rated from unreacted and partially reacted dimer by TLC, extracted with CH_2Cl_2, and compared with a batch of known stereochemistry (ref 2, Scheme IV). After further cleanup in a small column of silica (eluent hexane, then CH_2Cl_2) and drying, the product had $[\alpha]^{25}_D$ + 103.6° (±3°) ($CHCl_3$, 6.7 mg/cm^3), corresponding to an enantiomeric purity of 80.9%. From these data, $[\alpha]^{25}_D$ of dimer **10** is +114° (±7°).

Acknowledgment. We thank the donors of the Petroleum Research Fund administered by the American Chemical Society, and the Israel Commsion for Basic Research for financial support. We thank Professor M. D. Cohen and Dr. Ziva Berkovitch-Yellin for interesting discussions and Edna Gati for technical assistance in some of the experiments.

Registry No. (±)-**1**, 64634-78-2; (+)-(*S*)-**1**, 64666-23-5; **2**, 56796-82-8; **3**, 73389-59-0; **4**, 73389-58-9; **5a**, 81408-87-9; **5b**, 81408-88-0; **6a**, 81408-89-1; **6b**, 81445-47-8; (±)-**7a**, 81408-90-4; (+)-**7a**, 81445-48-9; (−)-**7a**, 81445-49-0; (+)-**7b**, 81408-91-5; (−)-**7b**, 81445-50-3; **8**, 73389-60-3; **9**, 73389-61-4; **9** trimer, 81408-95-9; (±)-**10**, 81408-92-6; (+)-**10**, 81445-51-4; **11**, 81408-93-7; **12a**, 81423-17-8; **13**, 81408-94-8.

Attempted Amplification of Optical Activity by Crystallization of Chiral Crystals of Photopolymerizing Dienes in the Presence of Their Topochemical Products[1]

Jan van Mil, Lia Addadi,* Edna Gati, and Meir Lahav*

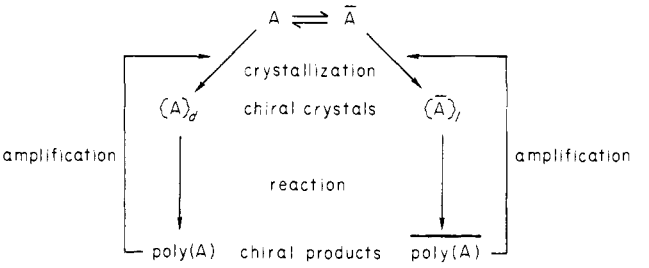
Contribution from the Department of Structural Chemistry, The Weizmann Institute of Science, Rehovot, 76100, Israel. *Received August 12, 1981*

Abstract: Monomeric dienes **1–7**, which pack in chiral crystal structures and yield upon irradiation chiral cyclobutane dimers, trimers, and oligomers, have been crystallized in the presence of small amounts of their photoproducts ("impurities"). An efficient asymmetric induction was observed in these crystallizations; the absolute configuration of the phase precipitating in excess is always found to be opposite to that of the crystalline phase from which the impurity was generated. A mechanism is proposed in which small amounts (~1%) of the chiral additives are stereospecifically adsorbed onto the growing sites of the stereochemically similar crystal, thereby delaying its growth. Experiments yielding evidence in support of this mechanism are presented. Possible applications of the results of this study to the optical resolution of conglomerates in general in the presence of "tailor-made" impurities are discussed.

In the preceding paper,[2] we described a successful "absolute" asymmetric synthesis of chiral cyclobutane dimers, trimers, and oligomers from achiral unsymmetrically substituted dienes packing in chiral crystals, where the two nonequivalent double bonds are appropriately aligned for a topochemically controlled ($2_\pi + 2_\pi$) photopolymerization (Scheme II). However, since the chances of obtaining crystals of either chirality are equal, in a large number of independent experiments we shall repeatedly obtain equal amounts of the enantiomorphous parent crystals, and therefore, also of the chiral products of opposite chiralities. This is the consequence of a very fundamental principle stated by P. Curie in 1894: "A physical event cannot have a symmetry lower than that of the event that caused it".[3] However, if a very efficient amplification mechanism is coupled with a rare generation step, formation of products with one specific chirality may be envisaged.

Assuming that the chiral product of the first experiment could preserve and amplify its chiral information in a subsequent crystallization of the starting material, oligomers of that single chirality may be generated. The overall process is outlined in Scheme I, where poly(A) and $\overline{\text{poly(A)}}$ are the chiral products formed from the reaction of nonchiral monomer A inside the chiral crystals $\{\}_d$ and $\{\}_l$, respectively.

Scheme I



There have been many studies dealing with asymmetric induction by crystallization in the presence of chiral additives. Pincock[4] investigated the system binaphthyl–mandelic acid, and Harada[5] showed that glutamic acid induced preferential crystallization of the aspartic acid–copper complex of opposite absolute configuration. Green and Heller[6] looked at the induction from the point of view of possible amplification of chirality; they studied the crystallization of *p,p'*-dimethylchalcone in the presence of the chiral dibromide generated by the reaction of the crystalline chalcone with bromide vapor and found a striking control of the product upon crystallization of the parent compounds. This system, however, is inappropriate for amplification, since the crystal phase obtained in excess has a chirality opposite to that required.

