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SUGAR ALCOHOLS AS TEMPLATES FOR PHOTOCHEMICAL ASYMMETRIC SYNTHESIS*

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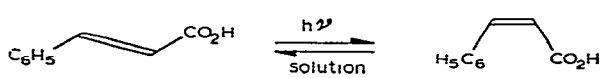
ABSTRACT

Efficient asymmetric induction (optical yields ranging from 22 to 85%) is accomplished through the photoaddition reactions of residues linked to sugar alcohols. Benzene solutions of dicinnamate (**5,6**), tetracinnamate (**2,3,4**), and hexacinnamate (**1**) derivatives of D-mannitol were irradiated through Pyrex. Each compound underwent smooth intramolecular ($2\pi+2\pi$) photocycloaddition to yield cyclobutanes having the truxinic acid (head-to-head) constitution. The chiral sugar alcohol derivative used to induce asymmetry was readily removed by ester exchange with methanol, and in addition to other products, optically active dimethyl δ-truxinate (**8**) was afforded in either dextro- or levo-rotatory form, depending on the starting material. In the course of these studies, evidence was obtained for the photoaddition of a *trans*- and a *cis*-cinnamate residue.

INTRODUCTION

The production of non-racemic, enantiomeric compounds in high chemical and high optical yield continues to be an actively pursued goal in organic synthesis[1–3]. It is therefore surprising that the large and varied arsenal of organic photochemical reactions has not been brought to bear on this problem. Few photochemical asymmetric syntheses have been reported[4–9] and, apart from experiments[10,11] with circularly polarized light, none have been systematically studied.

One of the approaches which we have undertaken to achieve asymmetric synthesis involves the intramolecular photocycloaddition reaction of cinnamic acid residues linked to chiral derivatives. In solution, the irradiation of cinnamic acid and its derivatives leads to *cis*⇌*trans* photoisomerization; no photodimerization is observed[12,13].



*Dedicated to the memory of Dr. Hewitt G. Fletcher, Jr.
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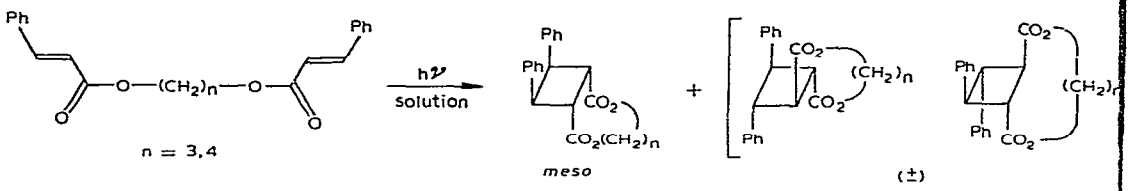
However, if the cinnamate groups are linked by a polymethylene bridge, then intramolecular cyclobutane formation takes place to yield the *meso* (β-truxinate) and (±) (δ-truxinate) derivatives[14]. We posed the question whether chiral centers on the polymethylene bridge would induce appreciable differences in the yields of the (now diastereomeric) (+) and (−) isomers.

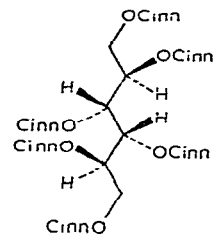


The use of sugar alcohols as the chiral agents seemed advantageous since these materials have known stereochemistry, are easily modified by well-established procedures, and are inexpensive and readily available[15]. It was anticipated that the chiral sugar alcohol backbone might serve as a template along which the cinnamate residues would be aligned in ground-state conformations affording chiral adducts upon photoexcitation. The newly formed chiral molecules could then be removed and, in principle, the chiral inducer would be regenerated. Our first experiments using D-mannitol hexacinnamate (**1**) indicated that this approach held promise for efficient asymmetric syntheses[16], and we now describe results on a series of simpler, blocked cinnamate derivatives of D-mannitol.

RESULTS AND DISCUSSION

The D-mannitol cinnamic acid esters, **1–6**, were prepared by conventional methods and characterized. D-Mannitol was chosen because of its molecular two-fold axis, a feature which is of use in the synthesis of derivatives, simplifies the n.m.r.-spectral characterization of these derivatives, aids in the interpretation of product structures, and appreciably restricts the total number of possible products which may be formed.

The starting materials, **1–6**, were irradiated in benzene solution through Pyrex, using a 450-watt, medium-pressure mercury lamp. After photolysis, the reaction mixtures were subjected to exhaustive ester exchange with methanol; this procedure both removed the chiral templates and converted the newly formed moieties into derivatives which were separable and easily characterized. The mixtures of methyl esters were then chromatographed on silica gel, and the specific rotations were measured directly on the eluted samples without any intervening crystallization steps or other procedures which might have altered the enantiomeric ratio. The results are presented in Table I.



