Photochemical and Thermal Rearrangement of Oxaziridines. Experimental Evidence in Support of the Stereoelectronic Control Theory

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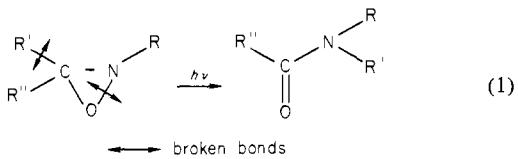
Abstract: The irradiation of an optically pure isomer of a spirooxaziridine, (2*R*,α*S*)-6(e)-*tert*-butyl-2-(α-methylbenzyl)-1,2-oxazaspiro[2.5.]octane, gave a single lactam, (5*S*,α*S*)-5-*tert*-butyl-1-(α-methylbenzyl)hexahydro-2-azepinone. The absolute configurations of these two compounds were established by chemical methods and X-ray crystal structure analysis. The comparison between the configurations of the reactant and product leads to the conclusion that the C–C bond cleaved is the bond in the anti position with respect to the lone pair of the oxaziridine nitrogen atom. This work provides clear evidence in support of the stereoelectronic theory that explains the regioselectivities observed in photochemical and thermal rearrangements of oxaziridines. The mechanism of the photochemical conversion of oximes (photo-Beckmann) can also be understood in terms of stereoelectronically controlled rearrangement of intermediate oxaziridines.

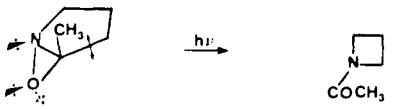
We have previously[2] shown that the photochemical rearrangement of oxaziridines into amides is a highly stereoselective and regioselective reaction involving the singlet state of these heterocycles (eq 1). Thermal reactions give the same products, but the degree of regioselectivity is slightly lower.[3,4]



(1)

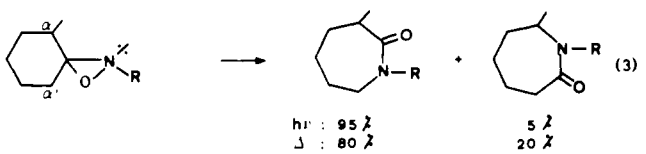
Experimental[2-8] and theoretical[9] results suggest a possible mechanism for these rearrangements. During the photochemical process, the lowest singlet excited state($n \rightarrow \sigma^*_{NO}$ transition) relaxes to a low energy hole of the potential surface corresponding to a breaking of the NO bond. After deexcitation on the ground-state surface, migration of the C substituent occurs, as in the thermal reaction. The process is continuous, and regioselectivity seems to be controlled by stereoelectronic factors: the C–C bond that is anti to the nitrogen lone pair seems to be cleaved more easily than the bond that is syn to the lone pair. This interpretation is based on the fact that the high energy barrier for nitrogen inversion in oxaziridines (≳30 kcal/mol)[10] excludes syn–anti isomerization at room temperature, on theoretical results[9] and on indirect experimental evidence.[2-8]

In this paper we put forward a definitive experimental argument in support of this interpretation. However, first of all, it would be useful to give a short summary of some experimental facts that can be explained on the basis of stereoelectronic arguments: (i) the ring contraction of fused bicyclic oxaziridines[5] (eq 2), (ii) the



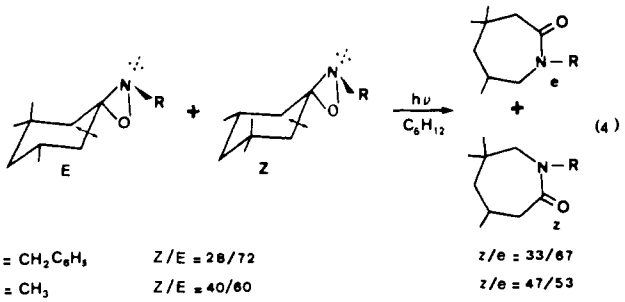
(2)

regioselectivity observed in the ring expansion of spirooxaziridines unsymmetrically substituted in α or in α,α′ positions with respect to the spiro atom[2,4,8] (eq 3) (in these cases, it was possible to follow



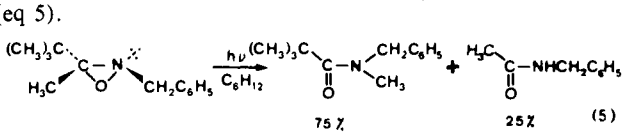
(3)

the photoreaction using ^1H NMR spectroscopy, and isomerization of the starting oxaziridine was not observed; thus, nitrogen inversion does not compete efficiently with the photochemical rearrangement); (iii) the influence of the distribution of *Z* and *E* isomers on the relative percentage of isomeric lactams (*z* and *e*) in the photolysis reaction[2] (eq 4), and (iv) the regioselectivity



(4)

observed during the rearrangement of monocyclic oxaziridines[2,11,12] (eq 5).



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(2) Oliveros, E.; Rivière, M.; Lattes, A. *Nouv. J. Chim.* **1979**, *3*, 739–753.

(3) Oliveros, E.; Antoun, H.; Rivière, M.; Lattes, A. *J. Heterocycl. Chem.* **1976**, *13*, 623–624.

(4) Oliveros, E.; Rivière, M.; Lattes, A. *J. Heterocycl. Chem.* **1980**, *17*, 1025–1027.

(5) Parello, J.; Rivière, M.; Desherces, E.; Lattes, A. *C. R. Hebd. Seances Acad. Sci., Ser. C* **1971**, *273*, 1097–1100.

(6) Desherces, E.; Rivière, M.; Parello, J.; Lattes, A. *C. R. Hebd. Seances Acad. Sci. Ser. C* **1972** 275, 581–584.

(7) Oliveros-Desherces, E.; Rivière, M.; Parello, J.; Lattes, A. *Synthesis* **1974**, 812–813.