(1) (a) This paper should be considered "Useful Impurities for Optical Resolution", Part 4. For Part 3 in this series, see: Addadi, L.; Gati, E.; Lahav, M. *J. Am. Chem. Soc.* **1981**, *103*, 1251. For preliminary communications of part of this work, see: (b) van Mil, J.; Addadi, L.; Gati, E.; Lahav, M. *Ibid.* **1981**, *103*, 1248. (c) Addadi, L.; van Mil, J.; Lahav, M. *Ibid.* **1981**, *103*, 1249. (d) Part of this work was presented at the Symposium on the Generation and Amplification of Optical Activity, Bremen, July 1980 (*Origins Life* **1981**, *11*, 107) and at the IUPAC Meeting on Macromolecules, Firenze, Italy, Sept 1980. Part of the Ph.D. Thesis of J. van Mil to be submitted to the Feinberg Graduate School.

(2) Addadi, L.; van Mil, J.; Lahav, M., preceding paper in this issue.

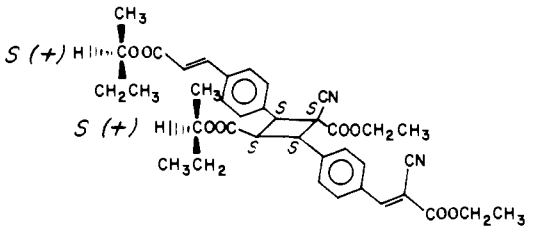
(3) Curie, P. *J. Phys. Theor. Appl.* **1894**, *3*, 393.

(4) (a) Pincock, R. E.; Wilson, K. R. *J. Am. Chem. Soc.* **1971**, *93*, 1291. (b) Pincock, R. E.; Perkins, R. R.; Ma, A. S.; Wilson, K. R. *Science* **1971**, *174*, 1018. (c) Pincock, R. E.; Lu, M. D.; Fung, F.-N. Proceedings of the 3rd ISSOL Meeting, Jerusalem, 1980, p 347.

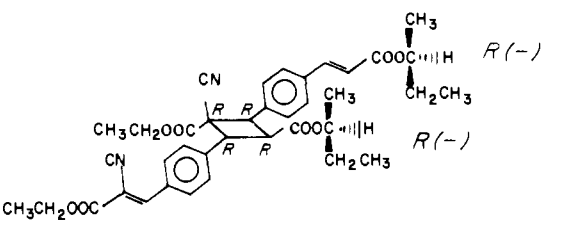
(5) (a) Harada, K. *Nature (London)* **1965**, *205*, 590. (b) Harada, K. *Naturwissenschaften* **1970**, *54*, 114. (c) Harada, K.; Tso, W. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 2895.

(6) Green, B. S.; Heller, L. *Science* **1974**, *185*, 525.

0002-7863/82/1504-3429$01.25/0

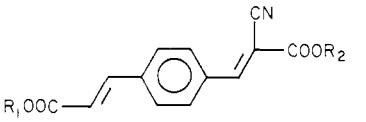


SSSS 10 (−)



RRRR 10 (+)

Table I. Space Groups and Cell Dimensions of Monomers 1-9



no.	R_1	R_2	space group	*a*, Å	*b*, Å	*c*, Å	β, deg	*z*
1	3-pentyl	methyl	$P2_1$	7.01	25.50	5.37	104	2
2a	3-pentyl	ethyl	*a*					
2b	3-pentyl	ethyl	$P\bar{1}$	14.88	13.66	5.28	97, 91, 114	2
3	3-pentyl	*n*-propyl	*P*1	7.33	4.95	14.90	98, 104, 104	1
4	(*R,S*)-*sec*-butyl	ethyl	*P*1	13.35	7.03	5.41	104, 93, 92	1
5a	(*R*)-*sec*-butyl	ethyl	*P*1	13.17	6.94	5.25	103.1, 95.5, 90.1	1
5b	(*S*)-*sec*-butyl	ethyl	*P*1	13.17	6.94	5.25	103.1, 95.5, 90.1	1
6	(*R,S*)-*sec*-butyl	*n*-propyl	*a*					
7	isopropyl-3-pentyl 1-1	ethyl	*P*1	13.53	6.90	5.28	102, 104, 94	1
8	*n*-propyl	ethyl	$P\bar{1}$	9.62	11.78	7.43	94, 98, 103	2
9	isopropyl	ethyl	$P\bar{1}$	12.56	9.91	7.52	102, 91, 92	2

[a] Suitable crystals for space group determination could not be grown, but the similarity of the powder diffraction pattern with those of 3, 4, 5, and 7 suggests a *P*1 structure.

Table II. Results of Crystallization from the Melt of Monomers 1-9 in the Presence of Resolved 10, and the Specific Rotations of the Product Dimers (deg)

	(+)-10 additive				(−)-10 additive			
	fast[a]	slow[a]			fast[a]	slow[a]		
monomer	15%[b]	15%[b]	8%[b]	3%[b]	15%[b]	15%[b]	8%[b]	3%[b]
1	−70[c]	−62	−74	−75		+61	+89	+83
2	−47[d]	0	0	0	+73	0	0	0
3	−67	−61	−40	−59	+38	+65	+54	+58
4	−22[e]	−21	−12	−3	+47	+33	+8	+0
6	−34	−31	−36	−27	+43	+45	+42	+40
7	−42[f]	−47	−51	−40	+46	+47	+56	+36
8	0				0			
9	0				0			

[a] Crystallization rate. [b] Additive concentration. [c] $[\alpha]^{25}_D$ of the product dimers: 1, 114°; 2, 110°; 4, 95°; 7, 100°. For the dimers of 3 and 6 it may be assumed that their $[\alpha]^{25}_D$ is of the same order of magnitude. [d] The chiral *P*1 structure is metastable and is obtained only upon fast crystallization. The slow process yields the stable centrosymmetric $P\bar{1}$ polymorph. [e] The induction effect is complicated by the existence of a eutectic point between the two chiral phases, $\{\}_d$ and $\{\}_l$. Furthermore, the product dimers still contain some of the original dimer used as the additive. [f] The given results refer to the homodimer with isopropyl/isopropyl side chains.