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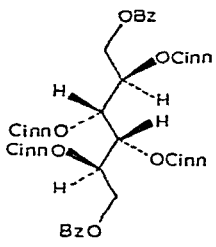

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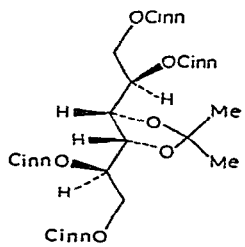

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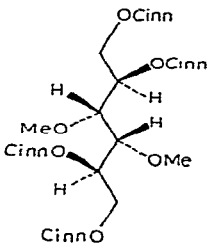

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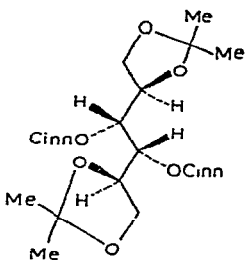

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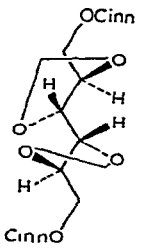

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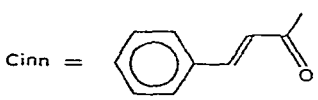


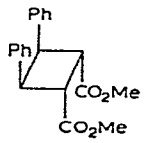
TABLE I

IRRADIATION OF D-MANNITOL DERIVATIVES **1–6** IN BENZENE SOLUTION

Compound (wt. in g)	*Irradiation time (h)*	*Percent Conversion*[a]	*Yields (%) of products based on consumed cinnamate (sign of rotation for optically active products) [optical yields]*		
			7	**8**	**9**
1 (2.0)	5	32	21	27 (+) [*42*]	~5
1 (2.0)	20	56	23	25 (+) [*46*]	—
1 (2.0)	68	93	21	26 (+) [*38*]	8 [~0][b]
2 (2.0)	23	89	75	20 (+) [*85*]	<3 (+) [*49*]
3 (2.0)	43	77	13	28 (+) [*82*]	3.7 (+) [*35*]
4 (2.0)	22	42	21	19 (+) [*22*]	<3
5 (2.0)	22	78	49	23 (+) [*54*]	6.2 (+) [*18*]
6 (1.5)	47	63	23	42 (−) [*48*]	3

[a]Amount of cinnamate reacted, calculated from the isolated methyl cinnamate. [b]In an experiment using a higher concentration of **1**, (+)-**9** was obtained with an optical yield of ~10% (see Experimental).

On the basis of results obtained during the irradiation of α,ω-polymethylene dicinnamates[14], it was expected that only dimethyl β-truxinate (**7**) and dimethyl δ-truxinate (**8**) would be formed but, as indicated in Table I, dimethyl neo-truxinate (**9**) was also isolated. The formation of **9** requires, formally, the photocycloaddition



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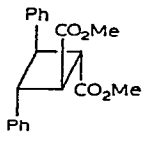

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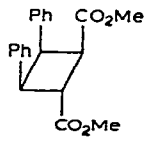


9

of a *cis*- and a *trans*-cinnamate residue, and since there had been no previous reports of this process or of the isolation of neo-truxinate *via* the photodimerization of a cinnamic acid derivative, it constitutes an interesting by-product of this investigation. The absence of neo-truxinate during the irradiations of 1,3-trimethylene dicinnamate and 1,4-tetramethylene dicinnamate[14] is probably due not to any intrinsic differences in the photochemistry of these dicinnamates and of **1–6**, but to the small quantities formed which may have been overlooked.

The total yield of dimeric products, *i.e.*, $(Ph–CH=CH–CO_2CH_3)_2$, other than **7–9**, was less than $\sim$1%. In each irradiation, variable quantities of "polymer" were also formed. These less-mobile fractions were eluted from the chromatography column with more-polar solvents and were not investigated further.

We formulate the cyclobutane-forming reaction as an intramolecular photocycloaddition, and not a photodimerization, on the basis of the following evidence. The primary intramolecular photoproducts have been isolated and characterized in several of the irradiations and, on ester exchange with methanol, they afford the products **7–9**. Thin-layer chromatographic analyses of the irradiation mixtures revealed products having the same mobility as the starting material and not the much less-mobile spots expected for intermolecular dimers. Finally, intramolecular photoreaction is consistent with the observation that the irradiation of compounds such as ethyl cinnamate yields no dimeric products[12].