(8) Oliveros-Desherces, E.; Rivière, M.; Parello, J.; Lattes, A. *Tetrahedron Lett.* **1975**, 851–854.

(9) Oliveros, E.; Rivière, M.; Malrieu, J. P.; Teichteil, C. *J. Am. Chem. Soc.* **1979**, *101*, 318–327.

(10) (a) Montanari, F.; Moretti, I.; Torre, G. *J. Chem. Soc., Chem. Commun.* **1968**, 1694–1695. (b) Boyd, D. R.; Spratt, R.; Jerina, D. M. *J. Chem. Soc. C* **1969**, 2650–2654. (c) Bjorgo, J.; Boyd, D. R. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1575–1577. (d) Ono, M.; Splitter, J. S.; Calvin, M. *Tetrahedron Lett.* **1973**, 4107–4110.

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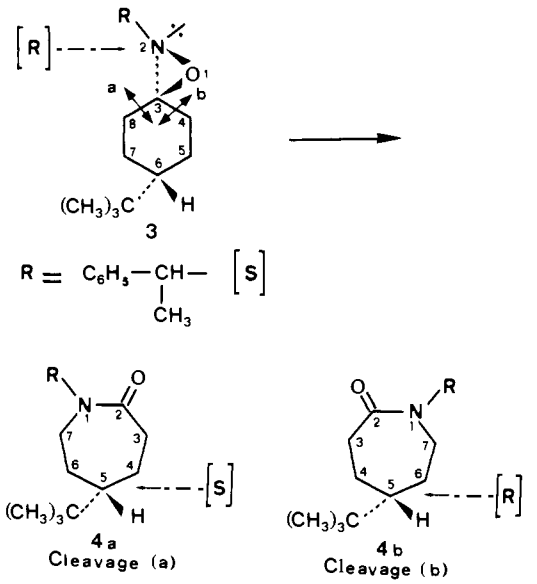
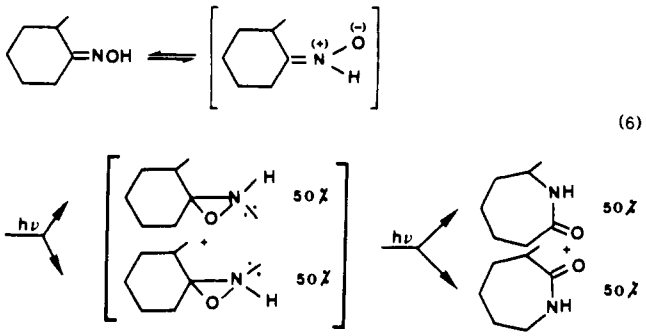
Scheme I



It should be added that the photo-Beckmann reaction, i.e., the photochemical conversion of oximes into the corresponding amides, can also be understood in terms of a stereoelectronically controlled rearrangement of intermediate oxaziridines. The lack of regioselectivity obseved for this reaction in protic solvents is probably due to proton exchange or inversion at the level of the intermediate nitrone (reaction 6).



(6)

As already stated, the above results can be rationalized on the basis of a stereoelectronic effect, but a substituent effect cannot be ruled out. The photolysis of unsymmetrically β,β'-substituted oxaziridines (reaction 4) represented our first attempt to eliminate the substituent effect or at least to reduce it to a second-order effect. More precise information could have been obtained if it had been possible to isolate and photolyze independently the two isomers, *Z* and *E*.

An alternative route to eliminate substituent effects is the investigation, using a substrate with two chemically identical bonds on the C atom of the oxaziridine ring, of the two possible cleavages leading to two stereochemically different lactams. Consequently, this task led us to the following: synthesis of a nonracemic diastereoisomer of a chiral oxaziridine; determination of the structure of this oxaziridine by X-ray analysis; photolysis of the oxaziridine; and analysis of the resulting lactam(s) by determination of the absolute configuration(s) to correlate the structures of the substrate and the product(s).

An optically pure oxaziridine appeared to be the most convenient substrate. Such oxaziridines have been previously prepared[13-15] by peracid oxidation of chiral imines. This reaction

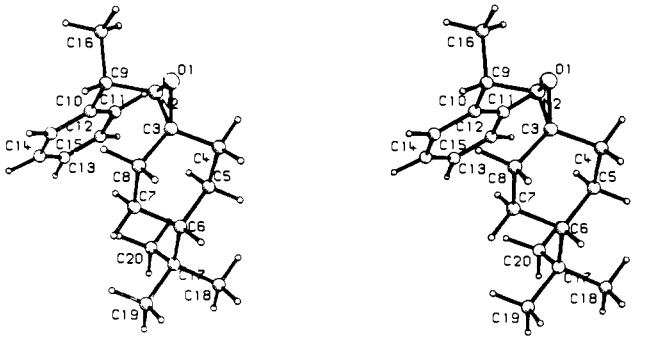
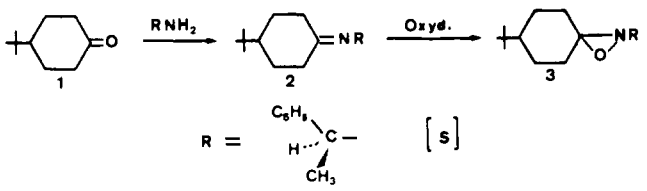


Figure 1. Stereoscopic view and the atom numbering of molecule **3**.

Scheme II



Scheme III

was found to produce diastereoisomeric oxaziridines in high optical yields, allowing complete separation of the diastereoisomers by TLC and yielding optically pure oxaziridines suitable for X-ray analysis. The oxaziridine **3** (Scheme I) was chosen because its C–C bonds, C(3)–C(4) and C(3)–C(8), can only be distinguished by stereoelectronic factors. Starting with a pure stereoisomer of known configuration, we expect to differentiate the two possible cleavages; since it is unlikely that nitrogen inversion will occur during the rearrangement,[2,9] the two cleavages (Scheme I, a and b) will lead to different diastereoisomers with opposite configurations at the C(5) atom.