In all of these studies no mechanistic rationalization of the observed effects was suggested, due to the absence of a clear understanding of the interaction between the chiral additive and the crystallizing enantiomorphic phases.

Without an understanding of the mechanism(s) involved, it is not possible to predict which system will give asymmetric induction in the required sense, or, in fact, whether any of the systems will. The study below is one of asymmetric inductions in a model system. It was selected to shed light on the mechanistic aspects of these inductions.

The stereochemical similarity between the chiral crystalline parent phase and the topochemical product, in the system of the unsymmetrically disubstituted dienes referred to above, is straightforward. Therefore, it is possible to select dienes which spontaneously resolve. If we use the product of the reaction as an additive in the crystallization of further parent dienes, this system provides a most appropriate model for a systematic investigation of the influence of chiral additives on the crystallization of enantiomorphic crystals (see Scheme II). The results of such a detailed study are reported here.

Table III. Results of Crystallization from the Melt with Resolved Trimer and Oligomer, and the Specific Rotation of the Product Dimers (deg)

	additive			
	trimer **11** (15%)		oligomer **12** (8%)	
monomer	(+)	(−)	(+)	(−)
1	−92[a]	+75	−11	+52
2	−30			
3	−31	+45	−21	+36
4	−39	+17		
6	−54	+30		
7	−41[b]	+30	−9	+15

[a] See Table II, footnote *c*. [b] See Table II, footnote *f*.

Results and Discussion

Seven disubstituted phenylenediacrylates, **1**–**7**, packing in chiral crystals (Table I) and with the structural motif of Scheme II, were crystallized in the presence of resolved dimer **10**, trimer **11**, and oligomers **12** of monomer **5**.[7,8] Since the topochemical reaction proceeds with quantitative enantiomeric yield, the asymmetric induction in the formation of the resulting crystalline phase was deduced from the enantiomeric excess of the dimers obtained after irradiation of these crystals.

(7) (+) and (−) trimers **11** and (+) and (−) oligomers **12** have the same absolute configuration around the C_4 ring as (+)- and (−)-**10** and the stereochemistry shown in Scheme II.

(8) Products of monomer **5** were used, since they are easily available in large quantities and high enantiomeric purity.

Scheme II

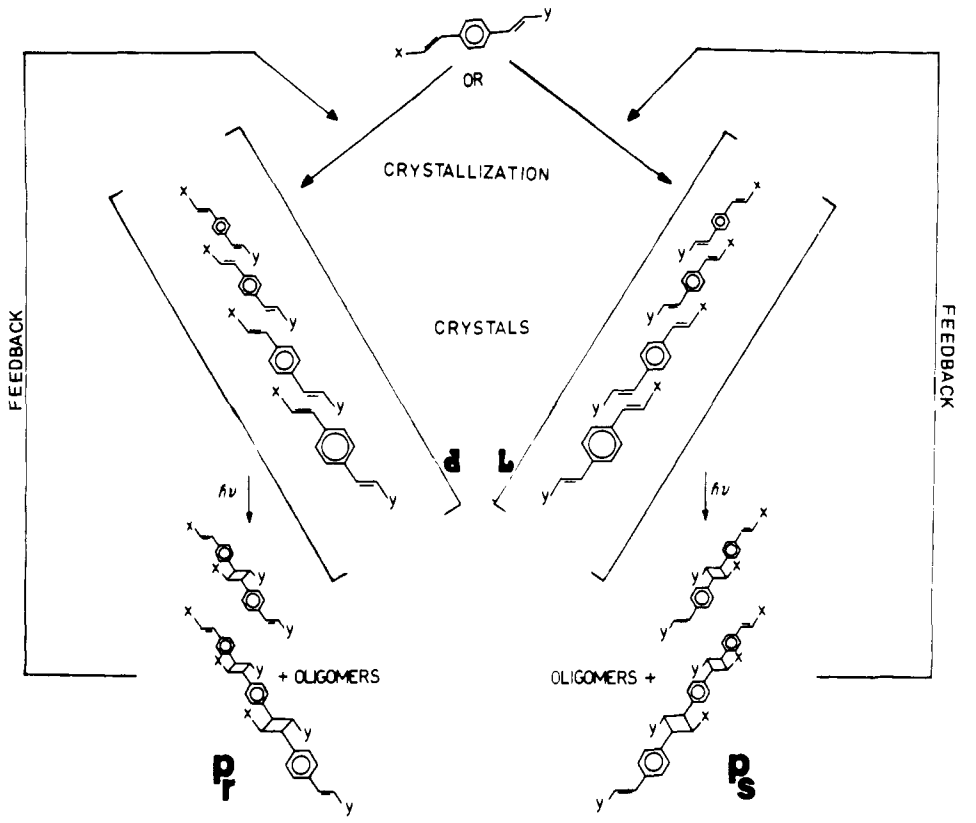


Table IV. Results of Crystallization of Monomers from Solution with Resolved Dimer 10[a] and the Specific Rotation of the Products (deg)

		induction with (+)-10			induction with (−)-10		
monomer	%	methylene chloride	*n*-hexane[b]	ethyl acetate	methylene chloride	*n*-hexane[b]	ethyl acetate
1	10	−92[c]	−106	−81	+82	+101	+79
1	5	−71	−100	−85	+88	+98	+81
3	10	−69	−89	−48	+62	+85	+51
3	5	−65	−82	−51	+71	+87	+57
7	10	−65[d]	−85	−53	+62	+95	+61
7	5	−61	−91	−59	+59	+92	+64

[a] These are the best results from a series of at least three experiments for each system. The maximum deviation for these results was 10%. [b] A few drops of methylene chloride were added to improve solubility. [c] See footnote *c*, Table II. [d] See footnote *f*, Table II.

