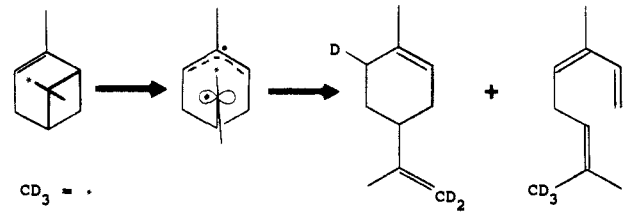
The original (liquid phase) kinetics were reported by Fuquitt and Hawkins[1] who found first-order behavior for all three reactions. A common biradical intermediate was proposed by Burwell.[2] This interpretation was popularized by Frost and Pearson[3] despite the very low activation energy and preexponential term for the formation of dipentene ($\log k = 11.47 - 37000/2.3RT$). Finnish workers studied the reaction in the gas phase and obtained different activation parameters, specifically, a higher activation energy and entropy for the formation of dipentene $\log k$(dipentene) = 13.30 − 40900/2.3RT and $\log k$(alloocimine) = 14.70 − 44500/2.3RT; these workers did not examine the racemization reaction.[4] We report here a reinvestigation of the gas-phase kinetics, including that for racemization, as well as a study of the primary hydrogen isotope effect in the kinetics of formation of products and the position of the label in the major products.

Pyrolyses of (−)-(*S*)-α-pinene (91.2 ± 0.1% optically pure) were conducted in the vapor phase in a vessel pretreated with dichlorodimethylsilane then with diisopropylamine. Without this conditioning, a myriad of products, presumably the same as those observed on GC injector pyrolyses,[5] were observed. Often rate constants drifted upward with concomitant formation of additional products, but the rate constants could be restored to the reported values by reconditioning. The temperature dependence of the rate over a 30 °C range led to the Arrhenius parameters $\log k$(dipentene) = 13.70 (±0.1) − 42000 (±200)/2.303RT, $\log k$(alloocimine) = 14.40 (±0.1) − 44000 (±200)/2.303RT, and $\log k$(enantiomer) = 14.5 (±0.9) − 45200 (±2000)/2.303RT, where the error limits are one standard deviation. The racemization was followed by GC on an α-cyclodextrin column.[6] The limonene formed had $[\alpha]_D$ −4°; thus, 4% of the *S* enantiomer and 96% of a racemic mixture (dipentene) were formed. It is important to note that the Arrhenius parameters for formation of dipentene are higher than in all previous reports.

When *syn*-7-(trideuteriomethyl)-α-pinene[8] was pyrolyzed at 256.7 °C, the rate of loss of starting material slowed by only 15 ± 15%, yet the ratio of dipentene to alloocimine dropped by a factor of 1.70 (±0.05). Since a primary hydrogen isotope effect is expressed in the product distribution but not in the rate, there must be an intermediate formed after the rate-determining step unless there is an unprecedented inverse kinetic isotope effect on the retro 2 + 2 reaction. The slight rate retardation is probably the result of some additional reclosure of the intermediate back to α-pinene, a reaction of significance as judged by its occurrence with a rate roughly 15% that of the other two processes.

A biradical is the likely intermediate for the two major processes, so its structure is of concern. Three observations bear on this question: (a) the dipentene is nearly racemic; (b) the deuterium distribution in the dipentene reveals that twice as much deuterium is transferred as hydrogen; (c) the alloocimine has more than 90% of the deuterium in the *Z* methyl group.[9] The preferential transfer of deuterium is unprecedented *if both C-6 methyls were equally disposed to transfer hydrogen.* It can only be concluded that the syn methyl resides over the allylic radical on the bisector of this necessarily achiral species.