Results

Synthesis of the Oxaziridine 3. **3** was prepared from the Schiff base of (−)-(*S*)-α-phenylethylamine and 4-*tert*-butylcyclohexanone by peracid oxidation (Scheme II). The oxidation of the chiral imine **2** gave one oxaziridine, which was isolated by crystallization (~50% yield). The enantiomeric purity (100%) of this isomer was checked by ^{1}H NMR spectroscopy using a chiral shift reagent.[16,17]

Crystal and Molecular Structure of the Oxaziridine 3. Taking into account the significance of the stereochemical arguments in this study, it seems important to present the X-ray results in some detail. Moreover, the oxaziridine cycle is not frequently studied by diffraction methods, and, therefore, the geometrical data are interesting in themselves. Figure 1 shows a stereoscopic view of the molecule and the atom numbering. The nonhydrogen atoms are numbered in an arbitrary way, which nevertheless maintains the IUPAC numbering for the spiro portion of the molecule.

The configuration of the asymmetric carbon atom of the nitrogen substituent, C(9), was known as *S*. The absolute configuration of the molecule could then be derived from X-ray results, which showed that the nitrogen atom had the opposite configuration to C(9), i.e., *R* configuration, and that the N(2)–C(3) bond was pseudoaxial and cis to the C(6)–C(17) bond. Oxaziridine **3** was then identified as (2*R*,α*S*)-6-(e)-*tert*-butyl-2-(α-methylbenzyl)-1,2-oxazaspiro[2.5]octane.

(11) Druelinger, M. L.; Shelton, R. W.; Lammert, S. R. *J. Heterocycl. Chem.* **1976**, *13*, 1001-1007.
(12) Splitter, J. S.; Calvin, M. *Tetrahedron Lett.* **1968**, 1445-1448.
(13) Belzecki, C.; Mostowicz, D. *J. Org. Chem.* **1975**, *40*, 3878-3880.
(14) Belzecki, C.; Mostowicz, D. *J. Chem. Soc., Chem. Commun.* **1975**, 244.
(15) Mostowicz, D.; Belzecki, C. *J. Org. Chem.* **1977**, *42*, 3917-3921.
(16) Whitesides, G. M.; Lewis, D. W. *J. Am. Chem. Soc.* **1971**, *93*, 5914-5916.
(17) Goering, H. L.; Eikenberry, J. N.; Koermer, G. S. *J. Am. Chem. Soc.* **1971**, *93*, 5913-5914.

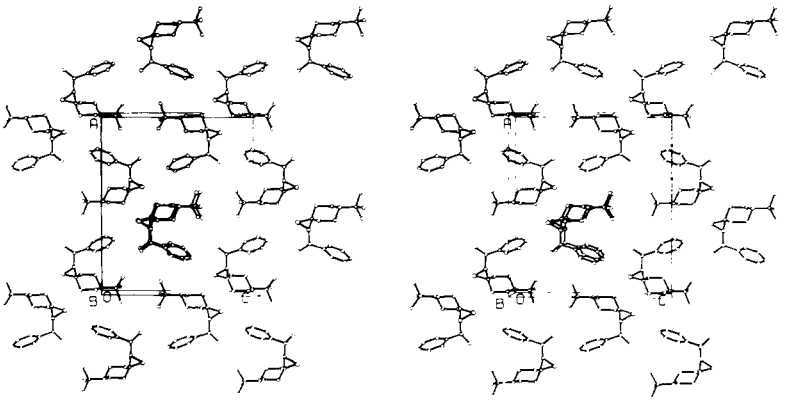


Figure 2. Stereoscopic view of the molecular packing (molecules **3**).

Table I. Fractional Atomic Coordinates ($\times 10^4$), Their Estimated Standard Deviations (in Parentheses), and the Equivalent Isotropic Temperature Factors (Å^2) for Oxaziridine **3**

	x	y	z	B_{eq}
O(1)	4032 (4)	−1271 (12)	2380 (3)	5.99
N(2)	3624 (4)	−2319 (13)	3146 (4)	4.72
C(3)	4230 (6)	−740 (18)	3245 (5)	4.94
C(4)	4942 (5)	−1829 (16)	3579 (5)	5.22
C(5)	4910 (5)	−1723 (16)	4581 (5)	4.79
C(6)	4863 (5)	682 (15)	4890 (5)	4.39
C(7)	4152 (5)	1728 (16)	4517 (5)	5.07
C(8)	4131 (6)	1644 (15)	3511 (5)	4.72
C(9)	2836 (5)	−1506 (15)	3148 (5)	4.75
C(10)	2555 (5)	−1686 (17)	4063 (6)	4.48
C(11)	2693 (5)	−3573 (15)	4528 (6)	5.06
C(12)	2428 (7)	−3680 (20)	5381 (8)	6.76
C(13)	2029 (7)	−2003 (37)	5733 (8)	10.08
C(14)	1877 (7)	−238 (30)	5264 (11)	9.02
C(15)	2149 (6)	19 (22)	4410 (8)	6.57
C(16)	2392 (6)	−2965 (26)	2524 (6)	8.90
C(17)	4883 (5)	815 (15)	5888 (6)	4.66
C(18)	5640 (6)	−33 (16)	6220 (6)	6.28
C(19)	4845 (7)	3228 (17)	6163 (6)	7.44
C(20)	4244 (5)	−383 (18)	6323 (6)	5.87

Table II. Bond Lengths (Å) and Their Estimated Standard Deviations (in Parentheses) for Oxaziridine **3**