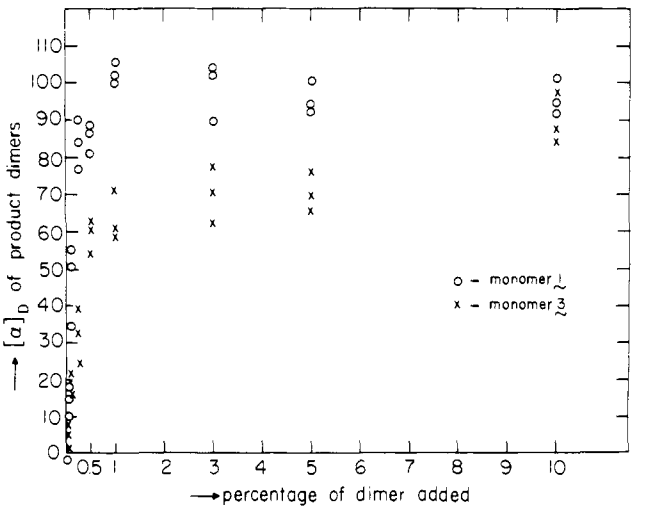


Figure 1. Dependence of the asymmetric yield of induction in the crystallization process on the additive concentration of monomers **1** and **3** in the presence of dimer **10**.

The X-ray powder diagram of each sample was checked prior to irradiation to confirm the structures. Blank experiments, i.e., crystallizations of the monomer in the absence of chiral additives, were performed in parallel with all experiments, and no appreciable enantiomeric excesses were detected. Monomers **8** and **9**, which pack in racemic crystals, were used as reference systems.

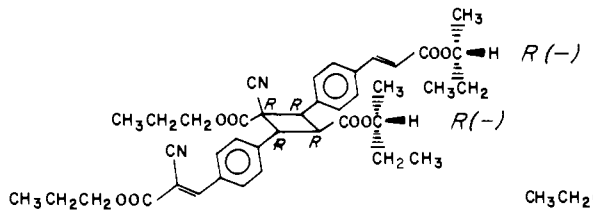
The first experiments were performed as follows: Samples of the monomer were crystallized from the melt in the presence of various amounts (3–15%) of an additive of either chirality. The samples were cooled either fast (several hours) or slow (several weeks), as reported in the Experimental Section.

Table II summarizes the results of the crystallization of monomers **1–9** in the presence of dimers. The results of the experiments carried out in the presence of trimers and oligomers are listed in Table III.

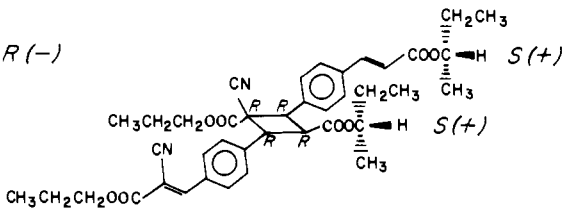
Inspection of these results shows that the nonchiral or chiral racemic monomers studied, which pack in chiral crystals and display the structural motif of Scheme II, are all affected by the additive. Furthermore, it is seen that, except for monomer **5**, an additive P_r (see Scheme II) causes preferred crystallization of the crystalline phase $\{\}_l$ of opposite absolute configuration, and vice versa. Chiral resolved monomer **5**, which always appears in only one stable enantiomorphic form, is not affected by an additive of either chirality.

The studies were subsequently extended to include crystallizations from solutions in various solvents (methylene chloride, hexane, and ethyl acetate). Solutions were slowly evaporated to dryness, and the samples were treated as in previous cases. The results are summarized in Table IV.[9] The results show that under

(9) Upon crystallization from methanol and ethanol the phenomenon of autoseeding was observed. This causes crystallization of the whole batch of the monomer into crystals with the chirality of the first seed precipitated. This peculiarity, which was exploited in previous work,[2] can lead to enantiomerically pure batches but of either chirality. No such effect was observed in blank experiments of crystallization from methylene chloride, hexane, or ethyl acetate.



13



14

Table V. Results of Crystallization of Monomers 1 and 3 with Dimers 13 and 14 and the Specific Rotations of the Product Dimers (deg)

monomer	additive 13[a]	additive 14
1	−83.8[b]	−68.5
	−104.6	−97.2
	−94.3	−91.2
3	−12.8[c]	−10.9
	−14.8	−11.6
	−12.0	−14.6

[a] Experiments were performed with methylene chloride/hexane solutions, and the workup procedure was as described. Amount of the dimer used was 10% (w/w). [b] See footnote *c*, Table II. [c] The dimer of monomer 3 could not be separated from the impurity, resulting in a lower optical rotation.

these conditions of crystallization there exists an effect similar to that observed in crystallization from the melt.

Induced seeding cannot account for these results, since it would lead to the precipitation of the second enantiomorph. Moreover, in all the experiments described above, we used dimer **10**, which is a liquid and, therefore, cannot enhance seeding. In the crystallizations from the melt, where 8 or 15% impurity was used, an excess of the dimer separated out as droplets on the wall of the vial and did not crystallize. This also indicates that only small amounts of additive are involved in the induction process. Therefore, we investigated the dependence of the asymmetric induction on the concentration of the additive.

Figure 1 shows the results of the crystallizations of monomers **1** and **3** from solutions in hexane/methylene chloride. In these systems, impurity concentrations as low as 0.05% (w/w) give rise to measurable effects, while 1% is sufficient to lead to maximum induction.

