above. The resulting mixture was worked up as described above. Subsequent distillation gave 9.14 g (89% yield) of methyl 2,4-dichlorodecanoate as a 1:1 mixture of the diastereomers, bp 110–113°C (2.0 mm). The structure of each diastereomer was confirmed by spectral data and elemental analysis after isolation by preparative GLC.

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Registry No.—**1**, 57196-88-0; **2**, 53781-38-7; **3**, 33037-20-6; **4**, 57196-89-1; **5**, 34405-09-9; **6**, 57196-90-4; **7**, 57196-91-5; **8a**, 57196-92-6; **8b**, 57196-93-7; $RuCl_2(PPh_3)_3$, 15529-49-4.

Supplementary Material Available. Table II, reporting the physical properties of adducts 1–8 (2 pages), will appear following these pages in the microfilm edition of this volume of the journal.

References and Notes

(1) For part II of this series, see H. Matsumoto, T. Nikaido, and Y. Nagai, *Tetrahedron Lett.*, 899 (1975).
(2) (a) M. Asscher and D. Vofsi, *J. Chem. Soc.*, 1887 (1963); 3921 (1963); (b) S. Murai and S. Tsutsumi, *J. Org. Chem.*, **31**, 3000 (1966); (c) D. J. Burton and L. J. Kehoe, *Tetrahedron Lett.*, 5163 (1966); *J. Org. Chem.*, **35**, 1339 (1970); (d) T. Susuki and J. Tsuji, *Tetrahedron Lett.*, 913 (1968); *J. Org. Chem.*, **35**, 2982 (1970).
(3) Y. Mori and J. Tsuji, *Tetrahedron*, **28**, 29 (1972).
(4) (a) S. Murai, N. Sonoda, and S. Tsutsumi, *J. Org. Chem.*, **29**, 2104 (1964); (b) Y. Mori and J. Tsuji, *Tetrahedron*, **29**, 827 (1973).
(5) H. Matsumoto, T. Nakano, and Y. Nagai, *Tetrahedron Lett.*, 5147 (1973).
(6) M. S. Kharasch, W. H. Urry, and E. V. Jensen, *J. Am. Chem. Soc.*, **67**, 1626 (1945).
(7) No data are available on the reaction of trichloroacetic acid esters with vinyl monomers catalyzed by peroxides and our investigation has shown that there was obtained only quite low yield of the 1:1 adduct when a 3:1 mixture of ethyl trichloroacetate and styrene was heated in the presence of 2 mol % (based on the olefin charged) of benzoyl peroxide at 80°C for 15 hr.
(8) T. A. Stephenson and G. Wilkinson, *J. Inorg. Nucl. Chem.*, **28**, 945 (1966).

A Stereoselective Total Synthesis of *exo*- and *endo*-Brevicomin

Philip J. Kocienski* and Robert W. Ostrow

Department of Chemistry,
State University of New York at Binghamton,
Binghamton, New York 13901

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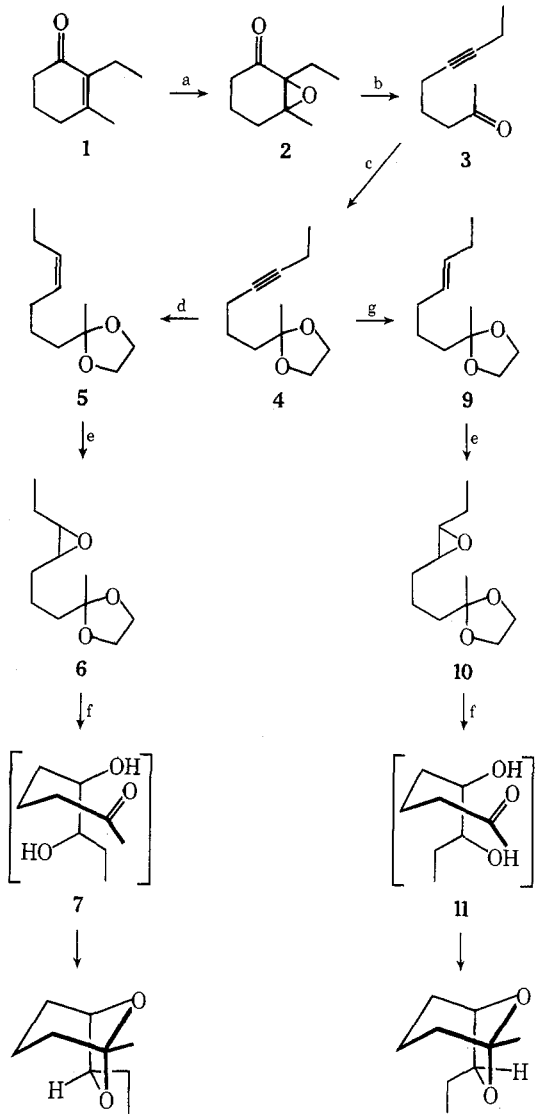
In 1968, Silverstein and co-workers[1] reported the structure determination of *exo*-brevicomin (**8**),[2] the principal sex attractant of the western pine beetle *Dendroctonus brevicomis*. The unusual 6,8-dioxabicyclo[3.2.1]octane skeleton has since been demonstrated in two other sex pheromones: frontalin, from the southern pine beetle *Dendroctonus frontalis*,[3] and multistriatin, from the elm bark beetle *Scolytus multistriatus*.[4] Since the use of *exo*-brevicomin for the manipulation of the mating habits of *D. brevicomis* may provide an ecologically advantageous means for the population control of this destructive insect,[5] we have developed a practical stereoselective synthesis of both *exo*-brevicomin (**8**) and the corresponding endo isomer **12**[6] which should be amenable to large-scale preparation. With one exception,[8] previous syntheses of **8** are inefficient and/or nonstereoselective.[7-10]