Simple stretching of the C-1,C-6 leads to nearly the correct biradical geometry. What little twist is necessary about the C-5,C-6 bond is in the same sense as in all cyclobutane ring openings that appear to be nonconcerted on the basis of activation energies being comparable to the estimated dissociation energy of the bond being broken.[10] While not specifically determined, the stereomode of the 1,3-shift to give enantiomerized α-pinene is probably the suprafacial-inversion mode if the biradical described above closes to the 1,3-shift product with least motion control. The observation of such stereochemistry, however, could not be attributed to conservation of orbital symmetry in a concerted reaction unless such control is expressed in the ring opening only and is relinquished necessarily, vide infra, in the form of an intermediate whose least motion ring closure would give what would appear to be the "allowed" product. Such an ad hoc rationalization, however, could not be applied to the suprafacial-inversion 1,5-carbon shift in bicyclo[4.1.1]octa-2,4-diene.[8]

Acknowledgment. We thank the National Science Foundation for generous financial support, Prof. W. T. Borden for experimental details to prepare the trideuterio-α-pinene, Professor P. Magnus for nopinone, and Prof. W. R. Dolbier, Jr., for a copy of Dr. Fuguitt's Ph.D. Thesis at the University of Florida.

(1) Fuquitt, R. E.; Hawkins, J. E. *J. Am. Chem. Soc.* **1945**, *67*, 242. Fuquitt, R. E.; Hawkins, J. E. *J. Am. Chem. Soc.* **1947**, *69*, 319.
(2) Burwell, R. H., Jr. *J. Am. Chem. Soc.* **1951**, *73*, 4461.
(3) Frost, A. A.; Pearson, R. G. "Kinetics and Mechanism", 2nd ed.; Wiley: New York, 1961; pp 373–378.
(4) Riistoma, K.; Harva, O. *Finn. Chem. Lett.* **1974**, 132.
(5) Crowley, K. J.; Traynor, S. C. *Tetrahedron* **1978**, *34*, 2783.
(6) Sybilska, D.; Koscielski, T.; Jurczak, J. *J. Chromatogr.* **1983**, *280*, 131. Sybilska, D.; Koscielski, T. *J. Chromatogr.* **1983**, *261*, 357.
(7) Aldrich Catalog/Handbook of Fine Chemicals, 1984–1985.
(8) Borden, W. T.; Lee, J. G.; Young, S. D. *J. Am. Chem. Soc.* **1980**, *102*, 4841.
(9) The double bond in allocimine is *E* as judged by the large proton coupling constant. A heteronuclear 2D NMR experiment revealed that the upfield methyl ^{13}C resonance was associated with the deuterium, and the *Z* methyl resonance is normally the upfield one. Further, the proton resonances of the double-bond methyl groups have been assigned in a variety of related materials (Bellamy, A J.; Crilly, W. *J. Chem. Soc., Perkins Trans. 2* **1973**, 122] and are consistent with the assignments above.
(10) Gajewski, J. J. "Hydrocarbon Thermal Isomerizations"; Academic Press: New York, 1981; p 220.

A Transacylase Partial Mimic[1]

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The serine transacylases combine a complexing site with three cooperating functional groups: a serine hydroxyl, a histidine imidazole, and an aspartate carboxyl. In past work, compounds **1** and **3** were prepared in an incremental approach to serine transacylase mimics.[2] Compound **3** in $CDCl_3$ with R_3N–R_3NHClO_4 buffer at 25 °C reacted with **8** with an estimated second-order rate constant $\sim 10^{11}$ times that of nonbonding model compound **9**. A thirty-step synthesis of **5** has now been completed which also provided **4**, **6**, **7**, and **11**. Other studies provided **2**.[4]

Here we report that **5** and **9** very rapidly reacted at 0.012 M in 20% pyridine-d_5–80% $CDCl_3$ (by volume) to produce **12**, which $\sim 10^2$ more slowly gave **13**.[5] Only the N-3 nitrogen of the imidazole can accept and donate the acyl group without strain in the **5**·**8** complex (CPK molecular model examination).[6,7] Table

