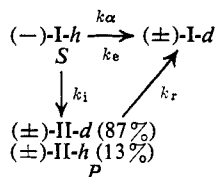


polarimeter cell. To the flask was added quickly 4.84 ml of a stock solution of 0.0712 *N* potassium methoxide in methanol-*O-d* for run 9 (0.0590 *N* for run 10) with a syringe, which was used to rapidly mix the reagents, and transfer 1 ml of the reacting mixture to the polarimeter cell, as described in run 8. A rapid reading of the observed rotation at zero time was facilitated by presetting the analyzer near the expected rotation ( $\sim -5^\circ$ ) independently with a negatively rotating nonreacting solution. The first reading was made within 40 sec after the solution was mixed. Periodic readings were taken at the prescribed times. Eleven readings were taken in run 9 and forty readings were taken in run 10. The data were analyzed as described in the Results section.

#### Appendix. Derivation of the Kinetic Expression for $k_\alpha$

The following definitions are used in the derivation of the kinetic expression for  $k_\alpha$ :  $S_0$  is the initial concentration of (-)-I-*h*,  $S$  is the concentration of optically pure (-)-I-*h* at any time  $t$ ,  $T$  is the total concentration of I at any time,  $f$  is the fraction of total I which is optically pure ( $f = S/T$ ),  $P$  is the concentration of racemic II at any time ( $P = S_0 - T$ ), and  $f_{II}$  is the mole

Chart III



fraction of II at any time. Chart III shows the major reactions involved before enough isotopic exchange of I had occurred to start to effect the amount of isotopic-exchanged ( $\pm$ )-II formed by the reaction ( $\pm$ )-I-*d*  $\rightarrow$  ( $\pm$ )-II-*d*. This chart also serves to define  $k_\alpha$ ,  $k_e$ , and  $k_i$ . The rate of loss of I by isomerization to II is given by eq 6. The rate of loss of optically active material

$$\frac{dT}{dt} = k_r S_0 - (k_r + k_i)T \quad (6)$$

is given by eq 7, which by use of the definition of  $f$  gives eq 8. Solution of eq 6 and 8 for  $df/dt$  and the use of the

$$\frac{dS}{dt} = (k_\alpha + k_i)S \quad (7)$$

$$\frac{df}{dt} = (k_\alpha + k_i)f - \frac{f dT}{T dt} \quad (8)$$

definition of  $f_{II}$  ( $f_{II} = P/T = (S_0/T) - 1$ ) gives eq 9.

$$\frac{df}{dt} = -(k_\alpha + k_r f_{II})f \quad (9)$$

For all aliquots of run 8,  $f_{II} \leq 0.25$ , and  $k_r \approx 10^{-6}$  sec $^{-1}$ . Thus, for run 8,  $k_r f_{II}$  can be neglected to a good approximation, and  $k_\alpha$  calculated.

## (CH)<sub>10</sub>CO<sub>2</sub> Interconversions. The Electrophilic Addition of Chlorosulfonyl Isocyanate to Bullvalene<sup>1</sup>

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Contribution from the Department of Chemistry, The Ohio State University, Columbus, Ohio 43210. Received December 14, 1969

**Abstract:** Treatment of bullvalene with chlorosulfonyl isocyanate afforded  $\beta$ -lactam **3b**  $\rightleftharpoons$  **4b**, lactone **5b**, and lactam **6b**. Longer reaction times and higher temperatures gave greatly reduced yields of the  $\beta$ -lactam. The structure of **3b**  $\rightleftharpoons$  **4b** was deduced from its temperature-dependent nmr spectra. Spectral analysis was also employed for structural assignment to **5b** and **6b**, chemical confirmation of which was achieved by ozonolysis and esterification to dimethyl malonate in each instance. Exposure of **5b** to 30% sulfuric acid at room temperature resulted in rearrangement to lactone **10**, a mechanism for which is suggested. Double- and triple-resonance studies at 100 MHz were employed for structural assignment to this and the ensuing (CH)<sub>10</sub>CO<sub>2</sub> isomers. Photo-rearrangement of **10** led to the formation of three isomeric  $\gamma$ -lactones: **14**, **20**, and **30**. In the cases of **14** and **20**, the rearrangements are believed to be initiated by Norrish type I cleavage of the carbonyl group.

Despite the innate capability of bullvalene (**1**) for degenerate Cope rearrangement to more than 1.2 million equivalent tautomeric forms,<sup>2</sup> little is yet known about the reactivity of this very interesting fluxional molecule.<sup>3</sup> For instance, only two examples

(1) Unsaturated Heterocyclic Systems. LXXI. For the previous paper in this series, see L. A. Paquette, M. F. Wyvratt, and G. R. Allen, Jr., *J. Amer. Chem. Soc.*, **92**, 1763 (1970).

(2) (a) The prediction of these spectacular properties of bullvalene was initially made on theoretical grounds: W. von E. Doering and W. R. Roth, *Tetrahedron*, **19**, 715 (1963); the synthesis of bullvalene was subsequently realized; (b) G. Schröder, *Angew. Chem. Intern. Ed. Engl.*, **2**, 481 (1963); *Chem. Ber.*, **97**, 3140 (1964); (c) R. Merenyi, J. F. M. Oth, and G. Schröder, *ibid.*, **97**, 3150 (1964); (d) W. von E. Doering, B. M. Ferrier, E. T. Fossel, J. H. Hartenstein, M. Jones, Jr., G. Klumpp, R. M. Rubin, and M. Saunders, *Tetrahedron*, **23**, 2943 (1967).

(3) For recent reviews, see (a) G. Schröder, *Angew. Chem. Intern. Ed. Engl.*, **4**, 752 (1965); (b) G. Schröder and J. F. M. Oth, *ibid.*, **6**, 414 (1967).

of electrophilic addition to **1** have been reported, these being bromination<sup>4a</sup> and chlorination.<sup>4b</sup> Our interest in molecules which exhibit rapid and degenerate valence isomerization<sup>5</sup> prompted an investigation of the electrophilic addition of chlorosulfonyl isocyanate (CSI)

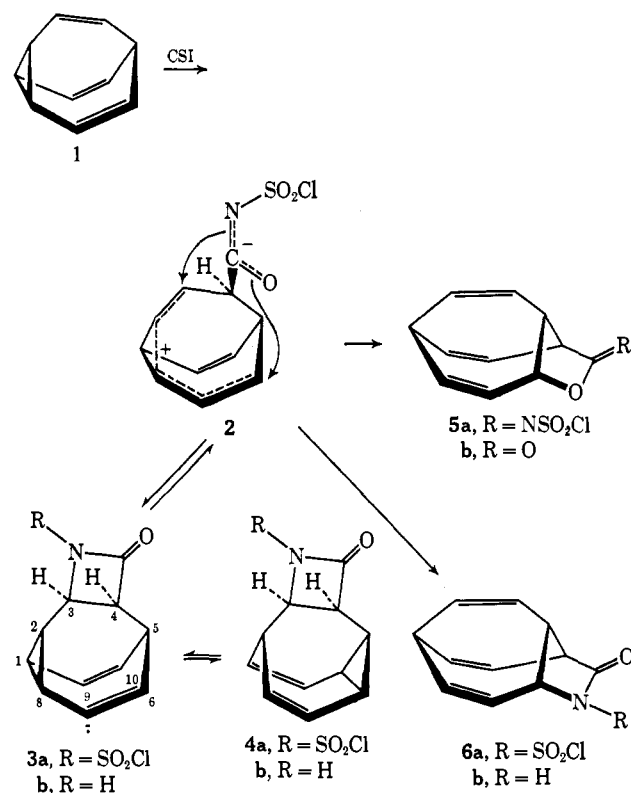
(4) These halogenation reactions have been formulated as 1,4 cyclo-additions: (a) J. F. M. Oth, R. Merenyi, J. Nielsen, and G. Schröder, *Chem. Ber.*, **98**, 3385 (1965); (b) J. F. M. Oth, R. Merenyi, H. Röttele, and G. Schröder, *Tetrahedron Lett.*, 3941 (1968).

(5) (a) L. A. Paquette, J. R. Malpass, G. R. Krow, and T. J. Barton, *J. Amer. Chem. Soc.*, **91**, 5296 (1969); (b) L. A. Paquette, G. R. Krow, and J. R. Malpass, *ibid.*, **91**, 5522 (1969); (c) L. A. Paquette and J. R. Malpass, *ibid.*, **90**, 7151 (1968); (d) L. A. Paquette and G. R. Krow, *ibid.*, **90**, 7149 (1968); (e) L. A. Paquette, G. R. Krow, J. R. Malpass, and T. J. Barton, *ibid.*, **90**, 3600 (1968); (f) L. A. Paquette, T. J. Barton, and E. B. Whipple, *ibid.*, **89**, 5481 (1967); (g) L. A. Paquette and T. J. Barton, *ibid.*, **89**, 5480 (1967); (h) L. A. Paquette, J. R. Malpass, and G. R. Krow, *ibid.*, **92**, 1980 (1970).

to **1**. The dual goals of this study were to realize controlled modes of cycloaddition to **1** and gain synthetic entry to novel polyunsaturated molecules in order to examine their possible structural rearrangements. The present paper describes the results of these studies.

**The Addition of CSI to Bullvalene.**<sup>6</sup> Admixture of equimolar amounts of **1** and CSI in methylene chloride solution at 0°, followed by standing at ambient temperature for 15 min, hydrolysis with thiophenol-pyridine-water in acetone at -25°, and chromatography on Florisil afforded three products. In order of elution, these substances were subsequently characterized as lactone **5b** (31%),  $\beta$ -lactam **3b**  $\rightleftharpoons$  **4b** (19%), and lactam **6b** (15%, see below). Significantly, if the solution was warmed to 40° for 2 hr prior to work-up, the yield of  $\beta$ -lactam dropped to only 2%; **5b** (15%) and **6b** (17%) were the remaining characterizable products. The progress of the cycloaddition reaction could be conveniently followed by both infrared and nmr spectroscopy. In the first instance, there appeared two bands at 1820 and 1770 cm<sup>-1</sup> immediately upon preparation of a 10% solution of **1** and CSI in CHCl<sub>3</sub> at room temperature. Repeated scanning of the 1600-2000-cm<sup>-1</sup> region revealed a gradual diminution in the intensity of the 1820-cm<sup>-1</sup> absorption due to **3a**  $\rightleftharpoons$  **4a** and a corresponding intensification of the 1770-cm<sup>-1</sup> band. Nmr spectroscopy likewise demonstrated that although **3a**  $\rightleftharpoons$  **4a** was produced somewhat faster than either **5a** or **6a** at lower temperatures (10°), the N-(chlorosulfonyl)  $\beta$ -lactams were thermodynamically unstable relative to **5a** and **6a** into which they were

Scheme I

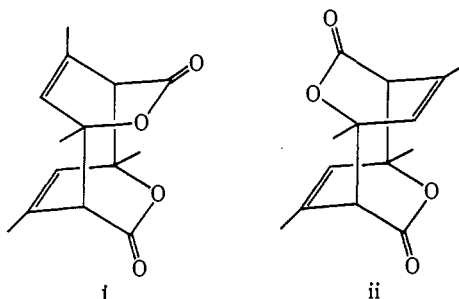


(6) For a preliminary account of a portion of this work, see L. A. Paquette, S. Kirschner, and J. R. Malpass, *J. Amer. Chem. Soc.*, **91**, 3970 (1969).