Another question that may be raised is whether the asymmetric induction is due to the chiral influence of the rigid backbone of the impurity (with the chiral cyclobutane ring) or to the influence of the chiral *sec*-butyl groups attached to the side chains.

The following experiments were performed to clarify this point. Crystallization of monomers **1** and **3** in the presence of the resolved dimer of nonchiral monomer **2** (not containing *sec*-butyls) gave rise to an induction with an order of magnitude equal to that of the induction using the chiral dimers **10**. On the other hand, resolved monomer **5**, which contains the chiral *sec*-butyl handle, does not have a measurable effect on the crystallization of the other monomers studied. Crystallization of **1** and **3** in the presence of the resolved diastereoisomers **13** (C_4 *SSSS*/*sec*-butyls-*R*,*R*) and **14** (C_4 *SSSS*/*sec*-butyls-*S*,*S*),[9,10] which have the same absolute configuration of the chiral cyclobutanes but *sec*-butyl groups of opposite chiralities, yields, in both cases, an asymmetric induction of the same sense with an excess of phase $\}_d$ (Table V). All of these experiments demonstrate unequivocally that the asymmetric induction is due to the rigid cyclobutane backbone whereas the chiral *sec*-butyl group only exerts a minor effect, if any.

Mechanism of the Process. The results described thus far clearly indicate that the induction process during crystallization,

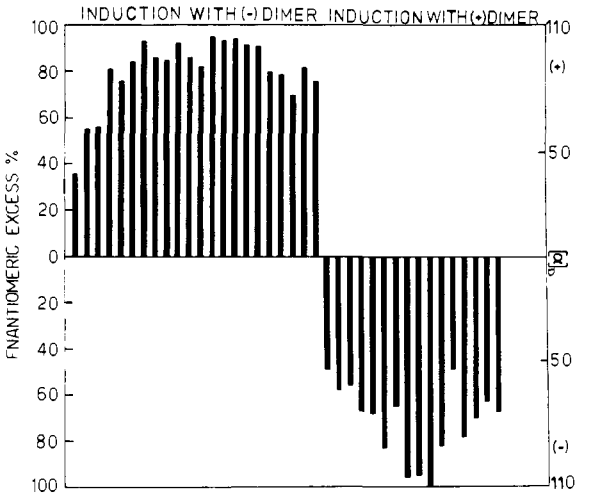


Figure 2. Asymmetric yields of induction on monomer **1** with (+) and (−) dimers of **10** under various experimental conditions.

as performed here in more than 300 experiments on various monomers and under various conditions of crystallization, always yields an excess of the crystalline phase with an arrangement enantiomeric to the one from which the impurity was generated.

A compilation of the results of a large number of induction experiments carried out on monomer **1** under different experimental conditions is given in Figure 2. It is evident that changes in solvent, temperature, rate of crystallization, etc., only have a quantitative effect on the induction, while the resemblance between the structure of one of the enantiomorphic crystalline phases and the stereochemistry of the additive is a necessary requirement for the success of the induction process.

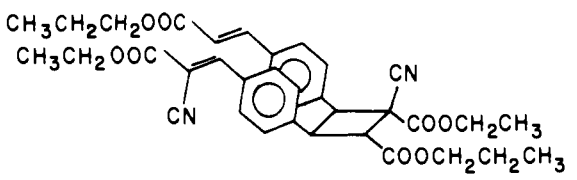
Trivial explanations for this effect, particularly induced seeding by the dimer, have already been excluded; also, the possibility of formation of quasi-racemates was ruled out on crystallographic grounds. Since small amounts (~1%) of additive are sufficient to obtain maximal effect, it is difficult to rationalize the asymmetric induction on the basis of selective interactions in solution or in the melt phase.

The explanation that we propose involves stereoselective adsorption of the dimer, trimer, and oligomer onto the surface of a growing monomer crystal with the same absolute configuration. Such adsorption could inhibit the growth of monomer crystals of this configuration and favor the crystallization of the enantiomorph from the fast racemizing mixture in solution. This interpretation is based on reports on inhibition of crystal growth by small amounts of impurities, performed mainly in inorganic systems (see, for example, the effect of Mg^{2+} or Pb^{2+} ions on NaCl, or the effect of dyes on inorganic salts[11]) which results both in drastic habit changes and in an overall decrease in the growth rate of these crystals.

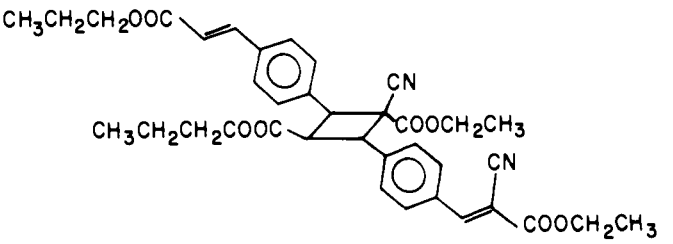
In order to invoke a similar mechanism in the present case, we need to demonstrate that the resolved product is indeed adsorbed preferentially onto the enantiomorphous crystals stereochemically related to it. This point was clarified by: Resolved monomer **5**, which, by virtue of its stabilizing chiral handle, appears exclusively in one enantiomorphic form [*S*(+) in l, *R*(−) in d], (see Scheme

(10) A full description of these compounds will appear in a separate communication: Van Mil, J.; Addadi, L.; Lahav, M.; Leiserowitz, L. *J. Chem. Soc., Chem. Commun.*, in press.

(11) *Discuss. Faraday Soc.* **1949**, *5*, Chapter 2.