The preparation of both *endo*- and *exo*-brevicomin required that our synthetic plan incorporate an intermediate which was sufficiently flexible to permit conversion to both products. The acetylenic ketal **4** seemed ideally suited for this purpose since stereoselective reductions of acetylenes to the requisite cis or trans olefins are well established.

Scheme I[a]



[a] a, H_2O_2–NaOH/MeOH; b, *p*-$TsNHNH_2/CH_2Cl_2$–HOAc; c, $HOCH_2CH_2OH$, H^+; d, BH_3·Me_2S–ether, HOAc; e, *m*-$ClC_6H_4CO_3H$; f, 0.1 *N* $HClO_4$; g, Na–NH_3.

Thus the fulcrum of the synthesis, **4**, was prepared in three steps (73% overall) from the known cyclohexenone **1**[11] as shown in Scheme I. Eschenmoser fragmentation[12] of the epoxy ketone **2** yielded 6-nonyn-2-one (**3**) which incorporated the carbon skeleton appropriately functionalized for eventual conversion to the desired products.

The *exo*-brevicomin (**8**) was prepared in 42% overall yield[13] from the acetylenic ketal **4** by a three-step sequence involving reduction of the acetylene with BH_3·Me_2S followed by protonolysis to give first the cis olefin **5** (75%).[15] Epoxidation of **5** (73%) followed by stereospecific acid-catalyzed cleavage of the resultant cis epoxide **6**[16] with concomitant hydrolysis of the ketal function afforded *exo*-brevicomin (**8**, 72%). No attempt was made to isolate or detect the presumed threo keto diol intermediate **7**. The *exo*-brevicomin thus obtained was contaminated with <1% of the endo isomer **12** by VPC analysis.

Similarly, *endo*-brevicomin (**12**) was prepared in three steps (77% overall) from the acetylenic ketal **4** by Na–NH_3 reduction of **4** to the trans olefin **9** (96%).[15] Epoxidation of **9** (93%) followed by acid hydrolysis gave the intermediate erythro keto diol **11** which cyclized under the reaction con-

ditions to give *endo*-brevicomin (**12**, 86%) which was contaminated with <1% of the exo isomer **8** by VPC analysis.

In contrast with the previous syntheses of **8**,[7-10] the procedure reported herein derives considerable advantage from the fact that all nine carbons of the brevicomin skeleton are already present in the starting enone **1**. Since the starting material is relatively inexpensive and since each step proceeds in good to excellent yield, the sequence described should provide an economical and highly stereoselective source of *exo*- and *endo*-brevicomin.

Experimental Section

Infrared spectra were obtained with a Perkin-Elmer 457 spectrometer; NMR spectra were recorded with Varian A-60 or HA-100 instruments in CCl_4 solution using Me_4Si as internal standard. All yields quoted are based on products by isolated simple distillation. Purity of products was ascertained by VPC using a Perkin-Elmer 3920 gas chromatograph with thermal conductivity detectors. Unless otherwise stated, 4 ft × 0.25 in. 10% SE-30 and/or 10% Carbowax 20M on Chromosorb P (60–80 mesh) columns were used throughout. The *m*-chloroperbenzoic acid (85%) obtained from Eastman Organics was used without further purification. The BH_3·Me_2S was obtained from Aldrich Chemical Co.