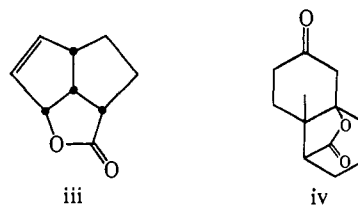
transformed quite rapidly at 38°. Of further import to the mechanism was the observation that execution of the cycloaddition under either of the two previous sets of conditions, but with hydrolysis with the more polar sodium hydroxide-aqueous acetone combination, gave good yields of **5b** and **6b**, and variable but low yields of  $\beta$ -lactam.

Elemental analysis of the first substance to be eluted (**5b**) showed it to be a (CH)<sub>10</sub>CO<sub>2</sub> isomer. The presence of a lactone function was apparent from the intense infrared (CCl<sub>4</sub>) carbonyl stretching frequency at 1765 cm<sup>-1</sup> with a shoulder at 1735 cm<sup>-1</sup>. However, because substantial variations are known to occur in lactone carbonyl stretching frequencies,<sup>7</sup> an unequivocal assignment of a  $\gamma$ - or  $\delta$ -lactone formulation to **6b** was not possible on this basis alone. The ultraviolet spectrum of **5b** (C<sub>2</sub>H<sub>5</sub>OH) showed end absorption only; therefore, the lactone was nonconjugated. The 100-MHz nmr spectrum of **5b** in C<sub>6</sub>D<sub>6</sub> was characterized by well-separated multiplets, spin decoupling of which permitted analysis of all the major coupling constants (Table I).<sup>8</sup> Catalytic hydrogenation of **5b** over 5% Pd-C in methanol solution resulted in the rapid uptake of 3 equiv of hydrogen to yield a hexahydro lactone. The infrared spectrum of this substance exhibited 1758-cm<sup>-1</sup> carbonyl absorption. The degree of unsaturation in this (CH)<sub>10</sub>CO<sub>2</sub> isomer, when coupled with the requirement that no conjugation

(7)  $\delta$ -Lactones. K. K. Cheung, K. H. Overton, and G. A. Sim [*Chem. Commun.*, 634 (1965)] have made the claim that  $\delta$ -lactones can be assigned a boat or a half-chair conformation on the basis of their carbonyl absorptions. According to their data,  $\delta$ -lactones whose carbonyl stretching frequencies are in the 1765-1750 cm<sup>-1</sup> region exist predominantly in boat forms, while those showing  $\nu_{C=O}$  at 1740-1730 cm<sup>-1</sup> can be classified as half-chair forms. Although these correlations have recently been utilized for the purpose of conformational assignment [e.g., K. Sisido, K. Inomata, T. Kageyama, and K. Utimoto, *J. Org. Chem.*, **33**, 3149 (1968)], it is quite clear from the  $\nu_{C=O}$  of i (1760 cm<sup>-1</sup>) and ii (1734 cm<sup>-1</sup>) [P. deMayo and R. W. Yip, *Proc. Chem. Soc.*, 84 (1964); P. deMayo, personal communication] that such assignments are not



unequivocal, particularly in polyunsaturated systems.  $\gamma$ -Lactones. Variations of more than 20 cm<sup>-1</sup> are not uncommon, as borne out by the  $\nu_{C=O}$  of iii [1780 cm<sup>-1</sup>; T. Sakan and K. Abe, *Tetrahedron Lett.*, 2471 (1968)] and iv [1761 cm<sup>-1</sup>; F. Gantochi, O. Jeger, V. Prelog, and R. B. Woodward, *Helv. Chim. Acta*, **37**, 2280 (1954)].



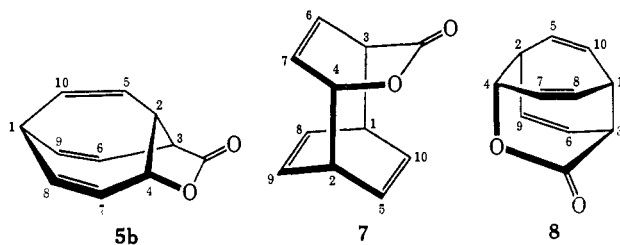
(8) (a) This spectrum was illustrated in the preliminary communication<sup>6</sup>; (b) nmr solvent shifts in lactones have been only very briefly studied: G. DiMaio, P. A. Tardella, and C. Iavarone, *Tetrahedron Lett.*, 2825 (1966).

Table I. Nmr Parameters of Lactone **5b** (100 MHz, C<sub>6</sub>D<sub>6</sub> solution)

Proton assignment	Chemical shift, $\delta$	Multiplicity and spin-spin interactions	Proton(s) irradiated	Result	Coupling constants, Hz
H <sub>1</sub>	2.58	Doublet of doublet of doublets; <sup>a</sup> $J_{1,5}$ ; $J_{1,9}$ ; $J_{1,10}$	H <sub>8</sub> , H <sub>9</sub> H <sub>8</sub> , H <sub>9</sub> , H <sub>10</sub>	Doublet <sup>c</sup> Singlet	$J_{1,8} = 8.8$ $J_{1,9} = 8.8$ $J_{1,10} = 8.2$
H <sub>2</sub>	2.64	Doublet of doublet of doublets; <sup>a</sup> $J_{2,3}$ ; $J_{2,4}$ ; $J_{2,5}$	H <sub>4</sub> H <sub>5</sub>	Doublet of doublets Doublet of doublets	$J_{2,3} = 8.2$ $J_{2,4} = 7.5$ $J_{2,5} = 8.4$
H <sub>3</sub>	2.90	Doublet of doublets; <sup>a</sup> $J_{2,3}$ ; $J_{3,8}$	H <sub>6</sub>	Doublet	$J_{3,6} = 5.5$
H <sub>4</sub>	4.38	Doublet of doublets; $J_{2,4}$ ; $J_{4,7}$	H <sub>2</sub> (H <sub>1</sub> ) <sup>b</sup> H <sub>7</sub> (H <sub>6</sub> ) <sup>b</sup>	Doublet Doublet	$J_{4,7} = 4.6$
H <sub>5</sub>	5.21	Doublet of doublets; <sup>a</sup> $J_{2,5}$ ; $J_{5,10}$	H <sub>2</sub> (H <sub>1</sub> ) <sup>b</sup> H <sub>10</sub>	Doublet Doublet	$J_{5,10} = 9.7$
H <sub>6</sub>	5.47	Doublet of doublets; <sup>a</sup> $J_{3,8}$ ; $J_{6,9}$	H <sub>3</sub> H <sub>9</sub> (H <sub>8</sub> ) <sup>b</sup>	Doublet Doublet <sup>c</sup>	$J_{6,9} = 11.0$
H <sub>7</sub>	5.48	Doublet of doublets; <sup>a</sup> $J_{4,7}$ ; $J_{7,8}$	H <sub>4</sub> H <sub>8</sub> (H <sub>9</sub> ) <sup>b</sup>	Doublet Doublet <sup>c</sup>	$J_{7,8} = 11.0$
H <sub>8</sub>	5.79	Doublet of doublets; $J_{1,8}$ ; $J_{7,8}$	H <sub>1</sub> (H <sub>2</sub> ) <sup>b</sup> H <sub>7</sub> (H <sub>6</sub> ) <sup>b</sup>	Doublet Doublet <sup>c</sup>	
H <sub>9</sub>	5.79	Doublet of doublets; <sup>a</sup> $J_{1,9}$ ; $J_{6,9}$	H <sub>1</sub> (H <sub>2</sub> ) <sup>b</sup> H <sub>8</sub> (H <sub>7</sub> ) <sup>b</sup>	Doublet Doublet <sup>c</sup>	
H <sub>10</sub>	6.08	Doublet of doublets; <sup>a</sup> $J_{1,10}$ ; $J_{5,10}$	H <sub>1</sub> (H <sub>2</sub> ) <sup>b</sup>	Doublet	

<sup>a</sup> Additional allylic coupling was clearly apparent in these instances. Although it was possible to measure  $J_{3,9}$  (1.7 Hz),  $J_{1,5}$  (1.3 Hz), and  $J_{4,8}$  (<0.5 Hz), spin-spin interactions between  $J_{1,8}$ ,  $J_{1,7}$ , and  $J_{2,10}$ , although present were not measurable. <sup>b</sup> Because of the very close proximity of these proton pairs, concomitant partial double irradiation of the proton in parentheses could not be avoided. <sup>c</sup> These absorptions are broad. Also, the multiplets due to H<sub>1,2,3</sub> changed significantly with dilution, a feature which was of considerable utility in the double irradiation experiments.

be present, suggested the possibility of three structures: **5b**, **7**, and **8**.



In view of the observed spin-spin interaction between proton pairs H<sub>2</sub>-H<sub>3</sub> (8.2 Hz) and H<sub>2</sub>-H<sub>4</sub> (7.5 Hz), these three protons must exist in a vicinal relationship such that C<sub>2</sub> is the central atom. Furthermore, H<sub>1</sub> and not H<sub>2</sub> was affected on simultaneous irradiation of H<sub>8,9,10</sub>. On this basis, structures **7** and **8** can be removed from further consideration. In contrast, all of the observed chemical shifts and coupling constants are completely compatible with **5b**. Ultimate confirmation of this assignment was derived from oxidation of the lactone, decomposition of the ozonide with 30% hydrogen peroxide in aqueous formic acid, and esterification with diazomethane. The principal (>90%) volatile product was identified as dimethyl malonate. The expected methanetricarboxylic acid is known to undergo decarbonylation to malonic acid under these conditions.<sup>9</sup>

Cycloadduct **6b** analyzed correctly for (CH)<sub>10</sub>CONH and displayed intense infrared carbonyl absorption at 1696 cm<sup>-1</sup>. It was therefore not a  $\beta$ -lactam; rather, this band was considered characteristic of a larger cyclic amide. In the ultraviolet, the presence of only a weak shoulder at 247 nm ( $\epsilon$  650) was interpreted to mean that this substance lacked extended conjugation.

(9) J. N. Labows, Jr., J. Meinwald, H. Röttele, and G. Schröder, *J. Amer. Chem. Soc.*, **89**, 612 (1967).