15



16

Table VI. Results of Preferential Adsorption of the Dimers of 4 onto Growing Crystals of Resolved Monomer 5

chirality of monomer	% of adsorbed dimer (w/w)	$[\alpha_D]$ of adsorbed dimer deg	chirality[a] of adsorbed dimer	enantiomeric excess, %
S(+)	0.57	−78.9	*SSSS*	71.7
S(+)	0.74	−69.8	*SSSS*	63.4
R(−)	0.59	+76.9	*RRRR*	70.0
R(−)	0.68	+70.5	*RRRR*	64.0
S(+)	0.56	−79.8	*SSSS*	72.5
S(+)	0.64	−76.4	*SSSS*	69.4
R(−)	0.47	+81.6	*RRRR*	74.1
R(−)	0.50	+78.8	*RRRR*	71.6

[a] Chirality of the four chiral centers of the cyclobutane ring. Irradiation of (*R*)(−)-5 leads to the formation of dimers with an absolute configuration of *RRRR* around the C_4, with $[\alpha]_D$ +110°.

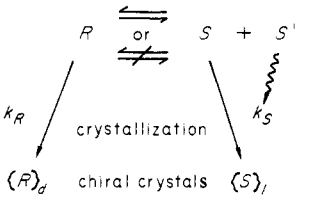
II), was crystallized in the presence of a 10% (w/w) racemic mixture of the chiral dimers of **4**. The dimers adsorbed onto the crystals during partial crystallization were isolated by chromatography, and the enantiomeric excess was evaluated by specific rotation measurements. The results show that the dimers of **4** are present in amounts of 0.5–1% in the crystals of **5** and, indeed, with a large preference for the dimer of the expected stereochemistry (Table VI).[12]

Similar crystallization experiments, performed on monomers **1** and **3** in the presence of 10, 5, and 3% of racemic dimer of **4**, result in overall incorporation of the dimer in amounts of the same order of magnitude. This apparently is the maximum amount that can be incorporated and is in good agreement with the minimum amount of additive required in solution to obtain maximum induction (see Figure 1).[13]

An interesting possibility arises from the understanding of this mechanism, namely, that it may be possible to crystallize metastable phases of materials through kinetic inhibition of the growth of the stable form by suitable impurities. This approach is forcedly empirical, due to the lack of an understanding of the thermodynamics of the system. Therefore, it is not possible to predict the conditions needed for the appearance of such a phase. Some systems in the family of the disubstituted dienes have been analyzed in this respect, and, of these, only **8** gives a positive result. This compound crystallizes from the melt or from ethanol in a centrosymmetric structure of space group $P\bar{1}$ and yields on irradiation dimer **15**. However, when the monomer is crystallized (from the melt) in the presence of ~10% of **15**, the growth of the centrosymmetric form is suppressed and another crystalline phase is formed, which yields upon irradiation dimer **16**.

Another practical implication of the proposed mechanism, is the generalization that can be made concerning the resolution of

Scheme III[a]



[a] In the absence of *S'*, $k_R = k_S$; in the presence of *S'*, $k_R >> k_S$.

conglomerates (discussed in a previous communication[1b]). Since the asymmetric induction depends mainly on the stereochemical resemblance of the crystalline phase to the resolved impurity, the same effect should be applicable in general to the crystallization of a conglomerate ($\{R\} + \{S\}$), either fast racemizing or not, in the presence of a "tailor-made" impurity *S'* (stereochemically similar to *S*) (Scheme III).

Application of this principle enabled us to rationalize some peculiar resolutions of conglomerates in the presence of chiral additives (described in the literature) and to select effective tailor-made impurities for the resolution of a large set of conglomerates of diverse chemical natures.[12]

Returning to our initial aim of amplification, we conclude that a direct amplification, as evisaged in Scheme I, requires a different class of systems in which the product generated in a $\{\}_d$ crystal inhibits the growth of the $\{\}_l$ phase, and vice versa.

Experimental Section

General Remarks. NMR spectra were recorded on a Bruker 90-MHz instrument; mass spectra were measured on a Varian MAT 731 double focusing mass spectrometer at 70 eV with an ion source temperature of 250–270 °C and a sample temperature of ~200 °C; X-ray powder spectra were taken with a Philips PW 1380 powder diffractometer; optical rotations were measured with a Perkin-Elmer 141 polarimeter ($CHCl_3$, c = 1).

Chromatography was carried out on TLC plates (silica gel, Merck 5554) or in a column (silica gel) using cyclohexane–ethyl acetate 80:20 as the eluent. R_f values are reported as measured after one run.

Syntheses of monomers, as well as irradiation procedures for obtaining dimers, trimers, and oligomers, have been described elsewhere.[14] Characterization of monomers **1**, **2**, **4**, **5**, **7**, and **9** and their dimers have already been reported.[2,14]

Monomer 3 (R_1 = 3-pentyl, R_2 = *n*-propyl): mp 80.0–82.0 °C; ^{1}H NMR ($CDCl_3$) δ 0.93 (2 t, 6 H), 1.01 (t, 3 H), 1.50–1.91 (m, 6 H), 4.28 (t, 2 H), 4.90 (q, 1 H), 6.53 and 7.67 (AB system, J = 16 Hz, 2 H), 7.53–8.00 (4 H, aromatics), 8.20 (s, 1 H); mass spectrum, *m/e* 355 (P), 285 ($-C_6H_{10}$), 268 ($-C_5H_{11}O$), 243 ($-C_5H_{10}$, $-C_3H_6$); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.54.

