 18.55(4)$ Å, $c = 13.35(3)$ Å, $\beta = 101.8(3)°$, $V = 2379(9)$ Å^3, $Z = 2$, $\rho_{calc.} = 1.324$ gcm^{-3}, $\mu = 0.244$ mm^{-1}, $F(000) = 1000$. Number of reflections measured 3233 (2θ–θ scan, $3 < 2\theta < 45°$, T 293 K); 3224 unique reflections, of which 2881 with $I > 2\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXTL PLUS [57] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). The refinement converged at $R = 0.066$ ($wR = 0.061$); min. and max. rest electron density −0.33, 0.33 eÅ^{-3}; number of variables 558.

7.7. *Structure of* **20d** ($C_{19}H_{25}NO_5$). As described in *7.1* (CuK_α radiation, $\lambda = 1.5418$ Å). Colorless cube, 0.2 × 0.4 × 0.4 mm, orthorhombic, space group $P2_12_12_1$, $a = 9.009(2)$ Å, $b = 10.027(1)$ Å, $c = 21.073(5)$ Å, $V = 1903.7(6)$ Å^3, $Z = 4$, $\rho_{calc.} = 1.212$ gcm^{-3}, $\mu = 0.718$ mm^{-1}, $F(000) = 744$. Number of reflections measured 1585 (ω–2θ scan, $5 < 2\theta < 120°$, T 295 K); 1585 unique reflections, of which 1323 with $I > 3\sigma(I)$ were used for the

determination (direct methods, SHELXS-86 [56]). SHELXL-93 [58] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). Extinction but no absorption correction was applied. The refinement converged at $R = 0.037$ ($wR^2 = 0.096$); min. and max. rest electron density −0.17, 0.15 eÅ^{-3}; number of variables 227.

7.8. *Structure of* **24c** ($C_{33}H_{39}N_3O_3$). As described in *7.1.* Colorless cube, 0.2 × 0.3 × 0.4 mm, monoclinic, space group $P2_1$, $a = 8.437(6)$ Å, $b = 16.355(12)$ Å, $c = 10.750(9)$ Å, $V = 1466(2)$ Å^3, $Z = 2$, $\rho_{calc.} = 1.191$ gcm^{-3}, $\mu = 0.076$ mm^{-1}, $F(000) = 564$. Number of reflections measured 2266 (ω scan, $2 < 2\theta < 46°$, T 295 K); 2116 unique reflections, of which 1861 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXL-93 [58] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). The refinement converged at $R = 0.032$ ($wR^2 = 0.076$); min. and max. rest electron density −0.14, 0.10 eÅ^{-3}; number of variables 352.

7.9. *Structure of* **34** ($C_{27}H_{37}BNO_5P$). As described in *7.1.* Colorless cube, 0.6 × 0.8 × 0.8 mm, orthorhombic, space group $P2_12_12_1$, $a = 9.238(4)$ Å, $b = 16.390(5)$ Å, $c = 18.894(5)$ Å, $V = 2861(2)$ Å^3, $Z = 4$, $\rho_{calc.} = 1.157$ gcm^{-3}, $\mu = 0.130$ mm^{-1}, $F(000) = 1068$. Number of reflections measured 3162 (ω scan, $2 < 2\theta < 52°$, T 295 K); 3162 unique reflections, of which 2352 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXL-93 [58] was used for structure refinement (full-matrix least-squares). The non-H-atoms were refined anisotropically, the H-atoms were added to the molecule with const. isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). The refinement converged at $R = 0.044$ ($wR^2 = 0.112$); min. and max. rest electron density −0.41, 0.43 eÅ^{-3}; number of variables 317.

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