(1) We thank the U. S. Public Health Service for Grant GM 12640, which supported this research.
(2) (a) Cram, D. J.; Katz, H. E. *J. Am. Chem. Soc.* **1983**, *105*, 135–137. (b) Cram, D. J.; Katz, H. E.; Dicker, I. B. *Ibid.* **1984**, *106*, 4987–5000.
(3) Cram, D. J.; Lam, P. Y.-S. *Tetrahedron*, in press.
(4) Miesch, M.; Cram, D. J., unpublished results, compound fully characterized.
(5) Formation and disappearance of **12** was followed at 25 °C with the ^1H NMR signal at δ 8.52 due to the C-2 proton of acylated imidazole.
(6) Attempts to isolate **13** free of hydrolysis product failed, although a FAB-MS (Xe) of impure **13** gave a strong peak for **13** + H_2O − ClO_4.

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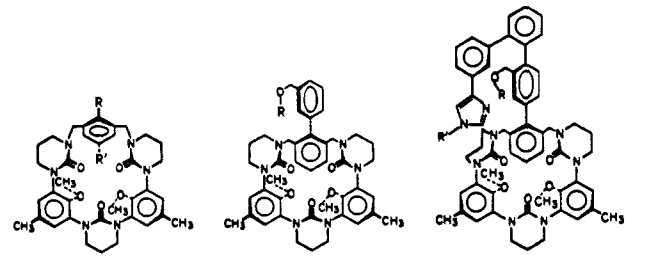


1, R = OCH_3, R' = CH_3

2, R = R' = H

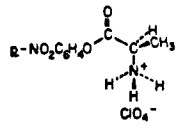
3, R = H

4, R = CH_3

5, R = R' = H

6, R = CH_2OCH_3, R' = H

7, R = CH_2OCH_3, R' = Ph_3C



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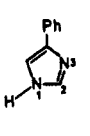
9



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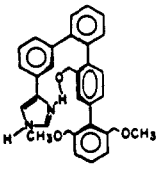

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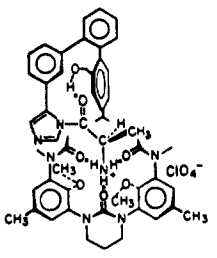

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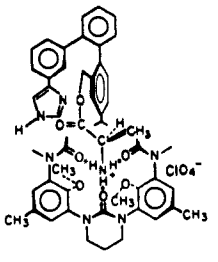

13

I reports the pseudo-first-order rate constants (k_{obsd}) for **8** reacting with 15 or more equiv of nucleophile in $CDCl_3$—0.03% by volume in $(CD_3)_2NCDO$.[8]

The factors by which various nucleophiles exceed imidazole **10** in k_{obsd} values (k_{obsd}^a/k_{obsd}^b of Table I) provide these conclusions. (1) The hydroxyl of **5** participates little in the rate-determining step within complex **5·8** since both **5·8** and **6·8** provide similar factors of $>10^5$ (runs 10 and 13, respectively). Competitive complexation by an added mole of Na^+ per mole of **5** or **6** (runs 11 and 14, respectively) depresses these factors by $\sim 10^3$.[9] The hydroxyl of the noncomplexing model **11** increases the factor by $\sim 10^1$ (run 9). (2) Complexation not only gathers and orients the reactants but it also activates the acyl donor toward external nucleophiles such as **10**. Thus **4·8** and **3·8** provide factors of 10^3–10^4 (runs 6 and 7, respectively). Furthermore, complex **2·8** reacted with D_2O in $CDCl_3$ about 10^1 faster than uncomplexed **8** (compare runs 3 and 4). (3) Saturation of the medium with D_2O ($\sim$0.046 M) increases the factor by values of 2–15 when the nucleophile is not complexed to **8** (runs 3–5) but decreases the factor by $\sim 10^1$ when the nucleophile complexes **8** (runs 12 vs. 10, and runs 15 vs. 13). Possibly the complexes were nonproductively hydrogen bonded to water in runs 12 and 15. (4)

(7) Others have shown the imidazole of chymotrypsin was acylated first by esters of nonspecific substrates (Hubbard, C. D.; Kirsch, J. F. *Biochemistry* **1972**, *11*, 2483–2493). Acylimidazoles are intermediates in many reactions involving protease model systems, e.g.: Ihara, Y. I.; Nango, M.; Kimurai, Y.; Kuraki, N. *J. Am. Chem. Soc.* **1983**, *105*, 1252–1255. No evidence exists to our knowledge that acylimidazoles intervene on the catalytic pathway when alcohols or amines are leaving groups in reactions catalyzed by the transacylases.