2-Ethyl-3-methyl-2,3-epoxycyclohexan-1-one (2). To a solution of 20.2 g (0.146 mol) of 2-ethyl-3-methylcyclohex-2-en-1-one (**1**)[11] in 150 ml of methanol cooled to 10° was added with magnetic stirring 55 ml (0.438 mol) of 30% hydrogen peroxide. While maintaining the temperature between 15 and 20°, 12.2 ml of 6 *N* NaOH (0.073 mol) was added dropwise over 5 min. After addition was complete, the reaction mixture was stirred for 3 hr at 20–22°. The reaction mixture was poured into 600 ml of water and extracted with 2 × 60 ml of ether. The combined organic layers were washed with 2 × 30 ml of water, dried over $MgSO_4$, concentrated in vacuo, and the resultant oil distilled to give 19.2 g (85%) of **2** as a colorless oil: bp 48–49° (0.3 mm); ir (CCl_4) 1710 cm^{-1}; NMR (60 MHz, CCl_4) δ 0.9 (t, 3 H), 1.39 (s, 3 H), 1.5–2.5 (br m, 8 H).

6-Nonyn-2-one (3). To a magnetically stirred solution of 17.7 g (0.115 mol) of epoxy ketone **2** in 115 ml of CH_2Cl_2 and 57 ml of HOAc at 0–2° was added 21.3 g (0.115 mol) of *p*-toluenesulfonylhydrazide in one portion. Stirring was continued at 0–2° for 3 hr followed by 3 hr at room temperature. The reaction mixture was poured into 450 ml of water and extracted with 2 × 200 ml of hexane. The combined organic layers were washed with 2 × 100 ml of water followed by 2 × 50 ml of saturated $NaHCO_3$. After drying over $MgSO_4$ and concentration in vacuo, the resultant oil was distilled to afford 14.5 g (91%) of **3** as a colorless oil: bp 50–51° (0.5 mm); ir (CCl_4) 1712 cm^{-1}; NMR (100 MHz, CCl_4) δ 1.11 (t, 3 H, J = 8 Hz), 1.68 (quintet, 2 H, J = 7 Hz), 2.06 (s, 3 H), 2.0–2.3 (m, 4 H), 2.47 (t, 2 H, J = 7 Hz).

6-Nonyn-2-one Ethylene Ketal (4).[7] A mixture of 14.5 g (0.105 mol) of **3**, 7.15 g (0.115 mol) of ethylene glycol, and 10 mg of *p*-TsOH in 120 ml of benzene was refluxed for 8 hr using a water separator. The cooled solution was washed with 2 × 25 ml of saturated $NaHCO_3$, dried over $MgSO_4$, and concentrated in vacuo. Distillation afforded 18.0 g (94%) of the ketal **4** as a colorless oil: bp 64–65° (0.3 mm); ir (CCl_4) 1070 cm^{-1}; NMR (100 MHz, CCl_4) δ 1.10 (t, 3 H, J = 7 Hz), 1.23 (s, 3 H), 1.4–1.8 (m, 4 H), 1.95–2.30 (m, 4 H), 3.83 (s, 4 H).

***cis*-Non-6-en-2-one Ethylene Ketal (5).** To a magnetically stirred solution of 8.00 g (43.9 mmol) of **4** in 80 ml of ether at 0° was added 1.5 ml (15.8 mmol) of BH_3·Me_2S dropwise via syringe over 5 min. After addition was complete the mixture was allowed to stir under nitrogen at 0° for 30 min whereupon 8 ml of glacial acetic acid was added. Ether was distilled off until the internal temperature reached 60°, an additional 12 ml of acetic acid was added, and the mixture was stirred at 60° for 1.5 hr. The reaction mixture was then poured with rapid magnetic stirring into a solution of 20 g of NaOH in 50 ml of water containing ~50 g of crushed ice. The product was extracted into 2 × 40 ml of hexane, washed with 50 ml of water, dried over $MgSO_4$, and concentrated in vacuo. Distillation afforded 6.29 g (75%) of **5** as a colorless oil:[17] bp 60–62° (0.4 mm); ir (CCl_4) 1060 cm^{-1}; NMR (CCl_4) δ 5.27 (m, 2 H), 3.80 (s, 4 H), 1.8–2.3 (m, 4 H), 1.3–1.8 (m, 4 H), 1.20 (s, 3 H), 0.97 (t, 3 H).