Reaction model. — In solution, the direct irradiation of cinnamic acid derivatives leads only to *cis–trans* isomerization; only in the presence of sensitizers[12] does dimerization become efficient. The absence of intermolecular dimerization reactions from simple cinnamic acid derivatives is ascribed to the short life-time of the singlet excited state[13]. From studies on the photodimerization of cinnamic acid derivatives in the crystalline state, it is known that a high degree of intermolecular orientation is required for reaction: the double bonds must be essentially parallel and have a center-to-center distance of $\sim$4 Å[17,18], *i.e.*, good overlap of the π-electron orbitals prior to photoexcitation is a prerequisite for efficient reaction[18,19]. In cases where the double bonds are very close, but the molecules are not sufficiently parallel to provide adequate π-orbital overlap, photodimerization of cinnamates does not take place[13,19,20].

In the α,ω-polymethylene dicinnamates[14,21,22], cinnamimide[23], and the materials described herein, there are presumably high concentrations of conformations containing pairs of cinnamates in the correct "topochemical" juxtaposition for photocycloaddition. Absorption of a photon in such an aligned pair should lead to a cyclobutane with nearly unit quantum efficiency[24], whereas photoexcited cinnamates, which are in poor register for 2+2 cycloaddition, would undergo *trans* → *cis* photoisomerization or return to the ground-state.

The proposed reaction model (Fig. 1) thus pictures pairs of cinnamate residues existing in a number of rapidly interconverting conformations, A⇌B⇌C⇌D⇌..., some of which, *e.g.*, A, B, C, contain olefinic groups aligned appropriately for photocycloaddition, whereas in other conformations, *e.g.*, D, the intermolecular orientation is such that photocycloaddition cannot take place and *trans* → *cis* isomerization occurs.

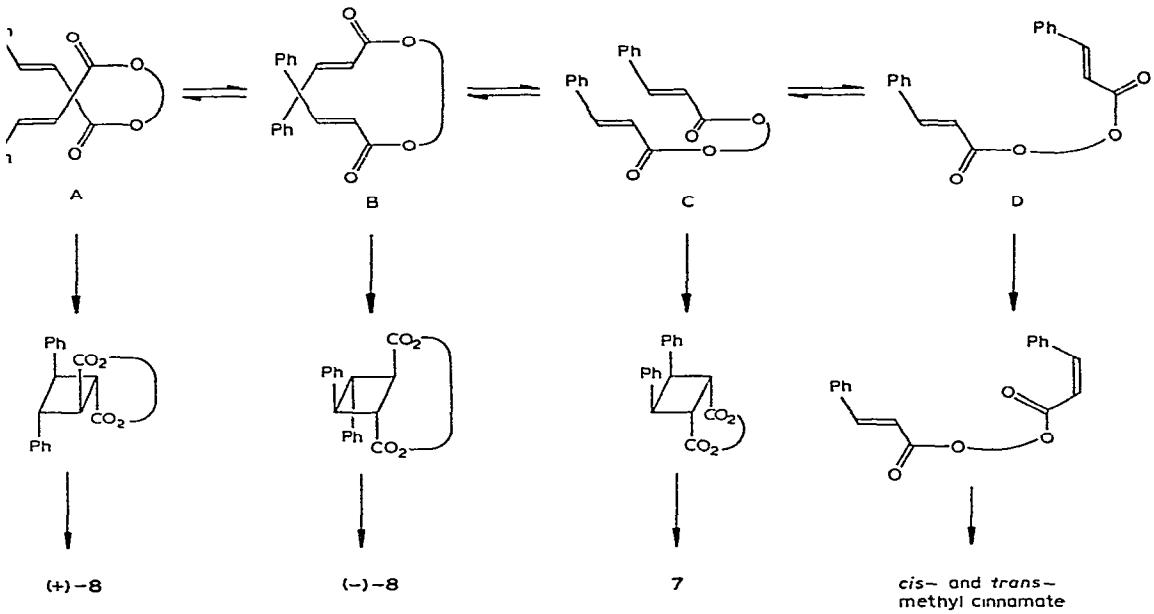
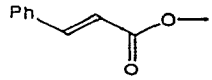


Fig. 1. Reaction model for the intramolecular photocyclodimerization of α,ω-polymethylene dicinnamates and compounds **1–6**. In conformations A, B, and C, the C=C double bonds are parallel and separated by a center-to-center distance of ~4 Å. (*Note*: An arbitrary assignment of enantiomer structure has been made; the absolute configuration of **8** is not yet known).