Monomer 6 (R_1 = (*R,S*)-*sec*-butyl, R_2 = *n*-propyl): mp 88.0–89.0 °C; ^{1}H NMR ($CDCl_3$) δ 0.95 (t, 3 H), 1.03 (t, 3 H), 1.29 (d, 3 H), 1.58 (m, 2 H), 1.76 (m, 2 H), 4.29 (t, 2 H), 4.99 (m, 1 H), 6.51 and 7.66 (AB system, J = 16 Hz, 2 H), 7.57–8.05 (aromatics, 4 H), 8.21 (s, 1 H); mass spectrum, *m/e* 341 (P), 285 ($-C_4H_8$), 268 ($-C_4H_9O$), 243 ($-C_4H_8$, $-C_3H_6$); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.49.

Monomer 8 (R_1 = *n*-propyl, R_2 = ethyl): mp 92.0–93.0 °C; ^{1}H NMR ($CDCl_3$) δ 1.00 (t, 3 H), 1.40 (t, 3 H), 1.70 (m, 2 H), 4.18 (t, 2 H), 4.39 (q, 2 H), 6.53 and 7.67 (AB system, J = 16 Hz, 2 H); 7.58–8.05 (aromatics, 4 H), 8.21 (s, 1 H); mass spectrum, *m/e* 313 (P), 271 ($-C_3H_6$), 268 ($-C_2H_5O$), 254 ($-C_3H_7O$); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.39.

(12) By using other systems that yield single crystals, we have demonstrated that the opposite monomer is only mechanically adsorbed onto the surface of the crystal and the appropriate enantiomer is also found in the bulk of the crystal. In the present case no single crystals were available to perform such an analysis. Addadi, L.; Weinstein, S.; Gati, E.; Weissbuch, I.; Lahav, M., submitted for publication in *J. Am. Chem. Soc.*

(13) The monomer and appropriate amounts of the dimer were dissolved in hexane–methylene chloride and crystallized by slow evaporation. When approximately half the material had precipitated, the crystals were filtered and dried overnight. The analysis was carried out using HPLC.

(14) Addadi, L.; Lahav, M. *J. Am. Chem. Soc.* **1978**, *100*, 2838.

Monomer 10 (R_1 = (*R*)- or (*S*)-*sec*-butyl, R_2 = *n*-propyl): mp 94.5–96.5 °C; ^{1}H NMR and mass spectra identical with those of **6**.

Dimer of 3 (R_1 = 3-pentyl, R_2 = *n*-propyl): ^{1}H NMR δ 0.30 (t, 6/2 H), 0.82 (t, 3 H), 0.80 (t, 6/2 H), 0.93 (t, 6 H), 0.93 (m, 2 H), 1.03 (t, 3 H), 1.26 (m, 4/2 H), 1.46 (m, 4/2 H), 1.65 (m, 4 H), 1.80 (m, 2 H), 3.82 (m, 6 H), 4.29 (t, 2 H), 4.40 (d, 1 H), 4.45 (d, 1 H), 4.52 (m, 1 H), 4.85 (m, 1 H), 5.02 (d, 1 H), 6.45 and 7.45 (AB system, J = 16 Hz, 2 H), 7.41–7.69 and 7.98–8.01 (aromatics, 8 H), 8.23 (*s*, 1 H); mass spectrum, *m/e* 710 (P), 623 ($-C_5H_{11}O$), 358 (asymmetric cleavage of the cyclobutane ring), 355 (symmetric cleavage); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.37.

Dimer of 6 (R_1 = (*R,S*)-*sec*-butyl, R_2 = *n*-propyl): ^{1}H NMR δ 0.37 (t, 3/2 H), 0.51 (d, 3/2 H), 0.72 (t, 3 H), 0.88 (t, 3/2 H), 0.92 (t, 3 H), 1.06 (t, 3 H), 1.09 (d, 3/2 H), 1.29 (d, 2 H), 1.25–3.60 (m, 8 H), 3.82 (m, 2 H), 4.28 (t, 2 H), 4.40 (d, 1 H), 4.49 (d, 1 H), ~4.50 (m, 1 H), ~5.07 (m, 2 H), 6.43 and 7.65 (AB system, J = 16 Hz, 2 H), 7.41–7.68 and 7.98–8.01 (aromatics, 8 H), 8.22 (s, 1 H); mass spectrum, *m/e* 682 (P), 626 ($-C_4H_8$), 609 ($-C_4H_9O$), 352 (asymmetric cleavage of the cyclobutane ring), 341 (symmetric cleavage), 330 (asymmetric cleavage); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.34.

Dimers of 8 (R_1 = *n*-propyl, R_2 = ethyl). (a) Centrosymmetric: ^{1}H NMR δ 0.96 (t, 6 H), 1.36 (t, 3 H), 1.39 (t, 3 H), 1.70 (m, 4 H), 4.13 (t, 2 H) 4.17 (t, 2 H), 4.33 (q, 2 H), 4.45 (q, 2 H), 4.85 (d, 2 H), 4.95 (m, 1 H), 6.32 and 7.54 (AB system, J = 16 Hz, 2 H), 6.99–7.85 (8 H, aromatics), 8.10 (s, 1 H); mass spectrum, *m/e* 626 (P), 581 ($-C_2H_5O$), 567 ($-C_3H_7O$), 415 (asymmetric cleavage), 313 (symmetric cleavage); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.14. (b) Chiral: ^{1}H NMR δ 0.69 (t, 3 H), 0.88 (t, 3 H), 1.26 (t, 3 H), 1.40 (t, 3 H), 1.90 (m, 4 H), 3.62 (m, 8 H), 4.42 (m, 3 H), 6.51 and 7.50 (AB system, J = 16 Hz, 2 H), 7.39–8.03 (aromatics, 8 H), 8.21 (s, 1 H); mass spectrum, *m/e* 626 (P), 581 ($-C_2H_5O$), 567 ($-C_3H_7O$), 324 (asymmetric cleavage), 313 (symmetric cleavage), 302 (asymmetric cleavage); TLC (silica gel, cyclohexane–ethyl acetate 80:20) R_f 0.18.