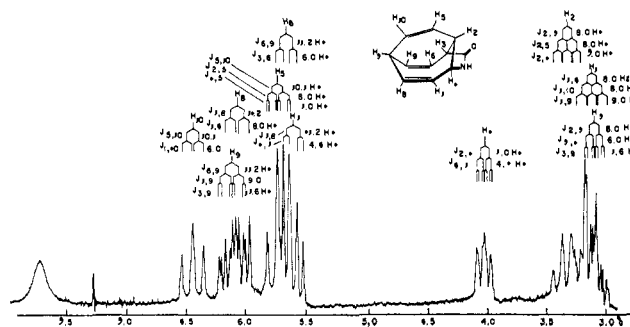


Figure 1. 100-MHz spectrum of **6b** in CDCl<sub>3</sub> at  $\sim 38^\circ$ .

The nmr spectrum of **6b** (Figure 1) revealed a great number of similarities to that of **5b**. Details of the spectral parameters, including double and triple irradiation studies, are summarized in Table II (the numbering is the same as that employed for **5b**). The spin decoupling in this instance enabled a clear distinction to be made between protons H<sub>5</sub>, H<sub>6</sub>, and H<sub>7</sub> since H<sub>2</sub>, H<sub>3</sub>, and H<sub>4</sub> (to which they are respectively coupled) occur at different chemical shifts in contrast to lactone **5b** where H<sub>1</sub> and H<sub>2</sub> are superimposed. H<sub>8</sub> and H<sub>9</sub> were at similar chemical shifts and positive identification could only be made through allylic coupling ( $J_{3,9}$ ) since the vicinal coupling in both instances was to H<sub>1</sub> and to H<sub>6</sub> or H<sub>7</sub> (neither of which could be separately irradiated). Particularly informative was the close correspondence in all the coupling constants for **5b** and **6b** (compare Tables I and II). These data, taken collectively in conjunction with the like ozonolytic degradation to dimethyl malonate, indicated that this lactam possessed structure **6b**.

When **6b** was treated with trimethyloxonium fluoroborate in methylene chloride solution at room temperature for 6 hr, imino ether **9** was obtained in 78% yield. The infrared spectrum (CHCl<sub>3</sub>) showed an in-

Table II. Nmr Parameters of Lactam **6b** (100 MHz, CDCl<sub>3</sub> solution)

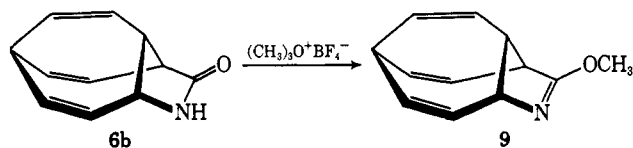
Proton assignment	Chemical shift, $\delta$	Multiplicity and spin-spin interactions	Proton(s) irradiated	Result	Coupling constants, Hz
H <sub>1</sub>	3.12	Doublet of doublets of doublets; <sup>a</sup> $J_{1,8}$ ; $J_{1,9}$ ; $J_{1,10}$	H <sub>8</sub> , H <sub>9</sub> H <sub>10</sub>	Doublet Triplet Singlet	$J_{1,8} = 8.0$ $J_{1,9} = 9.0$ $J_{1,10} = 8.0$
H <sub>2</sub>	3.32	Doublet of doublets of doublets; <sup>a</sup> $J_{2,3}$ ; $J_{2,4}$ ; $J_{2,5}$	H <sub>4</sub> H <sub>5</sub> (H <sub>6</sub> , H <sub>7</sub> ) <sup>b</sup>	Triplet Doublet of doublets	$J_{2,3} = 8.0$ $J_{2,4} = 7.0$ $J_{2,5} = 8.0$
H <sub>3</sub>	3.10	Doublet of doublets of doublets; $J_{2,3}$ ; $J_{3,8}$ ; $J_{3,9}$	H <sub>6</sub> H <sub>9</sub>	Doublet Doublet of doublets	$J_{3,8} = 6.0$ $J_{3,9} = 1.6$
H <sub>4</sub>	4.02	Doublet of doublets; <sup>a</sup> $J_{2,4}$ ; $J_{4,7}$	H <sub>2</sub> H <sub>7</sub> (H <sub>5</sub> , H <sub>6</sub> ) <sup>b</sup>	Doublet Doublet	$J_{4,7} = 4.4$
H <sub>5</sub>	5.73	Doublet of doublets of doublets; $J_{1,5}$ ; $J_{2,5}$ ; $J_{5,10}$	H <sub>2</sub> H <sub>1</sub> (H <sub>3</sub> ) <sup>b</sup> H <sub>10</sub>	Broad doublet Doublet of doublets Doublet	$J_{1,5} = 1.0$ $J_{5,10} = 10.1$
H <sub>6</sub>	5.65	Doublet of doublets; <sup>a</sup> $J_{3,8}$ ; $J_{6,9}$	H <sub>3</sub> (H <sub>1</sub> ) <sup>b</sup> H <sub>9</sub>	Doublet Doublet	$J_{6,9} = 11.2$
H <sub>7</sub>	5.59	Doublet of doublets; <sup>a</sup> $J_{4,7}$ ; $J_{7,8}$	H <sub>4</sub> H <sub>8</sub>	Doublet Doublet <sup>c</sup>	$J_{7,8} = 11.2$
H <sub>8</sub>	6.07	Doublet of doublets; <sup>a</sup> $J_{1,8}$ ; $J_{7,8}$	H <sub>1</sub> (H <sub>3</sub> ) <sup>b</sup> H <sub>7</sub> (H <sub>5</sub> , H <sub>6</sub> ) <sup>b</sup>	Doublet Doublet <sup>c</sup>	
H <sub>9</sub>	6.11	Doublet of doublets of doublets; $J_{1,9}$ ; $J_{3,9}$ ; $J_{8,9}$	H <sub>1</sub> (H <sub>3</sub> ) <sup>b</sup> H <sub>1</sub> (H <sub>3</sub> )	Doublet Doublet	
H <sub>10</sub>	6.44	Doublet of doublets; $J_{1,10}$ ; $J_{5,10}$	H <sub>1</sub> (H <sub>3</sub> ) <sup>b</sup> H <sub>5</sub> (H <sub>6</sub> , H <sub>7</sub> ) <sup>b</sup>	Doublet Doublet	

<sup>a</sup> Additional allylic coupling was clearly apparent in these instances; all values were less than 1 Hz and were difficult to measure accurately because of the overlap of certain proton chemical shifts. <sup>b</sup> Because of the very close proximity of these proton pairs, concomitant partial double irradiation of the proton(s) in parentheses could not be avoided. <sup>c</sup> These absorptions are broad.

Table III. Nmr Parameters of  $\beta$ -Lactam **3b** = **4b** (100 MHz, CD<sub>3</sub>OD solution,  $\sim 38^\circ$ )

Proton assignment	Chemical shift, $\delta$	Multiplicity and spin-spin interactions	Proton(s) irradiated	Result	Coupling constants, Hz
H <sub>5</sub>	2.15	Doublet of doublets of doublets; $J_{4,5}$ ; $J_{5,6}$ ; $J_{5,10}$	H <sub>4</sub> H <sub>8</sub> , H <sub>10</sub>	Triplet Doublet	$J_{4,5} = 6.0$ $J_{5,6} = 8.6$ $J_{5,10} = 8.6$
H <sub>2</sub>	2.52	Doublet of doublets of doublets; $J_{1,2}$ ; $J_{2,3}$ ; $J_{2,8}$	H <sub>1</sub> , H <sub>8</sub> H <sub>3</sub>	Doublet Triplet	$J_{1,2} = 10$ $J_{2,3} = 5.0$ $J_{2,8} = 10$
H <sub>8</sub> , H <sub>10</sub>	3.13	3-line multiplet; $J_{5,8}$ ; $J_{5,10}$ ; $J_{8,7}$ ; $J_{9,10}$	H <sub>5</sub> H <sub>7</sub> , H <sub>9</sub>	Doublet Doublet	$J_{8,7} = 8$ $J_{9,10} = 8$ $J_{3,4} = 6.0$
H <sub>4</sub>	3.56	Doublet of doublets; $J_{3,4}$ ; $J_{4,5}$	H <sub>5</sub>	Doublet	
H <sub>3</sub>	3.81	Doublet of doublets; $J_{2,3}$ ; $J_{3,4}$		Doublet	
H <sub>1</sub> , H <sub>8</sub>	4.40	4-line multiplet; $J_{1,2}$ ; $J_{1,9}$ ; $J_{2,8}$ ; $J_{7,8}$	H <sub>2</sub> H <sub>7</sub> , H <sub>9</sub>	3-line pattern 3-line pattern	$J_{1,9} = 10$ $J_{7,8} = 10$
H <sub>7</sub> , H <sub>9</sub>	5.89	3-line multiplet; $J_{1,9}$ ; $J_{7,8}$ ; $J_{8,7}$ ; $J_{9,10}$	H <sub>1</sub> , H <sub>8</sub> H <sub>6</sub> , H <sub>10</sub>	Doublet Doublet	
N-H	6.58	Broad singlet			

tense imino ether band at 1634 cm<sup>-1</sup> and the ultraviolet spectrum [shoulder at 245 nm ( $\epsilon$  165)] was very similar to that of its precursor. The 100-MHz nmr spectrum of **9** was examined in both CDCl<sub>3</sub> and C<sub>6</sub>D<sub>6</sub> solution



and it showed the same general features present in the spectra of **5b** and **6b**. However, because of the complexity of the vinyl region a full analysis of the spectrum was not completed.

On the basis of its intense infrared carbonyl band at 1752 cm<sup>-1</sup>, the second product to be eluted from the chromatographic column was recognized to be a

$\beta$ -lactam. Further structural evidence was derived from its 100-MHz spectrum which was found to be temperature dependent,<sup>8a</sup> a property recognized to be typical of *cis*-fused bicyclo[5.1.0]octa-2,5-diene systems.<sup>3</sup> However, because valence isomers **3b** and **4b** are not structurally identical, a difference in ground-state populations is to be expected. Double resonance experiments at 38° permitted detailed analysis of the spectrum and established, *inter alia*, that H<sub>2</sub> is spin coupled to H<sub>1</sub>, H<sub>3</sub>, and H<sub>8</sub>, whereas H<sub>5</sub> is spin coupled to H<sub>4</sub>, H<sub>6</sub>, and H<sub>10</sub> (Table III). The nmr spectra of numerous  $\beta$ -lactams attest to the fact that the proton adjacent to amide nitrogen invariably resonates at lower field than the  $\alpha$ -carbonyl proton;<sup>10</sup> accordingly, H<sub>3</sub> and H<sub>4</sub> can be assigned with certainty to the triplet patterns

(10) Unpublished results from this laboratory.

at  $\delta$  3.81 and 3.56, respectively. Because of the low-field position of  $H_1$  and  $H_8$  ( $\delta$  4.40) in this temperature range, it follows that these two protons experience an average lifetime which has appreciable vinylic character; conversely, the chemical shift of  $H_6$  and  $H_{10}$  ( $\delta$  3.13) requires that these protons reside chiefly in a cyclopropyl environment. These observations are uniquely congruent with the conclusion that **4b** is more stable than **3b**.