The number of conformational arrangements such as A, B, and C where cycloaddition can take place (the reaction "sites") rapidly increases with the number of cinnamate residues. For a molecule with only one pair of *trans*-cinnamate residues*

*Only s-cisoid enone stereochemistry has been considered for the  residues, since this is invariably the more-stable configuration in simple α,β-unsaturated carboxylic esters[25].

(*e.g.*, **5**, **6**), there are four sites, two leading to *β*-truxinate (**7**)*, one leading to (+)-**8**, and one leading to (−)-**8**. However, in mannitol hexacinnamate (**1**), there are nine different pairs of cinnamates (residues linked to carbon atoms 1 and 2 [1–2]; 1–3; 1–4; 1–5; 1–6; 2–3; 2–4; 2–5; 3–4) or a total of $(4\times 9)=36$ different reaction sites. These rapidly interchanging conformations are immobile on the time scale of the electronic excitation and cycloaddition step and are "trapped" by the absorbed quanta**. Since the quantum yield for photodimerization of cinnamates is not dependent on intermolecular environment[24] (only on the proper olefinic overlap), the distribution of products is a measure of the relative stability of the pre-reaction ground-state conformations A, B, C, *etc.* (corrected for the symmetry related species, *e.g.*, 1–2 and 5–6 are equivalent in **1**). Once a chemical change (cyclobutane formation; *trans* → *cis* isomerization) has occurred in a molecule, the set of reaction sites now available are all different in structure, and energy, from that of the unreacted molecule. For this reason, it was expected that the brief and long irradiations of **1** might give different product distributions and optical yields for **8**. Surprisingly, however, neither the product ratio nor the optical yields are significantly different (Table I). This result may not be general for other systems such as **2**–**4**.

Asymmetric induction. — Two of the newly formed species, dimethyl *δ*-truxinate (**8**) and dimethyl neo-truxinate (**9**) are chiral molecules. It was the asymmetric synthesis of the former that we had intended to accomplish and, indeed, all six of the starting materials afford optically active **8**; the optical yields range from 22–85%, and either dextrorotatory or levorotatory **8** is produced. When the optical yields are high (*e.g.*, in the irradiation of **3**), enantiomerically pure **8** can be obtained after one or two crystallizations from methanol. These reactions thus provide a relatively simple method for the preparation of an optically active dicarboxylic acid which, in turn, may have uses in other chiral transformations.

At present, the best preparative route to optically active (+)-**8** is probably *via* the tetracinnamate **2**, which may be prepared in large quantities and undergoes photocycloaddition efficiently (Table I). However, this starting material also affords a relatively high proportion of the *meso*-compound **7**. Since the ratio of **7** to **8** is strongly dependent on the length of the carbon chain separating the cinnamates (*e.g.*, a ratio of ~2:1 is obtained for the vicinal dicinnamate **5** compared to ~1:2 for the six-carbon-separated dicinnamate **6**), we believe that conditions for optimizing the proportion of **8**, as well as for affording even higher enantiomer excesses, may be found. One approach yet to be undertaken is a study of the dependence of these factors on temperature.

When the carbon chain linking the dicinnamates contains a chiral center, the pre-reaction conformational arrangements A and B (Fig. 1) are diastereomeric and thus have different energy contents. As stated above, the enantiomeric ratio reflects

*Considering the top and bottom olefinic *π*-electron orbitals of the cinnamate residues, there are two distinct ways of coupling (top+top; bottom+bottom) to produce **7**.

**For evidence that cycloaddition is faster than transfer of energy from residue to residue, see Ref. 26.

these ground-state conformation populations. It should thus be possible to utilize conformational energy calculations to estimate the relative energy content of the diastereomeric pre-cyclobutane geometries and predict not only the product distribution but also the absolute configuration of the predominant enantiomer formed during the irradiation of a particular chiral derivative. This approach, which may also indicate worthwhile starting-materials for irradiation, has recently been undertaken for a variety of sugar alcohol dicinnamates[27].

In the dicinnamates, where only two diastereomeric pre-**8** conformations are postulated, the enantiomeric ratio provides a measure of the equilibrium constant K and the free-energy difference ΔF between the pre-(+)-**8** and pre-(−)-**8** conformations. For **5**, pre-(−)-**8**⇌pre-(+)-**8**, $K \sim 3.3$, $\Delta F^{\circ}_{30^{\circ}} \sim 0.7$ kcal/mole; for **6**, pre-(+)-**8**⇌pre-(−)-**8**, $K \sim 2.8$, $\Delta F^{\circ}_{30^{\circ}} \sim 0.5$ kcal/mole.