(8) Reactions were followed at 25.0 ± 0.1 °C by appearance of *p*-nitrophenol (UV cell, 340 nm) (8–30 points). The medium was 0.0015 M in nucleophile and in additive (except D_2O, which was at saturation, $\sim$0.046 M) and 0.0001 M in **8**. Substraction of rate constants for medium alone from those with nucleophile and (or) additive gave k_{obsd} (r = 1.000–0.975, least-squares linear-regression analysis, reproducible within 10–20%, average of duplicate or triplicate determinations).

(9) Sodium picrate binds **5** and **6** better than methylammonium picrate in $CDCl_3$–D_2O at 25 °C.[3]

Table I. Rate Constant Factors for Acyl Transfer from L-Alanyl *p*-Nitrophenyl Ester Salt[a] (**8**) to Nucleophile[b]

run	nucleophile: kind	nucleophile: additive	$k_{obsd} \times 10^5$, s^{-1}	$(k_{obsd}^a/k_{obsd}^b)^c$
1	**10**	none	0.15	1
2[d]	**10**	**9**	0.16	1
3	**10**	D_2O	0.33	2
4	**10**	**2** + D_2O	2.2	15
5	D_2O	**2**	0.70	5
6	**10**	**4** + **9**	250	1700
7[d]	**10**	**3**	1000	6700
8[d]	**3**	none	58	390
9[d]	**11**	none	1.1	7
10[d]	**5**	none	32000	210000
11	**5**	$NaClO_4$	25	170
12	**5**	D_2O	2250	15000
13[d]	**6**	none	44000	290000
14	**6**	$NaClO_4$	11.5	77
15	**6**	D_2O	7400	49000
16	**7**·H_2O	none	1.2	8

[a] For convenience, the D configuration is formulated in **8**, **12**, and **13**. [b] Saturation kinetics were demonstrated in control runs for **3**, **5**, and **6**. [c] See ref 11. [d] Rate constants were unaffected by the presence of 2,4,6-trimethylpyridine at 0.003 M concentration.

Possibly water was hydrogen bonded to the OCH_2OCH_3 group of **7·8**·H_2O and was acylated by an alkyl–acylimidazole intermediate to provide the factor of $\sim 10^1$ observed in run 16.[10]

The disadvantages of comparing rate constants of reactions with different molecularities are avoided by referring to *uncomplexed* **8** and nucleophiles as *standard starting states* and the rate-limiting transition states as the *standard final states*.[2b,11] In the equation, $k_a/k_b = (k_{obsd}^a/k_{obsd}^b)K_a[\mathbf{10}]$, k_a is the calculated second-order rate constant for reaction of complexing nucleophile, k_b is the second-order rate constant for [**10**] reacting with **8**, and K_a is the association constant for nucleophile complexing **8**.[2b,11] The k_a/k_b value for **3** is 6×10^8 (run 8), for **5**, 3×10^{10} (run 10), for **5** in $CDCl_3$–D_2O, 2×10^9 (run 12), for **6**, 4×10^{11} (run 13), for **6** in $CDCl_3$–D_2O, 7×10^{10} (run 15), and for **7**·H_2O, 10^8 (run 16, Table I).[12] The greatest rate constant increase is provided by host nucleophile **6**, whose hydroxyl group is protected and whose imidazole and complexing site work cooperatively to stabilize the

(10) Attempts (temperatures of 150 °C and high vacuum) failed to remove the last mole of water from **3**–**7**.