***cis*-6,7-Epoxynonan-2-one Ethylene Ketal (6).** To a magnetically stirred solution of 8.00 g (43.4 mmol) of **5** in 70 ml of CH_2Cl_2 was added 9.45 g (47.6 mmol) of 85% *m*-chloroperbenzoic acid in portions over 30 min while maintaining the temperature below 7°. Stirring was continued at 0° for an additional 30 min after which the mixture was extracted with 25 ml of saturated $NaHSO_3$ and 2 × 50 ml of 1*N* NaOH. Distillation of the product obtained after drying over $MgSO_4$ and concentration in vacuo afforded 6.35 g (73%) of **6** as a colorless oil: bp 86–89° (0.4 mm); ir (CCl_4) 1060 cm^{-1}; NMR (CCl_4) δ 3.8 (s, 4 H), 2.7 (m, 2 H), 1.3–1.8 (m, 8 H), 1.22 (s, 3 H), 1.02 (distorted t, 3 H).

***exo*-Brevicomin (8).** A mixture of 2.86 g (14.3 mmol) of **6** and 14.3 ml of 0.1 *N* $HClO_4$ was rapidly stirred at ambient temperature for 2.5 hr. The product was extracted into 2 × 30 ml of ether and dried over $MgSO_4$. The solvent was removed in vacuo (bath temperature 20°) with a rotary evaporator and the residue distilled via Kugelrohr to give 1.72 g (77%) of *exo*-brevicomin (**8**), bp 70° (bath) (20 mm), having ir and NMR spectra identical with those published of the natural product.[18] The exo isomer (retention time 14.6 min) was contaminated with <1% of the endo isomer **12** (retention time 20.2 min) by VPC (10 ft × 0.25 in. 10% Carbowax 2000 on Chromosorb W, 150°, He flow 20 ml/min).

***trans*-Non-6-en-2-one Ethylene Ketal (9).** To a solution of 7.35 g (40 mmol) of **4** in 70 ml of anhydrous liquid NH_3 at −78° was added 3.0 g (0.13 g-atom) of sodium metal piecewise over a 10-min period. After addition was complete, the blue-colored reaction mixture was allowed to stir at −78° for 30 min. Sufficient solid ammonium chloride was added to discharge the blue color. After evaporation of the ammonia, the residue was dissolved in 75 ml of water and extracted with 2 × 50 ml of ether. The combined ether layers were washed with 2 × 30 ml of water, dried over $MgSO_4$, and concentrated in vacuo. Distillation afforded 7.11 g (96%) of the trans olefin **9** as a colorless oil: bp 50–51° (0.2 mm); ir (CCl_4) 1065, 970 cm^{-1}; NMR (100 MHz, CCl_4) δ 0.97 (t, 3 H, J = 7 Hz), 1.20 (s, 3 H), 1.25–1.70 (m, 4 H), 1.80–2.20 (m, 4 H), 3.81 (s, 4 H), 5.35 (m, 2 H).

***trans*-6,7-Epoxynonan-2-one Ethylene Ketal (10).** To a magnetically stirred solution of 6.24 g (33.9 mmol) of **9** in 65 ml of CH_2Cl_2 cooled to 0° was added in one portion 6.90 g (33.9 mmol) of 85% *m*-chloroperbenzoic acid. After stirring at 0° for 1 hr, the reaction mixture was extracted with 2 × 35 ml of 0.1 *N* KOH and washed with 30 ml of water, and the organic layer was dried over $MgSO_4$. Concentration in vacuo followed by distillation afforded 6.30 g (93%) of the epoxide **10** as a colorless oil: bp 75–78° (0.3 mm); ir (CCl_4) 1250, 1055, 860 cm^{-1}; NMR (100 MHz, CCl_4) δ 0.96 (t, 3 H), 1.22 (s, 3 H), 1.3–1.8 (m, 8 H), 2.4–2.6 (m, 2 H), 3.82 (s, 4 H).