The optical yields of **9** vary widely, from essentially zero in the irradiation of **1** to ~50% in the product from **2**. These yields are always considerably less than those of **8** and since the quantities isolated are also much smaller than those of **7** and **8**, the uncertainty in the values for **9** is much higher. There is no direct correlation between the optical yields of **8** and **9**. A better understanding of the route by which **9** is formed may be provided by examining the photobehaviour of pure, chiral *cis,trans*-dicinnamates.

In conclusion, the approach we have outlined has several advantages over other methods of asymmetric synthesis: the optical yields are high; unlike most asymmetric syntheses in which the optical yields are controlled only by the difference in the energy of the diastereomeric transition states[2], $\Delta\Delta G^{\ddagger}$, the enantiomeric ratio in the present method is a function of the difference (ΔE) in diastereomeric ground-state energies, which is much more amenable to estimation and influence; asymmetric synthesis is appreciable even when, as in **6**, the reactive centers are four bonds removed from the closest chiral centers.

EXPERIMENTAL

General methods. — Melting points were determined on a Fisher–Johns apparatus and are uncorrected. Optical rotations were measured with a Perkin–Elmer Model 141 automatic polarimeter at room temperature for solutions in 1-dm, semimicro tubes. Column chromatography was performed on Merck 0.05–0.20 mm silica gel. N.m.r. spectra were recorded with a Varian A-60 spectrometer, using deuteriochloroform as solvent and tetramethylsilane as internal standard, and are reported in δ units; the spectra were recorded by M. Grinberg and M. Jedda. Microanalyses were performed under the direction of R. Heller. Thin-layer chromatography (t.l.c.) was performed on DC-Karten SI F silica gel plates with fluorescent indicator (Riedel de Haën AG, Seelze-Hannover) and development with 9:1 benzene–ethyl acetate.

D-*Mannitol hexa*-trans-*cinnamate* (**1**). — To a solution of dry D-mannitol (10 g) in anhydrous pyridine (400 ml), a solution of cinnamoyl chloride (70 g) in dry benzene

(150 ml) was added. After storage at 40–50° for 24 h, the benzene was evaporated *in vacuo* and the dark residue was poured into ice–water with stirring. The oily layer was separated, and dissolved in methylene chloride, and the solution was washed successively with water, 10% aqueous sodium hydrogen carbonate, water, 10% hydrochloric acid, and water. The dried (Na_2SO_4) solution was concentrated and the residue was crystallised several times from ethanol–ethyl acetate to give **1** (40 g, 75%), m.p. 95–96°, $[\alpha]_D$ +11.5° (*c* 8, chloroform); lit.[28] m.p. 99–100°, $[\alpha]_D^{20}$ +13.2° (*c* 7.5, chloroform). N.m.r. data: δ 7.78 (d, *J* 16 Hz); 7.73 (d, 6 H, *J* 16 Hz, 6 Ph–C*H*=); 7.3 (m, 30 H, 6 Ph), 6.54, 6.43, 6.41 (3 d, 6 H, *J* 16 Hz, 6 CO–C*H*=); 6.0–5.5 (m, 4 H, 4 CH); 4.9–4.2 (8 line m, 4 H, 2 CH_2).

D-*Mannitol 1,6-dibenzoate 2,3,4,5-tetra*-trans-*cinnamate* (**2**). — To a solution of D-mannitol 1,6-dibenzoate[29] (3.9 g) in anhydrous pyridine (50 ml), cinnamoyl chloride (7.32 g) was added. The mixture was stirred for 48 h at room temperature and then kept at 50° for 2 h. The solution was concentrated *in vacuo* and the residue was triturated with several portions of cold water. A solution of the solid residue in ethyl acetate was washed successively with 2M hydrochloric acid, 5% aqueous sodium hydrogen carbonate, and water, dried, and concentrated. The residue was eluted from silica gel with 19:1 benzene–ethyl acetate to afford a yellow solid (7.7 g, 85%), which was further purified by passing a benzene solution through a short column of activated charcoal. After evaporation of the benzene, the residue was crystallized several times from ethyl acetate to give colourless crystals of **2**, m.p. 124–126°, $[\alpha]_D$ −12° (*c* 3, acetone). N.m.r. data: δ 8.2–7.85 and 7.7–7.2 (2 m, 34 H, 2 Ph and 4 Ph–CH=), 6.59 and 6.48 (2 d, 4 H, *J* 16 Hz, 4 CO–CH=), 6.1–5.5 (m, 4 H, 4 CH–O), 5.05–4.3 (eight line m, 4 H, 2 CH_2–O).

Anal. Calc. for $C_{56}H_{46}O_{12}$: C, 73.83; H, 5.09. Found: C, 73.65; H, 5.15.