The equilibrium constant for this  $\beta$ -lactam mixture at any given temperature can, in principle, be calculated from the equations

$$\delta_m = p\delta_v + (1 - p)\delta_c$$

$$p = (\delta_m - \delta_c)/(\delta_v - \delta_c)$$

$$K_m = p/(1 - p)$$

where  $\delta_m$  is the observed chemical shift at a temperature  $m$  of a proton undergoing rapid exchange,  $\delta_v$  and  $\delta_c$  are the chemical shifts, respectively, of the vinyl and cyclopropyl protons in the absence of rapid exchange, and  $p$  is the mole fraction of one of the isomers.<sup>11</sup> In the present instance,  $\delta_v = 5.82$  and  $\delta_c = 1.80$  (Table IV);<sup>12</sup> at 45°,  $\delta_m$  for the signal due

Table IV. Chemical Shift Differences between  $H_1$ ,  $H_8$ , and  $H_8$ ,  $H_{10}$  at Various Temperatures (100 MHz,  $CD_3OD$  solution)

Temp, °C	$H_1, H_8$ Hz from TMS	$H_8, H_{10}$ Hz from TMS	Difference in chemical shifts, Hz
85 <sup>a</sup>	419.7	311.7	108.0 <sup>c</sup>
76	421.2	309.8	111.4
66	421.4	307.8	113.6
55	421.7	305.2	116.5
45	423	303.5	119.5
31	425	300.0	125.0
45 <sup>b</sup>	436	317.0	119.0
31	438	313.0	125.0
0	443.5	309.5	134.0
-21	446	304.5	142.0
-60	582	180.0	402
-75	582	180.0	402

<sup>a</sup> With benzene added as internal lock. <sup>b</sup> With tetramethylsilane added as internal lock. <sup>c</sup> Estimated accuracy after subtraction of the two values is  $\pm 1$  Hz.

to  $H_1$  and  $H_8$  is seen to be located at  $\delta$  4.36. Thus, the concentration of **4b** at this temperature is 64%.  $K_m$  is then calculated to be 1.78 which represents a standard free-energy difference ( $\Delta G^\circ = 45^\circ$ ) of 365 cal/mol. The cause of the intrinsically higher energy of **3b** is not known at this time.

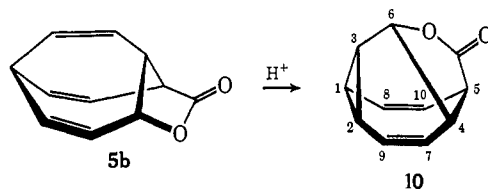
Scheme I summarizes in mechanistic detail the observations described above. It can be deduced from the spectral studies that **3a** isomerizes to **5a** and **6a** at the higher temperatures. Thus, although these 1,2 and 1,6 additions to bullvalene can be satisfactorily

(11) For application of the same principle to conformational analysis, see (a) E. L. Eliel, *Chem. Ind. (London)*, 78 (1959); (b) N. S. Bhacca and D. H. Williams, "Applications of Nmr Spectroscopy in Organic Chemistry," Holden-Day, San Francisco, Calif., 1964, pp 153-154; see also (c) J. A. Pople, W. G. Schneider, and H. J. Bernstein, "High-Resolution Nuclear Magnetic Resonance," McGraw-Hill, New York, N. Y., 1959, Chapter 10.

(12) These values are derived from spectra taken at  $-75^\circ$  or below. Note that as the temperature rises, the two multiplets approach each other corresponding to a trend toward a 50:50 mixture. This trend obeys a linear relationship.

represented by collapse of **2** via four- and five-centered transition states, the operation of a concerted or nearly concerted addition of CSI to **1** followed by irreversible passage of **3a** to **2** cannot be excluded. In actuality, recent developments in the area of CSI cycloadditions would seem to suggest that the latter mechanism is operative.<sup>13</sup>

**Acid-Catalyzed Rearrangement of 5b.** Although acid-catalyzed rearrangements of lactones are relatively few in number, alkyl migrations and 1,2-hydride shifts have been shown to occur most frequently.<sup>14</sup> In view of the  $(CH)_{10}CO_2$  nature of **5b**<sup>15</sup> and the obvious capability of this polyunsaturated system for manifold cationic rearrangements, it was of interest to examine the behavior of this lactone toward acid. Accordingly, **5b** was stirred in 30% aqueous sulfuric acid solution at room temperature for 16 hr. Extraction of the reaction mixture followed by chromatography on Florisil afforded a single isomeric product (**10**) in 58% yield. From an intense band at  $1775\text{ cm}^{-1}$  in its infrared spectrum, the presence of a lactone grouping could be inferred. The ultraviolet spectrum of **10** showed only a weak shoulder at 240 nm ( $\epsilon$  1030), thereby indicating a lack of extended conjugation. The 100-MHz nmr spectrum of **10** (Figure 2) in  $C_6D_6$  solution was particularly informative; not only did it reveal the presence of only four vinyl protons, but decoupling experiments permitted the assignment of nmr signals to the individual protons and the determination of all major coupling constants (Table V).



Specifically, it was noted that **10** contained a cyclopropane ring with  $C_3$  bonded to the carbon atom bearing the oxygen atom of the lactone function ( $C_6$ ), the latter being assigned on the basis of much chemical shift analogy. Another readily discernible point was the fact that  $C_5$  (adjacent to lactone carbonyl) was  $sp^3$  hybridized, with  $H_5$  spin coupled to  $H_4$  ( $C_4$  was also a saturated center) and vinyl proton  $H_{10}$ . Since  $H_4$  interacted likewise with  $H_6$  and  $H_7$ , its position in the molecular framework was secured. Similar analysis of the spin-spin interactions of  $H_8$  and  $H_9$  (Table V) necessitated the formal joining of  $C_1-C_8-C_{10}$  and  $C_2-C_9-C_7$ , respectively. These data could be uniquely reconciled with structure **10**.

(13) T. W. Doyle and T. T. Conway, *Tetrahedron Lett.*, 1889 (1969); E. J. Moriconi and W. C. Meyer, *ibid.*, 3823 (1968).

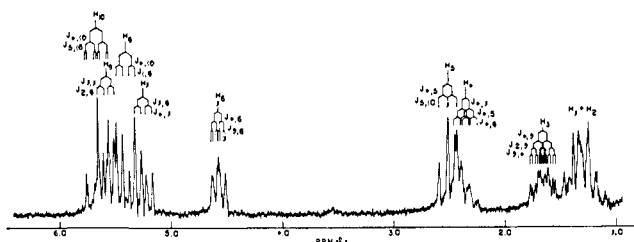
(14) (a) D. S. Noyce, H. I. Weingarten, and L. J. Dolby, *J. Org. Chem.*, 26, 2101 (1961); (b) L. J. Gough, T. F. Sanderson, V. I. Steinberg, and E. Wenkert, *ibid.*, 25, 1269 (1960); (c) L. A. Subluskey and T. F. Anderson, *J. Amer. Chem. Soc.*, 76, 3512 (1954); (d) A. C. Cope, J. M. McIntosh, and M. A. McKervey, *ibid.*, 89, 4020 (1967).

(15) The point we wish to emphasize here is that a compound of formula  $(CH)_{10}CO_2$  is directly related to a  $(CH)_{12}$  isomer by replacement of a  $-CH=CH-$  moiety with a lactone function. The chemistry and interrelationships of the  $(CH)_{12}$  hydrocarbons known to this time are to be found in the following references: (a) G. Schröder, *Chem. Ber.*, 97, 3131 (1964); (b) G. Schröder and W. Martin, *Angew. Chem. Intern. Ed. Engl.*, 5, 130 (1966); (c) J. N. Labows, Jr., J. Meinwald, H. Röttele, and G. Schröder, *J. Amer. Chem. Soc.*, 89, 612 (1967); (d) G. Schröder, W. Martin, and H. Röttele, *Angew. Chem. Intern. Ed. Engl.*, 8, 69 (1969); (e) L. A. Paquette and J. C. Stowell, *Tetrahedron Lett.*, 4159 (1969).

Table V. Nmr Parameters of Lactone **10** (100 MHz, C<sub>6</sub>D<sub>6</sub> solution)

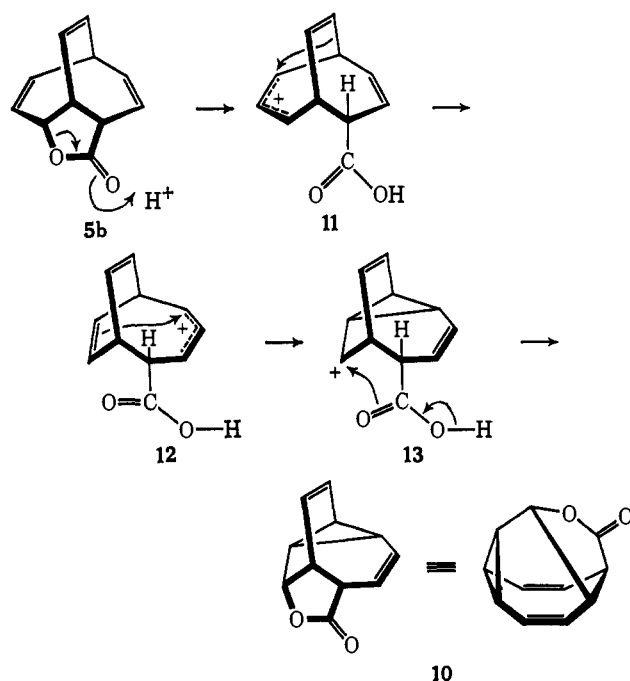
Proton assignment	Chemical shift, $\delta$	Multiplicity and spin-spin interactions	Proton(s) irradiated	Result	Coupling constants, Hz
H <sub>1</sub> , H <sub>2</sub>	1.05–1.45	Complex multiplet; coupled to H <sub>3</sub> , H <sub>8</sub> , H <sub>9</sub>			
H <sub>3</sub>	1.68	Multiplet; <sup>a</sup> $J_{1,3}$ ; $J_{2,3}$ ; $J_{3,8}$	H <sub>8</sub>	Triplet ( $J \sim 7.6$ Hz)	$J_{3,8} = 4.5$ $J_{1,3} \sim 7.6$ $J_{2,3} \sim 7.6$
H <sub>4</sub>	2.37	Doublet of doublets of doublets; <sup>a</sup> $J_{4,5}$ ; $J_{4,6}$ ; $J_{4,7}$	H <sub>7</sub>	Triplet	$J_{4,7} = 5.7$
H <sub>5</sub>	2.52	Triplet; <sup>a</sup> $J_{4,5}$ ; $J_{5,10}$	H <sub>10</sub>	Doublet ( $J = 8.0$ Hz)	$J_{4,5} = 8.0$ $J_{5,10} = 8.0$
H <sub>6</sub>	4.60	Doublet of doublets; <sup>a</sup> $J_{3,6}$ ; $J_{4,6}$	H <sub>3</sub>	Doublet	$J_{4,6} = 6.5$
H <sub>7</sub>	5.25	Doublet of doublets; $J_{4,7}$ ; $J_{7,9}$	H <sub>4</sub>	Doublet ( $J = 9.9$ Hz)	$J_{7,9} = 9.9$
H <sub>8</sub>	5.40	Doublet of doublets; $J_{1,8}$ ; $J_{8,10}$	H <sub>1</sub> (H <sub>2</sub> ) <sup>b</sup>	Doublet ( $J = 11.0$ Hz)	$J_{1,8} = 5.8$ $J_{8,10} = 11.0$
H <sub>9</sub>	5.58	Doublet of doublets; $J_{2,9}$ ; $J_{7,9}$	H <sub>2</sub> (H <sub>1</sub> ) <sup>b</sup>	Doublet ( $J = 9.9$ Hz)	$J_{2,9} = 5.2$
H <sub>10</sub>	5.66	Doublet of doublets; <sup>a</sup> $J_{5,10}$ ; $J_{8,10}$	H <sub>5</sub>	Doublet ( $J = 11.0$ Hz)	

<sup>a</sup> Additional allylic coupling was apparent in these instances; all values were less than 1 Hz. <sup>b</sup> Because of the very close proximity of these proton pairs concomitant partial double irradiation of the proton in parentheses could not be avoided.