(11) In eq 1 and 2, gL is **8**, hNuH is **3**, **5**, **6**, or **7**·H_2O, LH is *p*-

$$gL + hNuH \xrightarrow{k_a} gNuH + LH \qquad gL + hNuH \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} gL{\cdot}hNuH \quad (1)$$

$$K_a = k_1/k_{-1} \qquad gL{\cdot}hNuH \xrightarrow{k} gNuh + LH \quad (2)$$

$NO_2C_6H_4OH$, gL·hNuH is **3·8**, **5·8**, **6·8** or **7·8**·H_2O, and gNuh are compounds such as **12**. With K_a very high valued, at working concentrations of reactants, and with $k_{-1} > k$, the second-order rate constant (k_a) for acylation of hNuH by gL is expressed by eq 3. The reaction of **8** with phenylimidazole (**10**) to

$$k_a = k_{obsd}^a K_a, \ M^{-1}\ s^{-1} \quad (3)$$

give alanylphenylimidazole (AP) and LH is presumed to involve a bimolecular mechanism with a second-order rate constant, k_b. With [**10**] > [**8**] eq 4

$$\mathbf{8} + \mathbf{10} \xrightarrow{k_b} AP + LH \qquad k_b = k_{obsd}^b/[\mathbf{10}], \ M^{-1}\ s^{-1} \quad (4)$$

applies, which combined with eq 3 gives 5 (see ref 2b for qualifications of this

$$k_a/k_b = (k_{obsd}^a/k_{obsd}^b)K_a[\mathbf{10}] \quad (5)$$

treatment). In the runs of Table I, the concentration of **8** was always 0.0001 M, and those of **2**–**6**, **7**·H_2O, and **9**–**11** were always 0.0015 M.

(12) The K_a values for hosts **1**, **3**, and **5**–**7** binding the picrate salts of Li^+, Na^+, K^+, Rb^+, Cs^+, NH_4^+, $CH_3NH_3^+$, and *t*-$BuNH_3^+$ at 25 °C in $CDCl_3$–0.2% D_2O vary from 10^7 to 10^{11} M^{-1}.[2b,3] The values for $CH_3NH_3^+$ fall around the middle of this range: for **3**, 2.2×10^9 M^{-1}; for **5**, 2.2×10^8 M^{-1}; for **6**, 4.1×10^9 M^{-1}; for **7**, 5.5×10^{10}.[2b,3] In the same medium, chorand hosts complex *t*-$BuNH_3ClO_4$ with K_a values $\sim$60 times those for *t*-$BuNH_3Pic$ [Moore, S. S.; Tarnowski, T. L.; Newcomb, M.; Cram, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 6398–6405]. These comparisons provide the following conservative estimates for the binding of $CH_3CH(CO_2C_6H_4NO_2\text{-}p)NH_3ClO_4$ in $CDCl_3$–0.03% $(CD_3)_2NCDO$: for **3**, $K_a \sim 10^9$ M^{-1}; for **5**, 10^8 M^{-1}; for **6**, 10^9 M^{-1}; for **7**, 10^{10} M^{-1}. These estimates are 10^2 to 10^3 lower than those expected for $CH_3NH_3ClO_4$ in $CDCl_3$–0.03% $(CD_3)_2NCDO$.

transition state by complexation. Interestingly, the 4×10^{11} factor for **6** is comparable to the $\sim 10^{11}$ factor observed when **3** was similarly compared to noncomplexing **9** as a standard in the same medium but with R_3N/R_3NHClO_4 buffer present to deprotonate the hydroxyl of **3**. The R_3N present is $>10^4$ stronger as a base than the phenylimidazole group of **5** or **6**. Thus, covalently bonding a complexing site to an imidazole as in **5** or **6** provides large kinetic transacylation factors without addition of bases stronger than those present in the transacylase enzymes.