3,4-O-Isopropylidene-D-*mannitol 1,2,5,6-tetra*-trans-*cinnamate* (**3**). — To a solution of 3,4-*O*-isopropylidene-D-mannitol[30] (6 g) in anhydrous pyridine (60 ml) at 5°, a solution of cinnamoyl chloride (20 g) in dry benzene (50 ml) was added dropwise with stirring. After stirring for 2 h at 5° and 48 h at room temperature, the solvents were evaporated under reduced pressure and the oily residue was triturated with cold water. A solution of the residue in ethyl acetate was washed successively with 2M hydrochloric acid, 5% aqueous sodium hydrogen carbonate, and water, then dried, and concentrated. Elution of the residue from silica gel with 19:1 benzene–ethyl acetate afforded **3** (16.8 g, 84%) as a colourless, amorphous solid, $[\alpha]_D$ +59° (*c* 3.8, acetone). N.m.r. data: δ 7.73 and 7.68 (2 d, 4 H, *J* 16 Hz, 4 Ph–C*H*=), 7.4 (m, 20 H, 4 Ph), 6.46 and 6.42 (2 d, 4 H, *J* 16 Hz, 4 CO–CH=), 5.7–5.3 (m, 2 H, 2 CH–O–CO), 4.9–4.25 (m, 6 H, CH_2–O and CH–O), 1.50 (s, 6 H, 2 Me).

Anal. Calc. for $C_{45}H_{42}O_{10}$: C, 72.96; H, 5.44. Found: C, 73.14; H, 5.50.

3,4-Di-O-methyl-D-*mannitol 1,2,5,6-tetra*-trans-*cinnamate* (**4**). — To a solution of 3,4-di-*O*-methyl-D-mannitol[31] (2.1 g) in dry pyridine (30 ml), a solution of cinnamoyl chloride (7.3 g) in dry benzene (20 ml) was added dropwise. After storage at room temperature for 48 h, the reaction mixture was worked-up as described for **3**. The chromatographed product (6 g, 87%) crystallized on storage and had m.p. 47–50°,

$[\alpha]_D$ +50° (*c* 4.65, acetone). N.m.r. data: δ 7.81 and 7.75 (2 d, 4 H, *J* 16 Hz, 4 Ph–C*H*=), 7.48 (m, 20 H, 4 Ph), 6.53 and 6.48 (2 d, 4 H, *J* 16 Hz, 4 CO–CH=), 5.58 (broad m, 2 H, 2 CH–O–CO), 5.1–4.3 (eight-line m, 4 H, 2 CH_2O), 3.8 (broad d, 2 H, *J* 6 Hz, 2 C*H*OMe), 3.61 (s, 6 H, 2 Me).

Anal. Calc. for $C_{44}H_{42}O_{12}$: C, 72.31; H, 5.79. Found: C, 72.20; H, 5.60.

*1,2:5,6-Di-*O*-isopropylidene-*D*-mannitol 3,4-di-*trans*-cinnamate* (**5**). — To a solution of 1,2:5,6-di-*O*-isopropylidene-D-mannitol[32] (5.24 g) in dry pyridine (30 ml), a solution of cinnamoyl chloride (7.3 g) in dry benzene (20 ml) was added. After reaction and work-up as described for **3**, the product was eluted from silica gel with 19:1 benzene–ethyl acetate to afford material (8.46 g) which was crystallized from ethanol to yield **5** (7.3 g, 70%), m.p. 123–124°, $[\alpha]_D$ −14° (*c* 1.8, acetone). N.m.r. data: δ 7.83 (d, 2 H, *J* 16 Hz, 2 Ph–C*H*=); 7.45 (m, 10 H, 2 Ph); 6.52 (d, 2 H, *J* 16 Hz, 2 CO–CH=); 5.60 (broad d 2 H, *J* 5 Hz, 2 CH–O–CO); 4.5–3.9 (m, 6 H, 2 CH–CH_2); 1.40 and 1.34 (2 s, 12 H, 2 CMe_2).

Anal. Calc. for $C_{30}H_{34}O_8$: C, 68.95; H, 6.56. Found: C, 69.10; H, 6.52.