Figure 2. 100-MHz spectrum of **10** in C<sub>6</sub>D<sub>6</sub> at  $\sim 38^\circ$ .

Although a detailed mechanistic study of the **5b**  $\rightarrow$  **10** transformation has not been made, an entirely reasonable pathway is seen in Scheme II. Thus, pro-

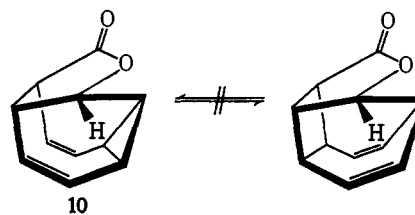
## Scheme II



tonation of the carbonyl oxygen atom followed by C–O bond heterolysis leads to allylic cation **11**. Focus-

ing attention initially on **11**, we see that the stereochemistry of the carboxyl group is such that it is *cis* to the positively charged bridge as a result of its genesis from the lactone function.<sup>16</sup> The passage of **11** to **13** can be formulated as a 1,2 shift of the ethylene bridge followed by cyclopropane ring formation. In the final step, this newly generated cyclopropylcarbiny cation (**13**) is attacked intramolecularly by the proximate carboxyl function. The possibility exists that **11** and **12** could also cyclize to **8** and **7**, respectively. However, no evidence was seen for the formation of either **7** or **8**; therefore, if these lactones were produced, they were thermodynamically unstable relative to **10** under the conditions employed.

Lactone **10** was examined by nmr spectroscopy at temperatures up to  $170^\circ$  in tetrachloroethylene as solvent. As with **5b**, there were no observed spectral changes over this temperature range.



**Photorearrangement of 10.** Recent studies by Simonaitis and Pitts have shown that the solution photochemistry of  $\gamma$ -butyrolactones leads not only to the formation of open-chain products, but results also in carbon dioxide expulsion to afford cyclopropanes.<sup>17</sup> Krull and Arnold have examined the mercury-sensitized vapor phase photolysis of  $\gamma$ -butyrolactone,<sup>18</sup> under these conditions, cyclopropane can be obtained in 36% isolated yield. In view of the  $\gamma$ -lactonic nature of **5b** and **10** and their possible interrelationship with the

(16) The possibility of enolization and subsequent epimerization of the carboxyl group during the rearrangement appears quite remote, particularly since it is bonded to a positively charged moiety throughout the bond reorganization process.

(17) R. Simonaitis and J. N. Pitts, *J. Amer. Chem. Soc.*, **90**, 1389 (1968); **91**, 108 (1969).

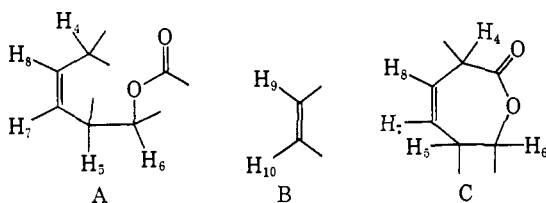
(18) I. S. Krull and D. R. Arnold, *Tetrahedron Lett.*, 1247 (1969).

(CH)<sub>12</sub> and (CH)<sub>10</sub> hydrocarbon series, we have investigated their photochemistry in preliminary fashion.<sup>19</sup>

Ultraviolet irradiation of **5b** under a variety of conditions was seen to lead consistently to a highly complex mixture of products. In contrast, irradiation of a dilute ether solution of **10** through quartz with a 450-W Hanovia mercury lamp yielded three isomeric lactones in high yield, as shown by vpc analysis.<sup>20</sup> Preparative scale vpc on a 5% SE-30 column permitted ultimate separation of this three-component mixture.

The first lactone to be eluted (56% yield) was obtained as colorless crystals, mp 140–141.5°. The ultraviolet spectrum of **14** (C<sub>2</sub>H<sub>5</sub>OH) showed only end absorption, whereas its infrared spectrum (CHCl<sub>3</sub>) displayed strong carbonyl absorption at 1770 cm<sup>-1</sup> and its nmr spectrum (CDCl<sub>3</sub>) consisted of multiplets at  $\delta$  2.10–2.50 (H<sub>1–3</sub>), 3.20–3.40 (H<sub>4</sub>), 3.60–3.85 (H<sub>5</sub>), 4.20–4.40 (H<sub>6</sub>), and 6.25–6.60 (H<sub>7–10</sub>). Due to the fact that H<sub>1</sub>, H<sub>2</sub>, and H<sub>3</sub> were closely spaced, measurement of coupling constants in this region of the spectrum could not be made. However, much information was obtained by irradiating this high-field multiplet (H<sub>1–3</sub>) throughout the spectral analysis and additionally irradiating H<sub>4</sub>, H<sub>5</sub>, and H<sub>6</sub> in consecutive fashion with a second oscillator. Under these conditions, the following coupling constants were determined:  $J_{4,7} = 1.7$  Hz;  $J_{4,8} = 6.4$  Hz;  $J_{5,6} = 4.1$  Hz;  $J_{5,7} = 6.5$  Hz;  $J_{5,8} = 1.8$  Hz;  $J_{7,8} = 8.3$  Hz; and  $J_{9,10} = 5.8$  Hz.

In view of the low-field position of H<sub>6</sub>, this proton is located adjacent to the lactone oxygen atom. Also, it was clear from the triple resonance experiments that no measurable spin-spin interactions occur between H<sub>9</sub>, H<sub>10</sub>, and any of the protons labeled H<sub>4</sub>–H<sub>8</sub>. On the basis of such information, part structures A and B could be formulated. Furthermore, in light of chemical shift considerations, the carbonyl group



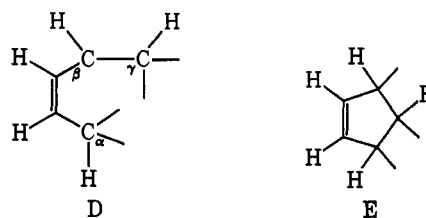
must be attached to either C<sub>4</sub> or C<sub>5</sub>. However, because bonding to C<sub>5</sub> would produce a  $\beta$ -lactone ring in disagreement with the infrared data, the carbonyl group is necessarily joined to C<sub>4</sub> giving rise to C. Since H<sub>9</sub> and H<sub>10</sub> in B do not interact with the protons of C, these units must be insulated by the three remaining sp<sup>3</sup>-hybridized carbon atoms (*cf.* D), and two of these atoms must be conjoined by a single bond. The joining of C <sub>$\alpha$</sub>  and C <sub>$\beta$</sub>  leads to a cyclobutene system, but this is inconsistent with the observed  $J_{9,10}$  (5.8 Hz).<sup>21</sup> The alternative possibility,

(19) The photochemical conditions employed herein are appreciably different than those reported in ref 17 and 18. This is a result of the fact that our work was completed prior to the appearance of these papers.

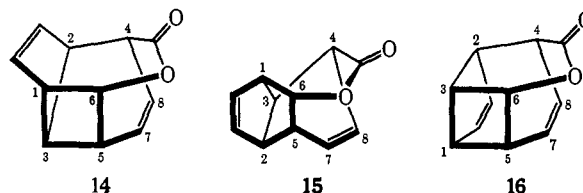
(20) The photolysis generally proceeded to 94% completion after 17 hr. The cited yields are based on recovered starting material and are derived from the relative areas of the individual vpc peaks obtained from a Varian-Aerograph A90-P3 gas chromatographic unit equipped with a thermal conductivity detector.

(21) The strong dependence of  $J_{\text{HC-CH}}$  on ring size has been established by several groups of workers; *cf.*, for example: (a) O. L. Chapman, *J. Amer. Chem. Soc.*, **85**, 2014 (1963); (b) G. V. Smith and H. Kriloff, *ibid.*, **85**, 2016 (1963). For cyclobutenes, the coupling constant lies in the range 2.5–3.7 Hz, while for cyclopentenes  $J = 5.1$ –7.0 Hz.

*i.e.*, the joining of C <sub>$\alpha$</sub>  and C <sub>$\gamma$</sub> , gives rise to a cyclopentene derivative (E), a ring size compatible with



the 5.8-Hz vicinal coupling constant.<sup>21</sup> Attachment of moieties C and E in the three possible combinations affords structures **14**–**16**.