O(1)-N(2)	1.535 (8)	C(9)-C(10)	1.513 (12)
O(1)-C(3)	1.428 (10)	C(9)-C(16)	1.537 (12)
N(2)-C(3)	1.456 (11)	C(10)-C(11)	1.386 (12)
N(2)-C(9)	1.483 (10)	C(10)-C(15)	1.380 (14)
C(3)-C(4)	1.521 (12)	C(11)-C(12)	1.410 (14)
C(3)-C(8)	1.529 (13)	C(12)-C(13)	1.362 (17)
C(4)-C(5)	1.562 (11)	C(13)-C(14)	1.333 (18)
C(5)-C(6)	1.553 (12)	C(14)-C(15)	1.423 (16)
C(6)-C(7)	1.529 (11)	C(17)-C(18)	1.531 (12)
C(6)-C(17)	1.556 (11)	C(17)-C(19)	1.541 (12)
C(7)-C(8)	1.567 (10)	C(17)-C(20)	1.511 (12)

Table III. Bond Angles (Deg) and Their Estimated Standard Deviations (in Parentheses) for Oxaziridine **3**

N(2)-O(1)-C(3)	58.7 (5)	N(2)-C(9)-C(10)	106.7 (7)
O(1)-N(2)-C(3)	57.0 (5)	N(2)-C(9)-C(16)	106.6 (8)
O(1)-N(2)-C(9)	107.8 (6)	C(10)-C(9)-C(16)	112.5 (8)
C(3)-N(2)-C(9)	118.2 (8)	C(9)-C(10)-C(11)	119.5 (9)
O(1)-C(3)-N(2)	64.3 (6)	C(9)-C(10)-C(15)	119.0 (10)
O(1)-C(3)-C(4)	115.2 (8)	C(11)-C(10)-C(15)	121.4 (10)
N(2)-C(3)-C(4)	111.0 (8)	C(10)-C(11)-C(12)	118.1 (10)
O(1)-C(3)-C(8)	116.4 (8)	C(11)-C(12)-C(13)	121.1 (11)
N(2)-C(3)-C(8)	125.4 (8)	C(12)-C(13)-C(14)	119.8 (13)
C(4)-C(3)-C(8)	115.0 (9)	C(13)-C(14)-C(15)	122.2 (14)
C(3)-C(4)-C(5)	107.0 (7)	C(10)-C(15)-C(14)	117.3 (13)
C(4)-C(5)-C(6)	110.5 (8)	C(6)-C(17)-C(18)	109.8 (7)
C(5)-C(6)-C(7)	109.0 (7)	C(6)-C(17)-C(19)	109.0 (8)
C(5)-C(6)-C(17)	110.9 (7)	C(18)-C(17)-C(19)	105.7 (8)
C(7)-C(6)-C(17)	112.0 (7)	C(6)-C(17)-C(20)	113.9 (8)
C(6)-C(7)-C(8)	112.6 (7)	C(18)-C(17)-C(20)	110.1 (8)
C(3)-C(8)-C(7)	107.4 (8)	C(19)-C(17)-C(20)	108.0 (9)

Table IV. Torsion Angles (Deg) for Oxaziridine **3** ($\langle\sigma\rangle < 2°$)

C(3)-O(1)-N(2)-C(9)	113
N(2)-O(1)-C(3)-C(4)	102
N(2)-O(1)-C(3)-C(8)	−119
O(1)-N(2)-C(3)-C(4)	−109
O(1)-N(2)-C(3)-C(8)	105
C(9)-N(2)-C(3)-O(1)	−94
C(9)-N(2)-C(3)-C(4)	158
C(9)-N(2)-C(3)-C(8)	12
O(1)-N(2)-C(9)-C(10)	−155
O(1)-N(2)-C(9)-C(16)	84
C(3)-N(2)-C(9)-C(10)	−94
C(3)-N(2)-C(9)-C(16)	146
O(1)-C(3)-C(4)-C(5)	−161
N(2)-C(3)-C(4)-C(5)	−90
C(8)-C(3)-C(4)-C(5)	60
O(1)-C(3)-C(8)-C(7)	164
N(2)-C(3)-C(8)-C(7)	88
C(4)-C(3)-C(8)-C(7)	−57
C(3)-C(4)-C(5)-C(6)	−59
C(4)-C(5)-C(6)-C(7)	60
C(4)-C(5)-C(6)-C(17)	−176
C(5)-C(6)-C(7)-C(8)	−58
C(17)-C(6)-C(7)-C(8)	179
C(5)-C(6)-C(17)-C(18)	64
C(5)-C(6)-C(17)-C(19)	180
C(5)-C(6)-C(17)-C(20)	−60
C(7)-C(6)-C(17)-C(18)	−174
C(7)-C(6)-C(17)-C(19)	−59
C(7)-C(6)-C(17)-C(20)	62
C(6)-C(7)-C(8)-C(3)	55
N(2)-C(9)-C(10)-C(11)	−45
N(2)-C(9)-C(10)-C(15)	136
C(16)-C(9)-C(10)-C(11)	72
C(16)-C(9)-C(10)-C(15)	−107
C(9)-C(10)-C(11)-C(12)	180
C(15)-C(10)-C(11)-C(12)	−2
C(9)-C(10)-C(15)-C(14)	178
C(11)-C(10)-C(15)-C(14)	0
C(10)-C(11)-C(12)-C(13)	2

The structure of oxaziridine **3** characterized by the *tert*-butyl group and the nitrogen atom, respectively, in equatorial and axial positions on the cyclohexane ring agrees with the conclusions concerning the formation of spirooxaziridines previously suggested by ^{1}H NMR studies (on the basis of the NMR results, we concluded that the peroxy acid attack occurs from the proequatorial face in imines showing no steric hindrance)[18,19] (Scheme III).

Table I gives the atomic positional parameters, and Tables II to IV show the bond lengths, bond angles, and torsion angles, respectively (see, Experimental Section). Figure 2 describes a stereoview of the molecular packing. The conformation of the molecule can be defined by the angles between the mean plane

(18) Oliveros, E.; Rivière, M.; Lattes, A. *Org. Magn. Reson.* **1976**, *8*, 601-606.
(19) Oliveros, E.; Rivière, M.; Lattes, A. *J. Heterocycl. Chem.* **1980**, *17*, 107-112.