*2,3:4,5-Di-*O*-methylene-*D*-mannitol 1,6-di-*trans*-cinnamate* (**6**). — To a solution of 2,3:4,5-di-*O*-methylene-D-mannitol[33] (6.18 g) in dry pyridine (50 ml), a solution of cinnamoyl chloride (11 g) in dry benzene (35 ml) was added. After reaction and work-up as described for **3**, the product was eluted from silica gel with 19:1 and 9:1 benzene–ethyl acetate to give **6** (11 g, 77%) which, after two crystallizations from methanol–methylene chloride, had m.p. 127–129°, $[\alpha]_D$ +48.5° (*c* 2.5, acetone). N.m.r. data: δ 7.81 (d, 2 H, *J* 16 Hz, 2 Ph–C*H*=), 7.6–7.3 (m, 10 H, 2 Ph), 6.54 (d, 2 H, *J* 16 Hz, 2 CO–CH=), 5.00 (s, 4 H, 2 O–CH_2O), 5.1–4.0 (m, 8 H, CH_2O and CHO).

Anal. Calc. for $C_{26}H_{26}O_8$: C, 66.94; H, 5.62. Found: C, 66.97; H, 5.75.

General irradiation procedure. — Materials were irradiated as solutions in dry benzene which had been deaerated with a stream of dry, oxygen-free nitrogen for at least 30 min. The irradiations were performed with a Hanovia 450-watt immersion lamp in a Pyrex apparatus while stirring the solution and bubbling through a slow stream of nitrogen. Reactions were monitored by n.m.r. spectroscopy. The general work-up procedure was to evaporate the solvent *in vacuo* and to treat the residue with boiling methanolic hydrochloric acid (prepared from 1 ml of thionyl chloride and 100 ml of methanol) for 24–48 h. After evaporation of the solvent *in vacuo*, a solution of the residue in methylene chloride (100 ml) was washed with water (3 × 30 ml), dried (Na_2SO_4), and concentrated to dryness in the presence of silica gel. The residue was then placed on a column of dry silica gel[34]; 20-ml fractions were collected.

Irradiation experiments. — (*a*) A solution of **1** (2 g) in benzene (150 ml) was irradiated for 5 h. Ester exchange and work-up afforded a mixture of methyl esters (1.8 g) which was eluted from silica gel (80 g) with 19:1 hexane–ethyl acetate (2.5 l). The fractions were appropriately combined on the basis of t.l.c. and/or n.m.r. data. Fraction 1 contained methyl cinnamate (1.39 g; ratio of *cis*:*trans* ~1:4). Fraction 2 contained (+)-dimethyl δ-truxinate (**8**, 0.17 g, 8.2% conversion; 27% yield based on recovered methyl cinnamate), $[\alpha]_D$ +4.67° (*c* 7.3, acetone); 42% optical yield based

on $[\alpha]_D$ +11.1° for the pure enantiomer[35]. N.m.r. data: δ 7.33 (m, 10 H, 2 Ph), 3.75 (s superimposed on the low-field half of an AA'BB' m, 8 H, 2 Me and 2 CH–CO), 3.6–3.25 (low-field half of an AA'BB' m, 2 H, 2 C*H*–Ph). Fraction 3 contained dimethyl *neotruxinate*[36] (**9**) and **8** (0.067 g; ~1:1 ratio). Fraction 4 contained dimethyl *β*-truxinate (**7**, 0.13 g, 6.2% conversion; 21% yield based on recovered methyl cinnamate), the n.m.r. spectrum of which was superimposable on that of an authentic sample. Elution with ethyl acetate afforded an oily mixture (0.09 g) which was not examined further.

Irradiation as described above, but for 20 h, afforded, after work-up and chromatography, methyl cinnamate (0.9 g); (+)-**8** (0.28 g), $[\alpha]_D$ +5.1° (*c* 5.1, acetone); **7** (0.26 g); elution with ethyl acetate then gave 0.23 g of an oily mixture.

Irradiation as described above, but for 68 h, and work-up afforded methyl cinnamate (0.13 g); (+)-**8** (0.48 g), $[\alpha]_D$ +4.28° (*c* 9.6, acetone); (±)-**9** (0.15 g), $[\alpha]_D$ ~0°; **7** (0.39 g); ethyl acetate then eluted 0.51 g of ill-defined mixtures.

In one irradiation experiment using a solution of 4 g of **1** in 180 ml of benzene and irradiating for 64 h, a small quantity of an unknown product (not **7**–**9**) was eluted prior to **8**. In this run, **8** had $[\alpha]_D$ +4.95° (*c* 7.8, acetone), and **9** had $[\alpha]_D$ +5.0° (*c* 7.7, acetone; optical yield 9.6% based on $[\alpha]_D$ +52.0° for the pure enantiomer[35]).