To distinguish between these possibilities, spin decoupling of the nmr spectrum of this lactone in C<sub>6</sub>D<sub>6</sub> solution was examined. In this solvent, the absorptions due to H<sub>1</sub>, H<sub>2</sub>, and H<sub>3</sub> were better resolved and it proved possible to measure the following coupling constants:  $J_{1,3} = 7.5$  Hz;  $J_{1,5} = <1$  Hz;  $J_{1,6} = 7.5$  Hz;  $J_{3,5} = 3.4$  Hz; and  $J_{3,6} = 1.7$  Hz. Furthermore, it could be demonstrated that H<sub>2</sub> is vicinal to H<sub>4</sub> and that H<sub>1</sub> and H<sub>2</sub> flank the –CH<sub>9</sub>=CH<sub>10</sub>– unit. Because of the requirement in **15** that H<sub>3</sub> be vicinal to H<sub>4</sub> and the observation that H<sub>3</sub> and H<sub>4</sub> do not spin couple, this structure can be eliminated from consideration. Structure **16** requires vicinal coupling between H<sub>3</sub>–H<sub>6</sub> and H<sub>1</sub>–H<sub>5</sub> and cross-ring coupling between H<sub>1</sub>–H<sub>6</sub> and H<sub>3</sub>–H<sub>5</sub>. The magnitude of the coupling constants do not agree with such a structural arrangement. In contrast, the atomic arrangement in **14** is uniquely consistent with all the spectral data, in particular the coupling interactions in the cyclobutene ring.<sup>22</sup>

Although the mechanistic details of the photoinduced transformation of **10** to **14** were not examined in detail, a suggested mechanistic pathway is advanced in Scheme III. It is seen that the first step consists of a Norrish type I cleavage to afford diradical **17** which is capable of degenerate valence bond isomerization. Rebonding of the carbonyl group at the alternative allylic center constitutes a 1,3-acyl shift formally analogous to the photorearrangement observed with a number of  $\alpha,\beta$ -unsaturated ketones.<sup>23</sup> The unique geometry and internal strain in **18** may then combine to cause two consecutive photochemical [1,3]-suprafacial shifts to be favored.<sup>24</sup> This would lead *via* intermediate **19** to lactone **14**.

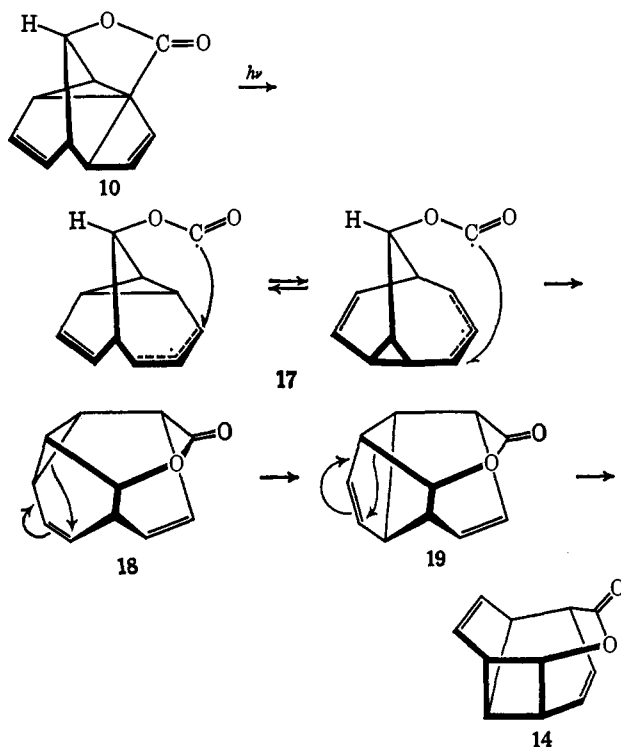
The second lactone (24% yield), also a colorless crystalline solid (mp 65.5–67°), exhibited an intense

(22) For recent data on the nmr spectra of cyclobutane derivatives, *cf.* (a) I. Fleming and D. H. Williams, *Tetrahedron*, **23**, 2747 (1967); (b) K. B. Wiberg and D. E. Barth, *J. Amer. Chem. Soc.*, **91**, 5124 (1969).

(23) For a leading reference, consult L. A. Paquette and G. V. Meehan, *J. Org. Chem.*, **34**, 450 (1969).

(24) The photoisomerization of vinyl cyclopropanes to cyclopentenes is a well-established reaction: (a) M. J. Jorgenson, *J. Amer. Chem. Soc.*, **91**, 6432 (1969); (b) P. J. Kropp, *ibid.*, **89**, 1126 (1967); (c) M. Jones, *ibid.*, **89**, 4237 (1967); (d) for a review, see R. N. Warrener and J. B. Bremner, *Rev. Pure Appl. Chem.*, **16**, 117 (1966).

Scheme III



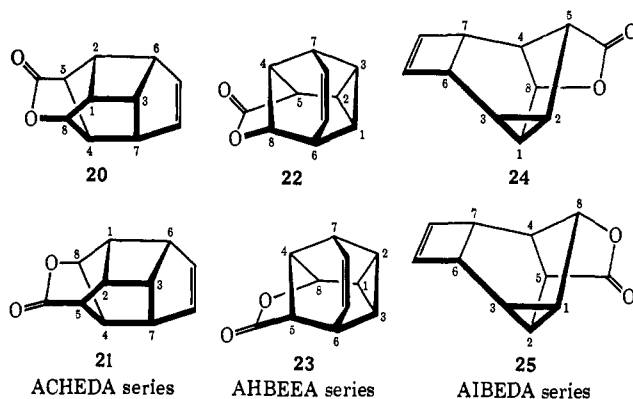
infrared ( $\text{CHCl}_3$ ) band at  $1772\text{ cm}^{-1}$  and weak ultraviolet ( $\text{C}_2\text{H}_5\text{OH}$ ) absorption at  $227\text{ nm}$  ( $\epsilon\ 800$ ). Although the nmr spectrum of this substance (**20**) was more complex than that of **14**, it was immediately apparent that only two vinyl protons were present and therefore that an additional ring had been formed. In  $\text{CDCl}_3$ , there was seen a series of multiplets at  $\delta$  1.00–1.25 (1 H), 1.80–2.05 (2 H), 2.35–2.70 (1 H), 2.85–3.40 (3 H), 3.75–4.00 (1 H), and 6.20–6.45 (2 H). Decoupling experiments provided the following facts: (i)  $\text{H}_6$  and  $\text{H}_7$  at  $\delta$  3.05–3.40 are the allylic protons; (ii)  $\text{H}_8$  ( $\delta$  3.75–4.00) is the proton adjacent to the lactone oxygen atom; (iii)  $\text{H}_5$  ( $\delta$  2.85–3.05) is the proton adjacent to the carbonyl function; (iv)  $\text{H}_4$  ( $\delta$  2.35–2.70) is spin coupled to  $\text{H}_5$  ( $J = 7.0\text{ Hz}$ ) and  $\text{H}_8$  ( $J = 7.6\text{ Hz}$ ), a result which necessitates that the lactone ring be five membered; and (v)  $\text{H}_4$  is not coupled to  $\text{H}_1$ ,  $\text{H}_2$ , or  $\text{H}_3$  ( $\delta$  1.00–2.05).

In order to deduce the structure of this lactone, attention was directed to Lederberg's computer program<sup>25</sup> which lists all the possible  $(\text{CH})_{12}$  isomers<sup>15</sup> in terms of polygonal<sup>26a</sup> and nonpolygonal graphs.<sup>26b</sup> Because the presence in the photoproduct of a single  $-\text{CH}=\text{CH}-$  unit in addition to the lactone function is equivalent to a doubly unsaturated  $(\text{CH})_{12}$  isomer, only the diene representations needed to be considered. It is important to realize, however, that, in the absence of symmetry elements, one such  $(\text{CH})_{12}$  structure actually leads to four lactone structures since either double bond can be treated as the lactone function. Evaluation of all the appropriate structures in the

(25) J. Lederberg, NASA report entitled "Dendral-64. A System for Computer Construction, Enumeration, and Notation of Organic Molecules as Tree Structures and Cyclic Graphs." The authors thank Professor R. Hoffmann for providing them with a copy of the computer-generated data.

(26) (a) Those molecules in which a continuous cycle of 12 atoms may be found; (b) those molecules which contain no continuous cycle of 12 atoms.

computer program with respect to the five spectral observations recorded above and the  $\gamma$ -lactonic nature of the substance resulted in elimination of most of the structures from further consideration. The various possible structural isomers, together with the reasons for their incompatibility, are summarized in Table VI.<sup>27</sup> It follows that all but six structures remain after rejection of those isomers which fail to meet the requisite criteria.

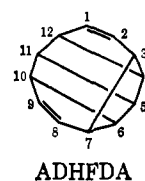


Further refinement of the structural features of this photolactone was gained from additional decoupling experiments.  $\text{H}_5$  ( $\delta$  2.85–3.05) was seen as a multiplet resembling a doublet of doublets with spacings of 3.5 and 7.0 Hz. Irradiation of  $\text{H}_4$  converted this multiplet to a doublet ( $J \approx 3.5\text{ Hz}$ ) while irradiation of the  $\text{H}_2\text{H}_3$  absorption removed the smaller coupling. Since the remaining hydrogens had no effect on  $\text{H}_5$ , this proton must then be adjacent to only  $\text{H}_4$  and  $\text{H}_2$  or  $\text{H}_3$ . Structure **23** is inconsistent with this observation.

Similar spin decoupling experiments disclosed that  $\text{H}_1$  (a 1:2:1 triplet of triplets) is coupled vicinally to  $\text{H}_2$  ( $J = 8.5\text{ Hz}$ ) and  $\text{H}_3$  ( $J = 8.5\text{ Hz}$ ), and also to  $\text{H}_6$  ( $J = 2\text{ Hz}$ ) and  $\text{H}_8$  ( $J = 2\text{ Hz}$ ). This indicated that  $\text{H}_1$  must be flanked by at least  $\text{H}_2$  and  $\text{H}_3$ , a fact which eliminated structure **21**.

At this stage, it was helpful to consider the chemical shifts of  $\text{H}_2$  and  $\text{H}_3$ . Although some deshielding contributions to the chemical shift of  $\text{H}_2$  in **24** are conceivable, the relatively low-field positions of both of these hydrogens ( $\delta$  1.80–2.05) cannot be adequately accommodated by structures **22–25**. However, all the peaks and multiplicities expected for **20** are found in the spectrum. These include the  $J_{1,2}$  and  $J_{1,3}$  cou-

(27) The compact notational system is due to Lederberg. A "span" is a line which links two atoms. If the two atoms linked are adjacent, the span is said to be of length A. If they are separated by one atom, it is of length B. If separated by two atoms, it is of length C, and so on to span lengths D, E, and F. Span lengths are shown below for a  $(\text{CH})_{12}$  isomer. It should be noted that one always proceeds in the same direction around the ring. Thus, a unique representation of an



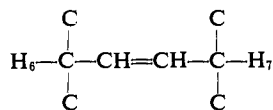
isomer is simply to give the span list, proceeding from an arbitrary point in a fixed sense around the ring, mentioning each span when either end is encountered. The above example is seen to be ADHFDA.