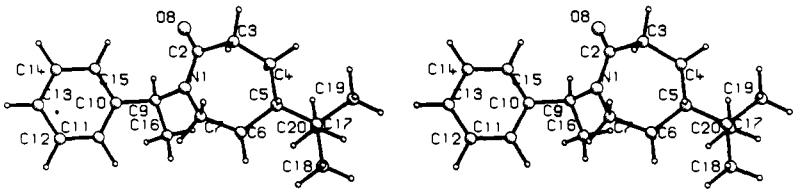


Figure 3. Stereoscopic view and the atom numbering of molecule **4a**.

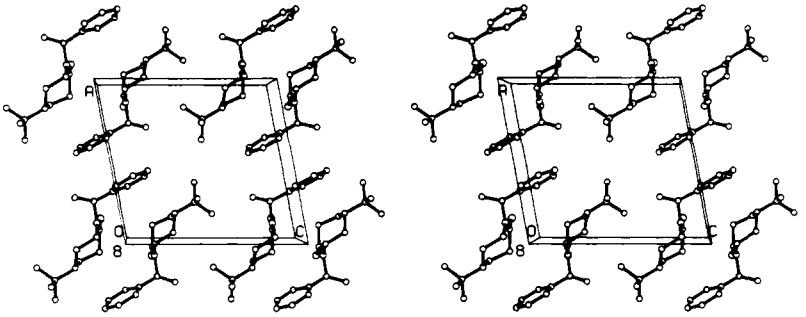


Figure 4. Crystal packing of molecules **4a**.

Table V. Fractional Atomic Coordinates ($\times 10^4$), Their Estimated Standard Deviations (in Parentheses), and the Equivalent Isotropic Temperature Factors (Å^2) for Lactam 4a

	x	y	z	B_{eq}
N(1)	1127 (2)	4921 (0)	8525 (2)	3.97
C(2)	642 (4)	3038 (8)	8552 (3)	4.65
C(3)	−780 (3)	2872 (7)	8322 (3)	5.06
C(4)	−1358 (4)	3472 (8)	7078 (3)	4.67
C(5)	−1631 (3)	5733 (7)	6869 (3)	3.99
C(6)	−436 (3)	7043 (7)	7188 (3)	4.43
C(7)	316 (3)	6715 (7)	8416 (3)	4.27
O(8)	1307 (3)	1518 (6)	8698 (3)	7.26
C(9)	2492 (3)	5182 (7)	8584 (3)	4.40
C(10)	3143 (3)	5908 (7)	9781 (3)	4.03
C(11)	3490 (3)	7893 (8)	10019 (3)	4.88
C(12)	4128 (4)	8442 (9)	11119 (4)	6.06
C(13)	4436 (4)	7012 (11)	11978 (4)	6.46
C(14)	4074 (4)	5012 (11)	11753 (4)	6.74
C(15)	3421 (4)	4466 (8)	10654 (3)	5.59
C(16)	2770 (4)	6489 (9)	7593 (3)	5.83
C(17)	−2359 (3)	6184 (8)	5614 (3)	4.74
C(18)	−2625 (4)	8465 (9)	5463 (4)	6.31
C(19)	−3620 (4)	5086 (11)	5390 (4)	8.15
C(20)	−1598 (5)	5558 (11)	4692 (3)	7.63

through the phenyl ring (plane 1), the plane of the oxaziridine ring (plane 2), and the plane containing the C(4), C(5), C(7), and C(8) carbons (plane 3). The dihedral angles have the following values: 1–2, 105°; 1–3, 22°; 2–3, 99°.

It is interesting to note that the cyclohexane ring easily accommodates the opening of the C(4)–C(3)–C(8) angle. This opening (from the normal 111°[20] to 115°) is associated with the closing of the two vicinal angles. The spiro structure of the molecule involving a three-membered ring leads to a slight puckering of the cyclohexane ring. Allowing for error, the bond lengths and angles for the oxaziridine ring are similar to values determined by Italian authors[21] in the case of (2*S*,α*R*)-2-(α-methylbenzyl)-3,3-diphenyloxaziridine (O–C 1.433 (4) Å, N–C 1.473 (3) Å, O–N 1.544 (3) Å; N–O–C 59.2 (2)°, O–N–C 56.7 (2)°, O–C–N 64.2 (2)°).

Photolysis of the Oxaziridine 3. According to Scheme I, our working hypothesis represented by cleavage a predicts that the rearrangement of **3** would lead to a lactam with an *S* configuration at C(5). Actually, irradiation of the optically pure oxaziridine **3** gave a single lactam with an 80% yield after purification and recrystallization. The optical purity (100%) of this lactam was checked by ^{1}H NMR spectroscopy and its structure established by X-ray analysis.

Table VI. Bond Lengths (Å) and Their Estimated Standard Deviations (in Parentheses) for Lactam 4a

N(1)-C(2)	1.347 (5)	C(9)-C(16)	1.514 (5)
N(1)-C(7)	1.461 (4)	C(10)-C(11)	1.373 (5)
N(1)-C(9)	1.470 (4)	C(10)-C(15)	1.384 (5)
C(2)-C(3)	1.510 (5)	C(11)-C(12)	1.389 (5)
C(2)-O(8)	1.224 (5)	C(12)-C(13)	1.371 (7)
C(3)-C(4)	1.524 (5)	C(13)-C(14)	1.385 (8)
C(4)-C(5)	1.528 (5)	C(14)-C(15)	1.393 (6)
C(5)-C(6)	1.538 (4)	C(17)-C(18)	1.533 (6)
C(5)-C(17)	1.560 (4)	C(17)-C(19)	1.518 (6)
C(6)-C(7)	1.527 (4)	C(17)-C(20)	1.522 (5)
C(9)-C(10)	1.522 (4)		

Table VII. Bond Angles (Deg) and Their Estimated Standard Deviations (in Parentheses) for Lactam 4a