Solutions of **1** (2 g) in ethyl acetate (150 ml) or aqueous *N*,*N*-dimethylformamide (1:5, 150 ml) were also irradiated (5 h). In the former experiment, (+)-**8** was isolated in 19% yield, $[\alpha]_D$ +4.3° (*c* 8.3, acetone); in the latter, the yield of (+)-**8** was 11%, $[\alpha]_D$ +3.65° (*c* 4.0, acetone). When molten **1** (2 g) at ~110° was irradiated with a 550-watt Hanovia medium-pressure mercury lamp for 5.5 h, the usual work-up and chromatography afforded (+)-**8** (15%), $[\alpha]_D$ +2.5° (*c* 1.8, acetone). Irradiation of crystalline **1** with Westinghouse sunlamps through Pyrex for 2 weeks led to no detectable reaction.

(*b*) A solution of **2** (2 g) in benzene (180 ml) was irradiated for 23 h. After ester exchange, the products were eluted from silica gel (80 g) with 19:1 hexane–ethyl acetate (3 l). The following fractions were obtained: (*1*) a mixture (~1:1 molar ratio) of methyl cinnamate (only traces of *cis*-isomer) and methyl benzoate (0.31 g); (*2*) (+)-**8** (0.25 g, 20%), $[\alpha]_D$ +9.45° (*c* 8.4, acetone); (*3*) (+)-**9** (0.03 g, <3%), $[\alpha]_D$ +25.7° (*c* 2.33, acetone); (*4*) **7** (0.95 g, 75%). Elution with ethyl acetate then gave a yellow oil (0.09 g).

(*c*) A solution of **3** (2 g) in benzene (180 ml) was irradiated for 43 h. The residue after ester exchange was eluted from silica gel (80 g) with 19:1 hexane–ethyl acetate (3 l). The following fractions were obtained: (*1*) methyl cinnamate (0.4 g); (*2*) (+)-**8** (0.38 g, 28%), $[\alpha]_D$ +9.09° (*c* 12.63, acetone). Recrystallization from methanol afforded optically pure **8**, m.p. 67–69°, $[\alpha]_D$ +11.7° (*c* 11.06, acetone); lit.[35] m.p. 45°*, $[\alpha]_D$ +11.1° (*c* 7.75, acetone); (*3*) (+)-**9** (0.05 g, 3.7%), $[\alpha]_D$ +18.1° (*c* 3.5, acetone); (*4*) **7** (0.17 g, 13.1%). Elution with ethyl acetate then gave a yellow oil (0.68 g).

(*d*) A solution of **4** (2 g) in benzene (180 ml) was irradiated for 22 h. The

*The reported[35] m.p. for enantiomerically pure **8** is apparently in error.

residue after ester exchange was eluted from silica gel (80 g) with 19:1 hexane–ethyl acetate (3 l). The following fractions were obtained: (*1*) methyl cinnamate (1.03 g; ratio of *cis:trans*, ~2:1); (*2*) (+)-**8** (0.14 g, 19%), $[\alpha]_D$ +2.47° (*c* 4.6, acetone); (*3*) a mixture (~1:1) of **8** and **9** (32 mg, 4.3%); (*4*) **7** (0.152 g, 20.5%). Ethyl acetate then eluted a yellow oil (0.36 g).

(*e*) A solution of **5** (2 g) in benzene (180 ml) was irradiated for 22 h. The residue after ester exchange was eluted from silica gel (70 g) with 19:1 hexane–ethyl acetate (3 l). The following fractions were obtained: (*1*) methyl cinnamate (0.27 g; almost pure *trans*-isomer); (*2*) (+)-**8** (0.22 g, 23%), $[\alpha]_D$ +6.0° (*c* 10.65, acetone); (*3*) mainly (+)-**9** (0.06 g, 6%), $[\alpha]_D$ +9.2° (*c* 2.85, acetone); (*4*) **7** (0.48 g, 49%). Ethyl acetate then eluted a yellow oil (0.14 g).

(*f*) A solution of **6** (1.5 g) in benzene (180 ml) was irradiated for 47 h. The residue after ester exchange was eluted from silica gel (50 g) with 19:1 hexane–ethyl acetate (2.2 l). The following fractions were obtained (*1*) methyl cinnamate (0.39 g; ratio of *cis:trans* ~1:1); (*2*) impure **8** (0.27 g, 42%); (*3*) **7** (0.15 g, 23%). Elution with ethyl acetate then afforded a mixture (0.37 g) of unidentified materials.

Rechromatography of fraction *2* (0.16 g) on silica gel (8 g) afforded (−)-**8** (98 mg), $[\alpha]_D$ −5.28° (*c* 4.52, acetone), and a mixture (59 mg) containing **8** and **9**.

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