Table VI. Relationship of All Possible Polygonal and Nonpolygonal 12-Vertex Graphs Containing Two A Components to Photolactone 20<sup>a</sup>

		I <sup>b</sup>			
(a) All isomers	AABBBB	AAEFBC	ABCFCFA	ACADBC	AIBBCA
	AABCCB	AAFFBB	ABDFBA	ACAEBB	AIBFCA
	AABDDDB	AAGBCB	ABEBEA	ACECEA	AIDBEA
	AABEBC	AAGCDB	ABEEAB	ACGCEA	AIFFEA
	AABFBB	AAGEBB	ABFADB	ACGEAC	AIGEAC
	AAECEC	ABBABB	ABFFAB	ACGEEA	12A:1,12:AGBDB
	AACFCB	ABBECA	ABGBEA	AEAFCB	12A:1,12:AGCDB
	AADFDB	ABCBCA	ABGCAB	AECGEA	12A:1,12:AGEBB
	AAEBEB	ABCEAB	ABGFCFA	AFAFDB	12A:1,13:AGEBB
	AAECEC	ABCEDA	ACACDB	AGEGEA	12A:1,13:ABFBB
(b) 1-Oxa-2-oxo and 2-oxa-1-oxo derivatives only <sup>c</sup>	ABBBDA	ABCCDA	ABGDEA	ADADDB	AIBEDA
	ABBDAB	ABDFDA	ACEBDA	ADAFBB	AIEFDA
	ABBDAA	ABFFDA	ACGBDA	ADBFDA	AIGDDA
(c) Others	8-Oxa-9-oxo-ABHECA		9-Oxa-8-oxo-ACHFCA		
	9-Oxa-8-oxo-ABHECA		8-Oxa-9-oxo-AHBEEA		
	9-Oxa-10-oxo-ACHBCA		9-Oxa-8-oxo-AHBEEA		
	10-Oxa-9-oxo-ACHBCA		5-Oxa-6-oxo-AHEAEB		
	8-Oxa-9-oxo-ACHFCA		6-Oxa-5-oxo-AHEAEB		
		II <sup>d</sup>			
(a) All isomers	ACHCDA	ADHFDA	AHEGDA	AHFDDA	AHHDDA
(b) 1-Oxa-2-oxo and 2-oxa-1-oxo derivatives only <sup>c</sup>	ABGDAC	ABHDDA	ACHBCA	ACHFCA	AHEAEB
	ABHDAB	ABHECA	ACHEDA		
(c) Others	9-Oxa-10-oxo-ABBBDA		5-Oxa-5-oxo-ADADDB		
	10-Oxa-9-oxo-ABBBDA		4-Oxa-5-oxo-ADAFBB		
	10-Oxa-11-oxo-ABCCDA		5-Oxa-4-oxo-ADAFBB		
	11-Oxa-10-oxo-ABCCDA		7-Oxa-8-oxo-AIEFDA		
	10-Oxa-11-oxo-ACEBDA		8-Oxa-7-oxo-AIEFDA		
	11-Oxa-10-oxo-ACEBDA		7-Oxa-8-oxo-AIGDDA		
	4-Oxa-5-oxo-ADADDB		8-Oxa-7-oxo-AIGDDA		
		III <sup>e</sup>			
(a) All isomers	ADHABB		12A:1,12:ABFBB		
(b) 7-Oxa-8-oxo and 8-oxa-7-oxo isomer pairs	ABGDAC		ABHDAB		
(c) 8-Oxa-9-oxo and 9-oxa-8-oxo isomer pairs	ABBDAB		ABHDDA		
	ABDFDA				
(d) 9-Oxa-10-oxo and 10-oxa-9-oxo isomer pairs	ACGBDA				
(e) Others	10-Oxa-11-oxo-ABBBDA		11-Oxa-10-oxo-ABBBDA		

<sup>a</sup> An A span is a double bond; the restriction to two A components is required because of only two sites of unsaturation in 20. <sup>b</sup> Structures failing to provide the necessary  $\gamma$ -lactone unit. <sup>c</sup> The first atom in span A is herein given the label of C<sub>1</sub>, the adjoining vinyl carbon C<sub>2</sub>, and so on, in the direction generated by this span. <sup>d</sup> Remaining structures possessing  $\gamma$ -lactone unit and also one of the following spin-spin interactions which are not present in 20:  $J_{1,4}$ ;  $J_{2,4}$ ;  $J_{3,4}$ ; the numbers employed to denote the coupling constants are derived from nmr data (see text); the numerical prefixes denote the substitution pattern following the numbering system presented in footnote c. <sup>e</sup> Remaining structures in which either the



moiety is lacking or C<sub>5</sub> and/or C<sub>7</sub> is part of a three-numbered ring; H<sub>6</sub> and H<sub>7</sub> are derived from nmr data whereas the numerical prefixes are computer generated (see footnote c). H<sub>6</sub> and H<sub>7</sub> must be noncyclopropyl in view of their chemical shifts ( $\delta$  3.05–3.40).

pling constants, the magnitudes of which are those expected based on the dihedral angles present in a puckered cyclobutane ring.<sup>22b</sup> A cross-ring cyclobutane coupling ( $J_{1,6}$ ) of 2 Hz is also seen, in agreement with values previously reported for such interactions.<sup>22, 28</sup> Examination of models of 20 suggested that the dihedral angle between H<sub>1</sub> and H<sub>6</sub> is approximately 55° which would lead to a small vicinal coupling constant. The measured  $J_{1,6}$  value (2 Hz) cor-

(28) The cross-ring coupling constant for the  $J_{2,3}$  interaction was not measurable because of the mutual overlap of the H<sub>2</sub>, H<sub>3</sub> absorptions.

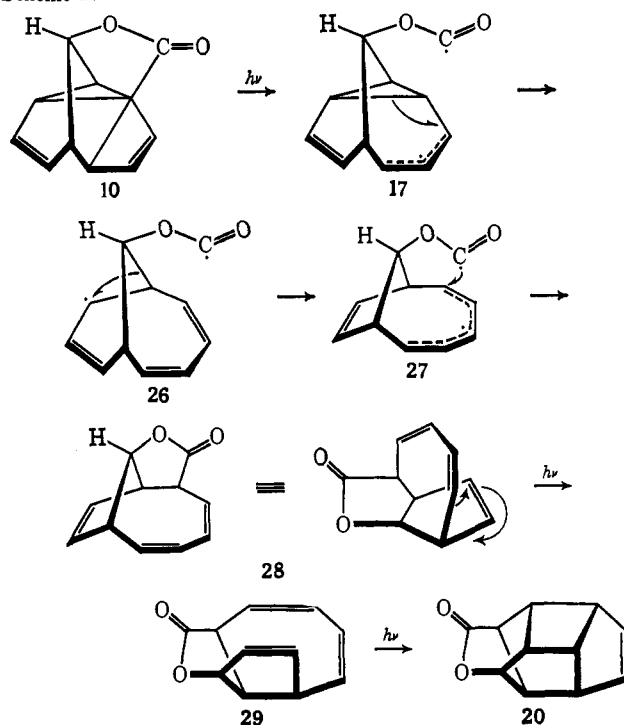
responds closely to the theoretical value expected for this spatial relationship.<sup>29</sup>

Further attempts to substantiate this structural assignment were not made because of very limited quantities of material. However, owing to the fact that all possible structures were considered and because 20 was found to be uniquely compatible with the spectral data, the assignment is evidently as soundly based as possible under the circumstances.

(29) (a) M. Karplus, *J. Chem. Phys.*, **30**, 11 (1959); (b) M. Karplus, *J. Amer. Chem. Soc.*, **85**, 2870 (1963).

The conversion of **10** to **20** clearly requires a series of intricate rearrangements which ultimately involve the incorporation of a double bond into a cyclobutane ring. The genesis of **20** can be derived in mechanistically plausible fashion by again invoking initial Norrish type I cleavage of **10**, followed by ring opening of the resulting cyclopropylcarbonyl radical (**17**) to give **26** which undergoes a 1,2 shift of the bridged carbon and radical recombination to give **28** (Scheme IV). All

Scheme IV



of these steps, including the pivoting of the bridged carbon, necessarily proceed with retention of configuration at the H—C—O— center and lead to the proper stereochemistry in **28**. The simplest conversion of **28** to **20** may be formulated as a sequence of two symmetry-allowed excited state reactions, *i.e.*, a 1,3-sigmatropic shift followed by (2 + 2) cycloaddition.

The third photolactone (**30**, 20%), mp 218–219.5°, was next considered. The infrared carbonyl absorption (in CHCl<sub>3</sub>) at 1770 cm<sup>-1</sup> was comparable to that of **14** and **20**; the ultraviolet spectrum showed end absorption only. The 100-MHz nmr spectrum (in CDCl<sub>3</sub>) exhibited multiplets at  $\delta$  1.80–2.35 (3 H), 3.20–3.65 (4 H), 4.90–5.20 (1 H), and 6.00–6.55 (2 H). Although these data indicate that **30** is a  $\gamma$ -lactone possessing only one ethylenic linkage, the substantial overlap of the various proton absorptions in a wide variety of solvents did not lend itself to double- and triple-resonance studies. As a result, the structure of **30** remains to be elucidated.

### Experimental Section<sup>30</sup>

#### Reaction of Bullvalene with Chlorosulfonyl Isocyanate. A. Room Temperature with Thiophenol–Pyridine–Water Work-up.

(30) Melting points are corrected. The microanalyses were performed by the Scandinavian Microanalytical Laboratory, Herlev, Denmark. The nmr spectra were determined with Varian A-60A and HA-100 spectrometers purchased with funds made available through the National Science Foundation.

To a stirred solution of 2.15 g (0.017 mol) of bullvalene (**1**)<sup>2b</sup> in 20 ml of methylene chloride cooled to 0° was added dropwise a solution of 2.32 g (0.017 mol) of chlorosulfonyl isocyanate in 30 ml of the same solvent. Upon completion of the addition, the reaction mixture was allowed to warm to room temperature during 15 min. The solvent was evaporated leaving a yellow oil which was dissolved in acetone (25 ml). After cooling this solution to -25°, thiophenol (3.63 g, 0.033 mol) was added followed by dropwise introduction of a solution of 1.98 g (0.025 mol) of pyridine in 15 ml of acetone during 30 min. The resulting solution was stirred for an additional 2 hr at -25° at which point 50 ml of water was added. The mixture was extracted with ether (3 × 150 ml) and the combined extracts were dried, filtered, and evaporated. The residual yellow oil was chromatographed on Florisil. Elution with petroleum ether (30–60°) afforded 150 mg of recovered bullvalene, mp 93–94°. Elution with petroleum ether–ether (1:1) gave 870 mg (31%) of lactone **5b**, mp 73–75° (from petroleum ether).

Anal. Calcd for C<sub>11</sub>H<sub>10</sub>O<sub>2</sub>: C, 75.84; H, 5.72. Found: C, 75.91; H, 5.85.

Continued elution with ether–methanol (99:1) yielded 510 mg (19%) of  $\beta$ -lactam **3b** = **4b**, mp 151–152° (from ether).

Anal. Calcd for C<sub>11</sub>H<sub>11</sub>NO: C, 76.27; H, 6.36; N, 8.09. Found: C, 76.31; H, 6.48; N, 7.84.

Finally, elution with ether–methanol (95:5) afforded 390 mg (15%) of lactam **6b**, mp 172–173° (from ether).