C(2)-N(1)-C(7)	121.2 (3)	C(10)-C(9)-C(16)	113.6 (3)
C(2)-N(1)-C(9)	119.6 (3)	C(9)-C(10)-C(11)	123.2 (3)
C(7)-N(1)-C(9)	119.1 (3)	C(9)-C(10)-C(15)	117.5 (3)
N(1)-C(2)-C(3)	116.5 (3)	C(11)-C(10)-C(15)	119.3 (3)
N(1)-C(2)-O(8)	122.4 (3)	C(10)-C(11)-C(12)	120.3 (4)
C(3)-C(2)-O(8)	120.9 (3)	C(11)-C(12)-C(13)	120.7 (5)
C(2)-C(3)-C(4)	112.2 (3)	C(12)-C(13)-C(14)	119.4 (4)
C(3)-C(4)-C(5)	116.0 (3)	C(13)-C(14)-C(15)	119.9 (4)
C(4)-C(5)-C(6)	112.3 (3)	C(10)-C(15)-C(14)	120.4 (4)
C(4)-C(5)-C(17)	112.6 (3)	C(5)-C(17)-C(18)	110.3 (3)
C(6)-C(5)-C(17)	112.1 (3)	C(5)-C(17)-C(19)	110.7 (3)
C(5)-C(6)-C(7)	115.2 (3)	C(5)-C(17)-C(20)	111.6 (3)
N(1)-C(7)-C(6)	113.8 (3)	C(18)-C(17)-C(19)	107.7 (4)
N(1)-C(9)-C(10)	111.7 (3)	C(18)-C(17)-C(20)	107.3 (4)
N(1)-C(9)-C(16)	111.4 (3)	C(19)-C(17)-C(20)	109.1 (4)

Crystal and Molecular Structure of the Lactam Resulting from the Photolysis of Oxaziridine 3. Figure 3 is a stereoscopic drawing of the compound, giving the atom numbering. We chose to keep IUPAC numbering for the seven-membered ring. The other nonhydrogen atoms were arbitrarily numbered. The knowledge of the C(9) *S* chirality led to the determination of C(5) absolute configuration, which is also *S*. The lactam was then identified as (5*S*,α*S*)-5-*tert*-butyl-1-(α-methylbenzyl)hexahydro-2-azepinone, i.e., lactam **4a** in Scheme I. The atomic coordinates, bond lengths, and bond angles are given in Tables V–VII. The relevant torsion angles are listed in Table VIII (see Experimental Section).

The disposition of the molecules in the unit cell is shown in Figure 4. The seven-membered ring adopts a chair conformation.

(20) Engler, E. M.; Andose, J. D.; von R. Schleyer, P. *J. Am. Chem. Soc.* **1973**, *95*, 8005–8025.

(21) Forni, A.; Garuti, G.; Moretti, I.; Torre, G.; Andreetti, G. D.; Bocelli, G.; Sgarabotto, P. *J. Chem. Soc., Perkin Trans. 2* **1978**, 401–405 and referneces cited therein.

Table VIII. Torsion Angles (Deg) for Lactam 4a ($\langle\sigma\rangle < 1°$)

C(7)-N(1)-C(2)-C(3)	7
C(7)-N(1)-C(2)-O(8)	−176
C(9)-N(1)-C(2)-C(3)	−172
C(9)-N(1)-C(2)-O(8)	5
C(2)-N(1)-C(7)-C(6)	−75
C(9)-N(1)-C(7)-C(6)	103
C(2)-N(1)-C(9)-C(10)	−104
C(2)-N(1)-C(9)-C(16)	127
C(7)-N(1)-C(9)-C(10)	77
C(7)-N(1)-C(9)-C(16)	−51
N(1)-C(2)-C(3)-C(4)	66
O(8)-C(2)-C(3)-C(4)	−111
C(2)-C(3)-C(4)-C(5)	−87
C(3)-C(4)-C(5)-C(6)	59
C(3)-C(4)-C(5)-C(17)	−173
C(4)-C(5)-C(6)-C(7)	−53
C(17)-C(5)-C(6)-C(7)	179
C(4)-C(5)-C(17)-C(18)	179
C(4)-C(5)-C(17)-C(19)	60
C(4)-C(5)-C(17)-C(20)	−62
C(6)-C(5)-C(17)-C(18)	−53
C(6)-C(5)-C(17)-C(19)	−172
C(6)-C(5)-C(17)-C(20)	66
C(5)-C(6)-C(7)-N(1)	80
N(1)-C(9)-C(10)-C(11)	−101
N(1)-C(9)-C(10)-C(15)	81
C(16)-C(9)-C(10)-C(11)	26
C(16)-C(9)-C(10)-C(15)	−152
C(9)-C(10)-C(11)-C(12)	−177
C(15)-C(10)-C(11)-C(12)	0
C(9)-C(10)-C(15)-C(14)	177
C(11)-C(10)-C(15)-C(14)	−2
C(10)-C(11)-C(12)-C(13)	1
C(11)-C(12)-C(13)-C(14)	−2
C(12)-C(13)-C(14)-C(15)	1
C(13)-C(14)-C(15)-C(10)	0

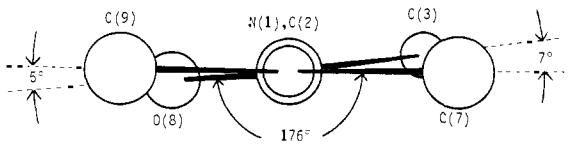


Figure 5. View of the amide group along the N(1)–C(2) bond of molecule **4a**.

The bond lengths of the lactam ring agree well with those Winckler and Dunitz[22] measured for unsubstituted hexahydro-2-azepinone (i.e., ϵ-caprolactam). Some differences are observed for bond angles and torsion angles, which are obviously more sensitive to substitution. The angle between the mean plane of the phenyl ring and the plane passing through N(1), C(2), and O(8) is approximately 116°. The deviation from planarity of the amide bond can be visualized in Figure 5.