Dimers 13 and 14 (R_1 = (*R*)- or (*S*)-*sec*-butyl, R_2 = *n*-propyl). (a) Dimer with *R/RRRR* or *S/SSSS* chirality, **13**: ^{1}H NMR identical to that of the dimer of the racemate with the exception of the triplet at 0.88 and the doublet at 0.51 (absent) and the doublet at 1.09 and the triplet at 0.37 (doubled in intensity); mass spectrum identical with the spectrum of the dimer of the racemate. (b) Dimer with *R/SSSS* or *S/RRRR* chirality, **14**: ^{1}H NMR identical with that of the dimer of the racemate with the exception of the doublet at 1.09 and the triplet at 0.37 (absent) and the triplet at 0.88 and the doublet at 0.51 (doubled in intensity); mass spectrum identical with the spectrum of the dimer of the racemate.

Large amounts of chiral resolved dimer **10**, trimer **11**, and oligomer **12** of monomer **5** were obtained by irradiation of the monomer for periods of 4–6 weeks. The products were separated by column chromatography and purified further by preparative TLC.

Induction Experiments. a. With Chiral Resolved Dimer 10 from the Melt. A 100-mg sample of the monomer and the appropriate amount of the dimer (15, 8, or 3% w/w) were put into closed nitrogen-flushed vials. One set of samples was melted and then cooled to room temperature over a period of several hours. The second set was immersed in a thermostated bath. The temperature of the bath was lowered at a rate of 0.5 °C/2 days starting at a temperature just below the melting point of the sample and continuing until complete crystallization occurred. The samples were kept at this temperature for an additional week. For workup procedure, see below.

b. With Chiral Resolved Trimers 11 and Oligomers 12 of Monomer 5. A 100-mg sample of the monomer and either the trimer (15%, w/w) or the oligomer (8%, w/w) were put into closed nitrogen-flushed vials. The samples were melted and then cooled to room temperature over a period of several hours. For workup procedure, see below.

c. With Chiral Resolved Dimer 10 from Solution.

i. Methylene Chloride. A 100 mg-sample containing 5 or 10% (w/w) of the dimer was dissolved in 2 mL of methylene chloride and the resulting solution filtered. The samples were left to crystallize by evaporation of the solvent (~12 h).

ii. *n*-Hexane. A 100 mg-sample containing 5 or 10% (w/w) of the dimer was dissolved in 3 mL of *n*-hexane (containing a few drops of methylene chloride) and the resulting solution filtered. The samples were left to crystallize by evaporation of the solvent (~24 h).

iii. Ethyl Acetate. A 100 mg-sample containing 5 or 10% (w/w) of the dimer was dissolved in 4 mL of ethyl acetate and the resulting solution filtered. The samples were left to crystallize by evaporation of the solvent (~36 h).

d. With Chiral Dimers 13 and 14. A 100-mg sample of the monomer and a 10% sample (w/w) of the dimer were dissolved in 3 mL of methylene chloride–*n*-hexane and the solution was filtered. The samples were left to crystallize by evaporation of the solvent (~24 h).

e. With Decreasing Amounts of Chiral Resolved Dimer 10. A 100-mg sample of the monomer and the appropriate amount of the dimer (10%, 5%, 3%, 1%, 0.5%, 0.25%, 0.1%, and 0.05%, w/w) were dissolved in 3 mL of methylene chloride–*n*-hexane and the solutions were filtered. The samples were left to crystallize by evaporation of the solvent (~24 h).

Workup Procedure for Induction Experiments. After crystallization, X-ray powder spectra were measured. The crystals were irradiated under Pyrex for ~2 weeks at 5 °C using four 40-W sunlamps. The product dimer was separated from the unreacted monomer, additives, and any higher polymerization products by TLC (silica gel, cyclohexane–ethyl acetate 80:20) and dried under vacuum.

Preferential Adsorption of the Racemic Dimer of Monomer 4 on Chiral Resolved Monomer 5. Three grams of chiral resolved monomer **5** [*R*(−) or *S*(+)] and 300 mg of the racemic dimer of monomer **4** were dissolved in 100 mL of boiling ethanol. The solution was left to cool and crystallize over a period of 24 h during which time approximately half of the monomer precipitated. The crystals were filtered off and dried. The presence of the dimer was established by TLC. The dimer was separated from the monomer by column chromatography and further purified by TLC.

Polymorphism of Monomer 8 (R_1 = *n*-Propyl, R_2 = Ethyl). The monomer was crystallized from solution (methanol or ethanol) or from the melt, and the powdered crystals were subjected to irradiation at 5 °C. The resulting centrosymmetric dimer **15** was isolated as described above. A 100-mg sample of the monomer and a 10% (w/w) sample of **15** were placed in closed vials, kept at the melting point for 48 h, and subsequently fast cooled to room temperature. Dimer **16** was isolated in the usual manner. Blank experiments were also run and yielded, without exception, the centrosymmetric dimer.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, and the U.S.–Israel Binational Foundation, Jerusalem, for support.

Registry No. 1, 73389-61-4; **2**, 73389-59-0; **3**, 76693-51-1; **4**, 64634-78-2; **5a**, 64666-22-4; **5b**, 64666-23-5; **6**, 76724-74-8; **8**, 81408-96-0; **9**, 73389-58-9; (+)-**10**, 81445-52-5; (−)-**10**, 66965-62-6; **11**, isomer 1, 81423-18-9; **11**, isomer 2, 81423-19-0; **12**, isomer 2, 81423-20-3; **12**, isomer 2, 66847-18-5; **13**, 81408-97-1; **14**, 81445-53-6.