In semiquantitative experiments, catalytic turnover was observed at 25 °C in $CDCl_3$ saturated with D_2O with **6** or **10** as catalyst.[13] Without catalyst, the hydrolysis of **8** had a 50-h half-life. With **10** present, 1.5 equiv of **8** hydrolyzed in 2 h. Host **6** produced a catalytic rate initially 3 times that of **10**, but the alanine produced acted as an inhibitor and slowed the rate until its crystallization maintained a steady state of turnover of about 1 equiv per 3–4 h. Addition of 25 equiv of **8** and 30 equiv of 2,4,6-trimethylpyridine (divided into five equal increments, one per day) to 1 equiv of **6** hydrolyzed all of the **8**, after which 63% of pure **6** was recovered. In the same medium, **5** reacted initialy faster than **10** but slower than **6** in reacting with **8**. Spectral experiments (^1H NMR) suggested that conformationally isomeric esters of **13** were produced in a 3:2 ratio at about 5–10 times the rate at which alanine was generated.

(13) The catalyst concentration was 0.01 M, that of **8** was initially 0.05 M, and 2,4,6-trimethylpyridine was 0.06 M. Liberation of *p*-nitrophenol (ArH protons give signals downfield of 8 ppm) was monitored by ^1H NMR spectra with tetrachloroethane as internal standard. The 2,4,6-trimethylpyridine was added to potentially buffer the accumulating *p*-nitrophenol as it was produced. The p*K*a values of *p*-nitrophenyl in water [Gordon, A. J., Ford, R. A., Eds. "The Chemists Companion"; Wiley: New York, 1972; p 61], protonated 2,4,6-trimethylpyridine [Pritchard, J. G., Long, F .A. *J. Am. Chem. Soc.* **1957**, *79*, 2365–2368], and protonated phenylimidazole [Potts, K. T., Ed. "Comprehensive Heterocyclic Chemistry"; 4A, Pergamon Press: Oxford, 1984: Vol, *5*, p 384] are 7.2, 7.4, and 6.1, respectively.

Trans–Cis Photoisomerization of 3-Styryl-2′,4′,6′-triisopropylstilbene: Steric Effects on Location of the Electronic Excitation

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Received September 3, 1985

We have recently studied the photocyclization reaction of 2,4,6-triisopropylbenzophenone and its polycarbonyl derivatives into the corresponding benzocyclobutenols in great detail.[1] Spectroscopic and photokinetic examinations of this reaction have led to the conclusion that excited states of meta-substituted aromatic polyketones can be represented by rapid intramolecular energy migration between the component carbonyl groups and, furthermore, that the electronic excitation resides predominantly at the strained carbonyl group ($K = k_{et}/k_{-et} >> 1$) (Scheme Ia).[1,2] We here present another reaction showing steric control of partitioning of the electronic excitation in polychromophoric molecules.

The trans,trans isomer (**1a**) of 3-styryl-2′,4′,6′-triisopropylstilbene was irradiated in hexane (0.01 M) under bubbling nitrogen with Pyrex-filtered light (>290 nm) and the progress of the reaction was followed by HPLC analyses. Isomerization to the trans,cis isomer **1b** (a major product) and the cis,trans isomer **1c** (a minor product) occurred immediately after exposure to light.

(1) Ito, Y.; Kawatsuki, N.; Giri, B. P.; Yoshida, M.; Matsuura, T. *J. Org. Chem.* **1985**, *50*, 283 and references cited therein.

(2) The preferential energy migration toward the strained carbonyl group ($K >> 1$) was ascribed to the entropy factor associated with the hindered rotation around bonds a and b.[1]