***endo*-Brevicomin (12).** A heterogeneous mixture of 5.15 g (25.7 mmol) of **10** and 25 ml of 0.1 *M* $HClO_4$ was rapidly stirred at ambient temperature for 2.5 hr. The product was extracted into 2 × 50 ml of ether, dried over $MgSO_4$, and concentrated with a rotary evaporator (bath temperature 20°). Kugelrohr distillation [bath temperature 60° (20 mm)] afforded 3.45 g (86%) of *endo*-brevicomin (**12**) which gave ir and NMR spectra identical with those published.[18] Analysis by VPC (10 ft × 0.25 in. 10% Carbowax 2000 on Chromosorb W, 150°, He flow 20 ml/min) showed *endo*-brevicomin (retention time 20.2 min) contaminated with <1% of the exo isomer (retention time 14.6 min).

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Registry No.—**1**, 13679-27-1; **2**, 57237-88-4; **3**, 57237-89-5; **4**, 24403-63-2; **5**, 24381-26-8; **6**, 24381-28-0; **8**, 20290-99-7; **9**, 24381-27-9; **10**, 24381-29-1; **12**, 22625-19-0; ethylene glycol, 107-21-1.

References and Notes

(1) R. M. Silverstein, R. G. Brownlee, T. E. Bellas, D. L. Wood, and L. E. Browne, *Science*, **159**, 889 (1968).
(2) *exo*-Brevicomin is the trivial name for *exo*-7-ethyl-5-methyl-6,8-dioxabicyclo[3.2.1]octane.
(3) The structure of frontalin (1,5-dimethyl-6,8-dioxabicyclo[3.2.1]octane) was determined by G. W. Kinzer, A. F. Fentman, T. F. Page, R. L. Foltz, J. P. Vite, and G. B. Pitman, *Nature (London)*, **221**, 477 (1969).
(4) G. T. Pearce, W. E. Gore, R. M. Silverstein, J. W. Peacock, R. A. Cuthbert, G. N. Lanier, and J. B. Simeone, *J. Chem. Ecol.*, **1**, 115 (1975), reported the structure determination of multistriatin (2,4-dimethyl-5-ethyl-6,8-dioxabicyclo[3.2.1]octane). See also W. E. Gore, G. T. Pearce, and R. M. Silverstein, *J. Org. Chem.*, **40**, 1705 (1975).
(5) W. D. Bedard and D. L. Wood in M. C. Birch, Ed., "Pheromones", American Elsevier, New York, N.Y., 1974, pp 441–449.
(6) The endo and exo isomers are both produced by the monogamous female but only the exo isomer appears to be active (cf. ref 7).

(7) T. E. Bellas, R. G. Brownlee, and R. M. Silverstein, *Tetrahedron*, **25**, 5149 (1969).
(8) H. H. Wasserman and E. H. Barber, *J. Am. Chem. Soc.*, **91**, 3674 (1969). See also J. O. Rodin, C. A. Reece, R. M. Silverstein, V. H. Brown, and J. I. DeGraw, *J. Chem. Eng. Data*, **16**, 380 (1971).
(9) K. Mori, *Tetrahedron*, **30**, 4223 (1974).
(10) B. P. Mundy, K. B. Lipkowitz, and G. W. Dirks, *Synth. Commun.*, **5**, 7 (1975), and references cited therein.
(11) The 2-ethyl-3-methylcyclohex-2-en-1-one was prepared by hydrolysis and decarboxylation of commercial (Aldrich) 2-ethyl-3-methyl-4-carboethoxycyclohex-2-en-1-one as described: L. I. Smith and G. F. Rouault, *J. Am. Chem. Soc.*, **65**, 631 (1943). The decarboxylation reaction did not occur spontaneously under the reaction conditions reported. However, acidification of the crude reaction mixture resulted in vigorous evolution of CO_2 to afford the desired cyclohexenone **1** in 84% yield after one recycling of recovered starting material.
(12) R. K. Müller, D. Felix, J. Schreiber, and A. Eschenmoser, *Helv. Chim. Acta*, **53**, 1479 (1970), and references cited therein.
(13) No attempt has been made to optimize the yields.
(14) To our knowledge, this reaction represents the first application of the relatively inexpensive and safe BH_3·Me_2S reagent for the reductive hydroboration of an acetylene. The use of BH_3·THF or disiamylborane in THF offered no advantage in yield or stereoselectivity and was considerably more expensive.
(15) We were unable to effect a separation of the cis and trans olefins **5** and **9** by VPC. However, an assay of the stereoselectivity of the reduction reactions was possible by an analysis of the corresponding epoxides **6** and **10** which were readily separable (see ref 7). Both **6** and **10** were contaminated with <1% of the corresponding isomer.
(16) J. G. Buchanan and H. Z. Sable in "Selective Organic Transformations", Vol. 2, B. S. Thyagarayan, Ed., Wiley, New York, N.Y., 1972, pp 8–11.
(17) Although the acetic acid was dried by reaction with acetic anhydride in the presence of a trace of *p*-TsOH and every effort maintained to exclude moisture from the reaction mixture during protonolysis of the vinylborane, the product obtained invariably contained anywhere from a trace to ~15% of *cis*-non-6-en-2-one. Reketalization afforded the desired ketal **5**.
(18) R. M. Silverstein, *J. Chem. Educ.*, **45**, 794 (1968).