Discussion

The photolysis of (2*R*,α*S*)-6(e)-*tert*-butyl-2-(α-methylbenzyl)-1,2-oxazaspiro[2.5]octane gave a single lactam identified as (5S,α*S*)-5-*tert*-butyl-1-(α-methylbenzyl)hexahydro-2-azepinone by our X-ray diffraction study. The *S* configuration of the carbon atom C(5) bearing the *tert*-butyl group can only be interpreted by the cleavage of the C–C bond in anti position with respect to the nitrogen lone pair.

These results (concerning a compound in which the two concurrent C–C bonds are chemically identical and can only be distinguished by stereoelectronic factors) provide clear evidence in support of the general stereoelectronic theory.

This theory has been developed by Deslongchamps[23] especially for the cleavage of tetrahedral intermediates that are formed during the hydrolysis of esters and amides. According to this author: "This general chemical process can take place whenever two heteroatoms (oxygen and/or nitrogen) and a leaving group are linked to the same carbon. The only requirement is a stereoelectronic one where each heteroatom should have a lone pair orbital oriented antiperiplanar to the leaving group." A theoretical justification of this rule has recently been given.[24] As for the oxaziridines, one of the two lone pairs is always provided by the oxygen atom, and consequently, the substituent migration is governed by the position of the nitrogen lone pair.

The importance of stereoelectronic factors in oxaziridines photochemical rearrangements is due to the following considerations: (i) The rearrangement of the singlet excited state (starting with the NO bond-breaking) is more efficient than a deactivation process inducing nitrogen inversion. (ii) During the rearrangement, nitrogen inversion cannot compete with the anti substituent migration, which occurs without any significant activation barrier.[9] The lower regioselectivity of thermal rearrangements[3,4] does not rule out the stereoelectronic theory; in this case, the energy required for the reaction is sufficient to induce nitrogen inversion in the starting oxaziridines and/or migration of the C substituent in syn configuration during the reaction process.

Experimental Section

General Data. IR spectra were recorded on a Beckman IR 20 A spectrophotometer; proton NMR spectra were determined in the indicated solvent on a CAMECA (250 MHz) spectrometer; chemical shifts are reported in ppm downfield from internal tetramethylsilane; coupling constants are given in hertz. Melting points are not corrected.

Preparation of (−)-(*S*)-*N*-(4-*tert*-Butylcyclohexylidene)-α-methylbenzylamine (2). This compound was prepared by condensation of 4-*tert*-butylcyclohexanone with (−)-(*S*)-α-phenylethylamine in benzene under azeotropic separation of water. After evaporating the solvent in vacuo, the product was purified by distillation in vacuo: yield 90%; bp 132 °C (0.7 mm Hg); $[\alpha]^{20}_D$ −57.5° (*c* 1.538, EtOH), $[\alpha]^{20}_{578}$ −60.6° (*c* 1.538, EtOH); IR (neat) 1660 cm^{-1} (C=N); ^{1}H NMR ($CDCl_3$) δ 0.60 (s, 9 H), 1.35 (d, 3 H, *J* = 6.5 Hz), 4.63 (m, 1 H, N–CH <), and aromatics.

Preparation of (2*R*,α*S*)-6(e)-*tert*-Butyl-2-(α-methylbenzyl)-1,2-oxazaspiro[2.5]octane (3). Oxidation of the imine was carried out as follows. A small excess of *m*-chloroperbenzoic acid (0.022 mol) in 40 mL of methylene chloride was added with stirring and cooling (0–5 °C) to a solution of 0.02 mol of the imine in 10 mL of the same solvent under a stream of nitrogen. After addition of the peracid, the mixture was allowed to stand at room temperature and filtered. The filtrate was washed twice with a dilute $NaSO_3$ solution, twice with a 10% Na_2CO_3 solution, and finally with water. The filtrate was dried with $MgSO_4$ and the solvent removed in vacuo. After crystallization from methanol, a pure diastereoisomer was obtained with 50% yield: mp 95–97 °C; $[\alpha]^{20}_D$ −30.6° (*c* 0.688, EtOH), $[\alpha]^{20}_{578}$ −32.7° (*c* 0.688 EtOH); IR (KBr) no absorption between 1500 and 1800 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.58 (s, 9 H), 1.58 (d, 3 H, *J* = 6.4 Hz), 3.60 (q, 1 H, *J* = 6.4 Hz), 7.30 (m, 5 H, aromatics).

The optical purity (100%) of the diastereoisomer **3** was checked by NMR using the chiral shift reagent tris[3-((trifluoromethyl)hydroxymethylene)-*d*-camphorato]europium(III).

X-ray Analysis of Oxaziridine 3. Single crystals were grown from a methanolic solution of $C_{18}H_{27}NO$. They presented an orthorhombic symmetry, space group $P2_12_12_1$, with *a* = 17.741 (6), *b* = 6.130 (2), and *c* = 15.558 (6) Å, *V* = 1692.0 (10) Å^3, *Z* = 4, M_r = 273.40, ρ(calcd) = 1.07 Mg m^{-3}.

The intensities of 1479 independent reflections were collected on a Syntex $P2_1$ diffractometer using graphite-monochromatized Mo Kα radiation (λ 0.7107 Å) and the ω-scan technique up to $2\theta = 47°$. Only 780 reflections were considered as having been observed [$I > 2.5(I)$]; these were included in the refinement. The structure was solved by direct methods using the MULTAN78 computer system.[25] An *E* map clearly showed all the nonhydrogen atomic positions of the molecule. The refinement was carried out by the SHELX76 program,[26] with anisotropic

(22) Winckler, F. K.; Dunitz, J. D. *Acta Crystallogr., Sect. B* **1975**, *21*, 268–269.