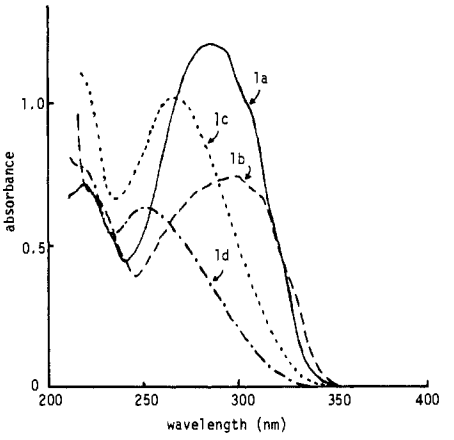
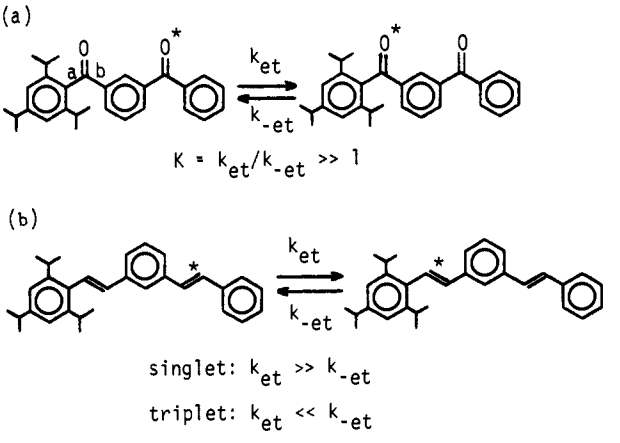
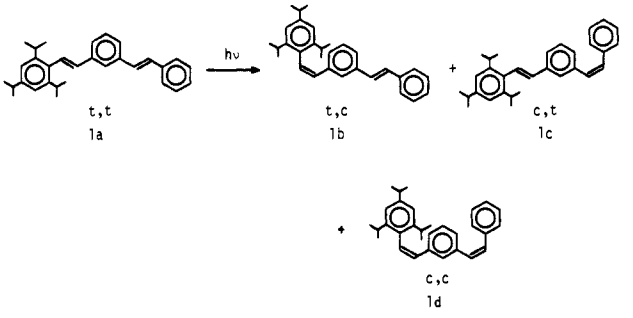


Figure 1. Absorption spectra for 3-styryl-2′,4′,6′-triisopropylstilbenes in hexane: **1a**, 3.0×10^{-5} M (—); **1b**, 2.5×10^{-5} M (- - -); **1c**, 3.1×10^{-5} M (•••); **1d**, 2.7×10^{-5} M (•-•).

Scheme I



Accumulation of the cic,cis isomer **1d** started only after significant amounts of **1b** and **1c** were formed. This fact precludes the possibility of two-double-bond isomerization (**1a** → **1d**) by one photon. Upon extended irradiation a photostationary mixture of the four isomers was reached (**1a**, 8%; **1b**, 20%; **1c**, 31%; **1d**, 41%), but several uncharacterized byproducts were slowly formed.



The four isomers were separated by column chromatography on silica gel using hexane as eluent. Their structures could be unequivocally determined by analyzing their 400-MHz NMR spectra. The signals for olefinic protons and ortho isopropyl methyls were as follows: **1a**, δ 7.16 (2 H, s), 7.23 and 6.51 (2 H, AB, J = 16.4 Hz), 1 22 (12 H, d, J = 7.0 Hz); **1b**, δ 6.85 and 6.70 (2 H, AB, J = 16.4 Hz), 6.69 and 6.67 (2 H, AB, J = 12.3 Hz), 1.16 (6 H, d, J = 6.8 Hz), 0.99 (6 H, d, J = 6.8 Hz); **1c**, δ 6.95 and 6.35 (2 H, AB, J = 16.5 Hz), 6.66 and 6.62 (2 H, AB, J = 12.3 Hz), 1.17 (12 H, d, J = 6.8 Hz); **1d**, δ 6.62 and 6.54 (2 H, AB, J = 12.4 Hz), 6.50 and 6.38 (2 H, AB, J = 12.2 Hz), 1.14 (6H, d, J = 6.8 Hz), 0.97 (6H, d, J = 6.8 Hz). The methyl signal of the ortho isopropyl group in **1b** and **1d** appeared as two doublets owing to slow rotation of the triisopropylphenyl ring on the NMR time scale, supporting the cis configuration of the

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