Communications

Synthetic Photochemistry with the Imide System. Norrish Type II Cyclization of Alicyclic Imides[1,2]

Summary: On irradiation a series of *N*-alkyl-substituted succinimides and glutarimides readily underwent photocyclization to afford ketolactams with ring enlargement by the two-carbon unit derived from the side chain in moderate yields; the efficiencies of the photoreactions of the alicyclic imides were distinctly larger than that for the aromatic counterparts (phthalimides), being comparable with that for simple ketones; the Norrish type II processes were proposed as the mechanism and general synthetic utility of the reaction was discussed.

Sir: In contrast to the extensive studies on photochemistry of common carboxylic acid derivatives such as esters and amides, the photochemical behavior of imides has been scarcely investigated. As part of broadly based studies of synthetic photoreactions of carbonyl derivatives, we have recently explored reactions of the excited states of an *aromatic* imide system, phthalimides.[3] We now wish to report a scheme which characterizes the photochemistry of *alicyclic* imides, and to present evidence which indicates its general synthetic utility.

A series of N-substituted succinimides **1a–i** and glutarimides **1j–m** were irrddiated[4] and the results are listed in Table I. Each major photoproduct was purified in most runs by vacuum distillation and identified by its ir, uv, NMR, and mass spectra and elemental analysis. In all cases ketolactams having two additional carbons in their rings were readily obtained in moderate isolated yields, accompanied by some elimination products (succinimide or glutarimide, 10–30%). In a representative example, the structural assignment for **2c** was based on (i) the presence of a carbonyl [uv 283 nm (ϵ 27); ir 1700 cm^{-1}] and an amide (ir 1660 mm^{-1}); (ii) the presence of the β [NMR 3.80 ppm ($C_\beta H$, m)] and the γ [NMR ~2.6 ppm ($C_\gamma H_2$)] carbons, methyl [1.35 ppm (d)], and NH (7.05 ppm); (iii) the molecular weight and composition, $C_7H_{11}NO_2$ (mass *m/e* 141; elemental analysis). Only one isomer (cis), **2g** and **2m**, was isolated from **1g** and **1m**, respeciively, hhereas a mixture of two stereoisomers, **2h** and **2i**, were obtained from **1h** and **1i**.

Table I
Products of Photolysis of the Cyclic Imides 1[a]

	1				2	
Compds	R_1	R_2	R_3	R_4	%	Mp, °C
			$n = 2$			
a	H	H	H	H	45	139–140
b	H	H	CH_3	H	42	120–121
c	H	CH_3	H	H	56	139.5–140.5
d	H	H	C_2H_5	H	31	85–87
e	H	H	CH_3	CH_3	33	109–110
f	CH_3	CH_3	H	H	49	175–176
g	H	$-(CH_2)_3-$		H	50	192.5–193.5
h	H	$-(CH_2)_4-$		H	42	Mixture
i	H	$-(CH_2)_5-$		H	38	Mixture
			$n = 3$			
j	H	H	H	H	37	117–118
k	H	H	CH_3	H	52	141–142
l	H	H	C_2H_5	H	33	149–150
m	H	$-(CH_2)_3-$		H	28	220–221.5

[a] A 60-W low pressure mercury lamp was used for 30 min, 10m*M* solution in acetonitrile.

The principal feature of the Norrish type II processes of the alicyclic imides is not the elimination but rather the cyclization forming ketolactams with ring enlargement by the two-carbon unit derived from the side chain (Scheme I). Quantum yield of the formation of **2a** was 0.64,[7] which is notably larger than that for the reactions of phthalimides, the aromatic counterparts, by a factor of 50,[8] indicating practical efficiency of the photolysis of the alicyclic imide system. General synthetic potential of the reaction on the basis of structural variation of the substrates is as follows.