Anal. Calcd for C<sub>11</sub>H<sub>11</sub>NO: C, 76.27; H, 6.36; N, 8.09. Found: C, 76.27; H, 6.67; N, 8.04.

**B. At 40° with Aqueous Sodium Hydroxide Work-up.** To a stirred solution of 1.24 g (9.6 mmol) of **1** in 20 ml of methylene chloride cooled to 0° was added dropwise 1.39 g (9.6 mmol) of chlorosulfonyl isocyanate in 30 ml of the same solvent. After addition was completed, the reaction mixture was warmed to 40° and maintained at that temperature for 2 hr. The solvent was evaporated leaving a brown oil which was dissolved in aqueous acetone and titrated with 4 N sodium hydroxide solution until neutrality was attained. The solution was extracted with methylene chloride (4 × 200 ml) and the combined extracts were dried, filtered, and evaporated. The residual oil was chromatographed on Florisil in the above manner to afford 15 mg of recovered bullvalene, 270 mg (16%) of **5b**, and 320 mg (20%) of **6b**. No  $\beta$ -lactam was obtained.

**Hydrogenation of 5b.** A solution of 100 mg (0.58 mmol) of **5b** in 25 ml of methanol was hydrogenated over 5% palladium on charcoal catalyst at atmospheric pressure. Three equivalents of hydrogen were consumed. The solution was filtered and evaporated to give 102 mg (100%) of crude hexahydrolactone. Three sublimations of this material at 40° and 20–25 mm afforded white crystals, mp 170–172°;  $\nu_{\max}^{\text{CHCl}_3}$  1758 cm<sup>-1</sup>.

Anal. Calcd for C<sub>11</sub>H<sub>18</sub>O<sub>2</sub>: C, 73.30; H, 8.95. Found: C, 73.30; H, 9.10.

**Ozonolysis of 5b.** Lactone **5b** (390 mg, 2.3 mmol) in 100 ml of methanol was treated with gaseous ozone until the uptake of ozone had ceased. At this point, there was added 2 ml of 30% hydrogen peroxide, 2 ml of water, and 2 ml of formic acid and the solution was refluxed for 1 hr. After cooling the solution to 0°, the excess hydrogen peroxide was destroyed by treatment with saturated potassium iodide solution, the excess iodide being titrated with sodium thiosulfate. The aqueous solution was extracted with methylene chloride (3 × 150 ml) and the combined extracts were dried and filtered. To this solution was added 0.82 g (0.02 mol) of diazomethane in 20 ml of ether. The excess diazomethane was decomposed with glacial acetic acid and the solution was washed with sodium carbonate solution (2 × 200 ml) and with water. The organic layer was dried, filtered, and evaporated and the residual oil was purified by preparative vpc (10 ft × 0.25 in. column packed with 10% SE-30). The principal product (>90%) was identified as dimethyl malonate.

Ozonolysis of lactam **6b** (380 mg, 2.2 mmol) in identical fashion likewise gave dimethyl malonate as the chief volatile product.

**Methylation of 6b.** To a solution of **6b** (500 mg, 2.9 mmol) in 25 ml of methylene chloride under a nitrogen atmosphere was added 0.67 g (4.5 mmol) of trimethylxonium fluoroborate and the mixture was stirred at room temperature for a period of 6 hr at which point a solution of 1.5 g of potassium carbonate in 2 ml of water was added. The organic layer was dried, filtered, and evaporated to give 0.50 g (91%) of **9**. Two sublimations (50°, 20 mm) and four recrystallizations from petroleum ether gave pure **9**, mp 49–50°;  $\nu_{\max}^{\text{CHCl}_3}$  1635 cm<sup>-1</sup>;  $\lambda_{\max}^{\text{C}_2\text{H}_5\text{OH}}$  245 sh nm ( $\epsilon$  165);  $\delta_{\text{TMS}}^{\text{CDCl}_3}$  5.50–6.30 (m, 6, vinyl), 4.10–4.30 (m, 1, >CHN<), 3.60–3.80 (s, 3, -OCH<sub>3</sub>), and 2.50–3.10 (m, 3, remaining allylic).

*Anal.* Calcd for  $C_{12}H_{13}NO$ : C, 76.97; H, 7.00; N, 7.48. Found: C, 77.02; H, 7.11; N, 7.48.

**Acid-Catalyzed Rearrangement of 5b.** Lactone **5b** (1.13 g, 6.4 mmol) was dissolved in 80 ml of 30% sulfuric acid and the reaction mixture was stirred at room temperature for a period of 16 hr. This solution was added to 300 g of ice-water and the solution was basified and extracted with ether ( $4 \times 150$  ml). The combined extracts were dried, filtered, and evaporated to give a greenish oil which was chromatographed on Florisil. Elution with petroleum ether-ether (1:1) afforded 0.64 g (58%) of **10**, mp 127–128° (from petroleum ether).

*Anal.* Calcd for  $C_{11}H_{10}O_2$ : C, 75.84; H, 5.79. Found: C, 75.82; H, 5.80.

**Photorearrangement of 10.** A solution of 490 mg (2.7 mmol) of **10** in 450 ml of anhydrous ether was irradiated for 17 hr through quartz with a 450-W Hanovia lamp. The progress of the reaction was followed by periodically removing aliquots and analyzing these by vpc. Evaporation of the ether left a semicrystalline residue which consisted of three products in the ratio of 56:24:20. These substances were separated by preparative vpc at 160° on a 12 ft  $\times$  0.25 in. column packed with 5% SE-30.

The first eluate (**14**, retention time 49 min) was recrystallized from petroleum ether to give white crystals, mp 140–141.5°.

*Anal.* Calcd for  $C_{11}H_{10}O_2$ : C, 75.84; H, 5.79. Found: C, 75.91; H, 5.84.

The second eluate (**20**, retention time 64 min) was sublimed at 50° and 20 mm and recrystallized from petroleum ether to give white crystals, mp 65.5–67°.

*Anal.* Calcd for  $C_{11}H_{10}O_2$ : C, 75.84; H, 5.79. Found: C, 76.11; H, 5.61.

The third eluate (**30**, retention time 72 min) was recrystallized from petroleum ether-ether to afford a white solid, mp 218–219.5°.

*Anal.* Calcd for  $C_{11}H_{10}O_2$ : C, 75.84; H, 5.79. Found: C, 75.59; H, 5.89.

**Acknowledgment.** This work was supported in large part by the National Science Foundation, Grant No. GP-8678. We wish also to thank the Badische Anilin und Soda Fabrik for the generous gift of cyclooctatetraene which made this work possible.

## 1,3-Dipolar Cycloaddition Reactions. LIII.<sup>1</sup> The Question of the 1,3-Dipolar Nature of $\Delta^2$ -Oxazolin-5-ones

Hans Gotthardt, Rolf Huisgen, and Horst O. Bayer

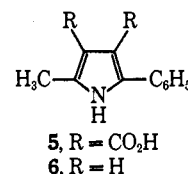
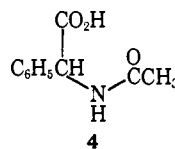
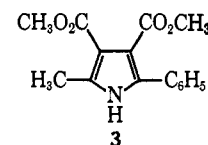
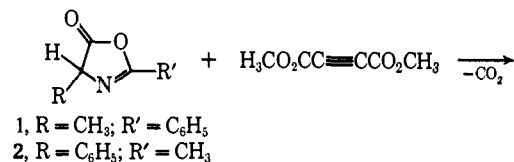
Contribution from the Institut für Organische Chemie der Universität München, Munich, Germany. Received December 6, 1969

**Abstract:** Azlactones such as 4-methyl-2-phenyl- (**1**) and 2-methyl-4-phenyl- $\Delta^2$ -oxazolin-5-one (**2**) react with dimethyl acetylenedicarboxylate to give dimethyl 2-methyl-5-phenylpyrrole-3,4-dicarboxylate (**3**) and carbon dioxide. These cycloadditions are preceded by a tautomerization of the parent azlactone to a mesoionic oxazolium 5-oxide (**19**) which, as a cyclic azomethine ylide, combines further with the dipolarophile. Ultraviolet and infrared studies of 2,4-diphenyloxazolin-5-one (**23**) support the formation of the 2,4-diphenyloxazolium 5-oxide tautomer (**25**). The equilibrium concentration of **25** in turn is highly dependent on the polarity of the solvent employed. 5-Ethoxy-2,4-diphenyloxazole (**13**) reacts with dimethyl acetylenedicarboxylate to give dimethyl 2-ethoxy-5-phenylfuran-3,4-dicarboxylate (**15**) and benzonitrile.

In 1961, when we discovered that azlactones ( $\Delta^2$ -oxazolin-5-ones) are capable of cycloaddition to acetylene derivatives,<sup>2</sup> an abundance of literature was available on this class of compounds.<sup>3,4</sup> In particular, their relationship to amino acid and peptide chemistry was responsible for the fact that the chemistry of this class of compounds was by no means "underdeveloped." Nevertheless, there had been no previous indications of their utility as partners in cycloaddition reactions.

**A. Reactions with Dimethyl Acetylenedicarboxylate.** On heating the azlactone of N-benzoylalanine (**1**) with 2 equiv of dimethyl acetylenedicarboxylate in refluxing xylene, carbon dioxide was evolved and a 71% yield of dimethyl 2-methyl-5-phenylpyrrole-3,4-carboxylate (**3**)

was obtained. Alkaline hydrolysis to **5** followed by destructive distillation of the calcium salt gave 2-methyl-5-phenylpyrrole (**6**) which was identical with a sample obtained from phenacetylacetone.<sup>5</sup>



The positions 2 and 4 of  $\Delta^2$ -oxazolin-5-one become equivalent in this pyrrole synthesis. To avoid handling

(5) F. Angelico and E. Calvello, *Gazz. Chim. Ital.*, **31** (II), 4 (1901).

(1) For paper LII in this series, see R. Huisgen and J. Wulff, *Chem. Ber.*, **102**, 1848 (1969).

(2) Preliminary communication: R. Huisgen, H. Gotthardt, and H. O. Bayer, *Angew. Chem. Intern. Ed. Engl.*, **3**, 135 (1964).

(3) For reviews, see H. E. Carter, *Org. Reactions*, **3**, 198 (1946); J. W. Cornforth in "The Chemistry of Penicillin," H. T. Clarke, J. R. Johnson, and R. Robinson, Eds., Princeton University Press, Princeton, N. J., 1949, p 730; E. Baltazzi, *Quart. Rev.* (London), **9**, 150 (1962); J. W. Cornforth in "Heterocyclic Compounds," Vol. 5, R. C. Elderfield, Ed., John Wiley & Sons, Inc., New York, N. Y., 1957, p 336.

(4) Monographs published since 1961: R. Filler in "Advances in Heterocyclic Chemistry," Vol. 4, Academic Press, New York, N. Y., 1965, p 75; W. Steglich, *Fortschr. Chem. Forsch.*, **12**, 77 (1969).