(23) Deslongchamps, P.; Cheriyan, U. O.; Pradère, J. P.; Soucy, P.; Taillefer, R. J. *Nouv. J. Chim.* **1979**, *3*, 343–350 and references cited therein.

(24) Lehn, J. M.; Wipff. G. *J. Am. Chem. Soc.* **1980**, *102*, 1347–1354 and references cited therein.

(25) Main, P.; Hull, S. E.; Lessinger, L.; Germain, G.; Declercq, J. P.; Woolfson, M. M. (1978), MULTAN78, A system of Computer Programs for the Automatic Solution of Crystal Structures from X-Ray Diffraction Data, Universities of York (England) and Louvain (Belgium).

(26) Sheldrick, G. M. (1976) SHELX76, A Program for Crystal Structure Determination, University of Cambridge (England).

thermal parameters for the nonhydrogen atoms. Hydrogen positions were determined from the geometry of the molecule. All the hydrogen atoms were refined with one overall isotropic temperature factor (8.9 Å^2). The final conventional R index was 0.061.

Photolysis of Oxaziridine 3. Nitrogen was bubbled through a cyclohexanic solution of oxaziridine **3** (100 mg/10 mL) for 30 min in order to remove all traces of air. The solution was then irradiated during 8 h in a Rayonet photochemical reactor, Model RPR 100, which was equipped with 16 RPR 2537-Å lamps.

The crude product (yellow oil) was purified by preparative TLC (Kieselgel 60 $PF_{254+366}$, 10% EtOH in $CHCl_3$). The yield of the pure lactam **4a** is ~80% from oxaziridine **3** (400 mg of starting substrate **3** yielded 311 mg of crystallized lactam **4a**): mp 90–95 °C; $[\alpha]^{20}_D$ −143° (c 0.32, MeOH); $[\alpha]^{20}_{578}$ −153° (c 0.32, MeOH); IR ($CHCl_3$) 1660 cm^{-1} (C=O amide); ^{1}H NMR ($CDCl_3$) δ 0.85 (s, 9 H), 1.47 (d, 3 H, J = 7.10 Hz), 5.96 (q, 1 H, J = 7.10 Hz), 7.20 (m, 5 H, aromatics); mass spectrum is in accord with the structure.

X-ray Analysis of Lactam 4a. Single crystals grown from a chloroform–ethanol 90/10 solution of $C_{18}H_{27}NO$ are monoclinic, space group $P2_1$ with a = 10.767 (8), b = 6.584 (3), and c = 11.666 (5) Å, β = 100.41 (5)°, V = 813.4 (8) Å^3, Z = 2, M_r = 273.40, ρ(calcd) = 1.12 Mg m^{-3}.

A total of 1321 reflections were collected, of which 1124 were considered as having been observed and were included in the refinement. All the experimental details that are not explicitly mentioned are the same as for oxaziridine **3**. For H atoms, B was 7.4 Å^2. The final conventional R index was 0.041.

Registry No. 1, 98-53-3; (*S*)-**2**, 81583-85-9; **3**, 81583-86-0; **4a**, 81583-87-1; (−)-(*S*)-α-phenylethylamine, 2627-86-3.

Supplementary Material Available: Tables of the final thermal parameters and observed and calculated structure factors for oxaziridine **3** and lactam **4a** (12 pages). Ordering information is given on any current masthead page.

Determination of Addition Rates of Benzenethiyl Radicals to Alkynes by Flash Photolysis. Structures of Produced Vinyl-Type Radicals

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Abstract: The addition rate constants (k_1) of substituted benzenethiyl radicals to CH≡CR (R = Ph, n-C_3H_7, and $COOCH_3$) have been determined by flash photolysis. The Hammett reaction constant (ρ^+) was estimated for each alkyne: ρ^+(CH≡CPh) = +1.38, ρ^+(CH≡CC_3H_7) = +1.34, and ρ^+(CH≡CCOOCH_3) = +1.28. A small ρ^+ value for CH≡CCOOCH_3 was attributed to a decrease in the polar effect in the transition state. Similar ρ^+ values were estimated for the corresponding alkenes. A small difference in the ρ^+ values suggests that the reactivities of the alkynes and alkenes toward a thiyl radical may be mainly determined by the thermodynamic stabilities of the produced radicals (PhSCH=$\dot{C}$R and PhS$CH_2\dot{C}$HR). The rate constants (in M^{-1} s^{-1}) for the benzenethiyl radical were as follows: k_1(CH_2=CHPh) = 2.0 × 10^7, k_1(CH≡CPh) = 7.9 × 10^5, k_1(CH_2=CHCOOCH_3) = 2.7 × 10^5, k_1(CH≡CC_3H_7) = 1.4 × 10^4, k_1(CH_2=CHC_4H_9) = 1.0 × 10^4, and k_1(CH≡CCOOCH_3) = 8.3 × 10^3. The unpaired electron of PhSCH=$\dot{C}$COOCH_3 may be localized, whereas the unpaired electron of PhS$CH_2\dot{C}$HCOOCH_3 is stabilized by the interaction with the ester group. The stability of PhSCH=$\dot{C}$Ph is intermediate between the linear π radical and the localized σ radical.

Thiols and hydrogen bromide add to alkynes via a free-radical mechanism to yield substituted alkenes.[1,2] The addition of radicals to a triple bond yields a vinylic radical; the stereoselectivity and reactivity are controlled by the structure of the vinylic radical. The relative reactivities of substituted alkynes and alkenes toward the methyl acrylate radical or the acrylonitrile radical estimated from the copolymer compositions by Doak[3] were in agreement with those toward the methyl radical estimated by Gazith and Szwarc:[4] styrene (3.5–4.5), phenylacetylene (1.0), 1-hexyne (0.05–0.06), and 1-hexene (0.02–0.07). Fairly high reactivity of phenylacetylene compared to 1-hexyne was attributed to higher resonance stabilization of the α-phenyl vinylic radical.[3,4] This conclusion seems to be compatible with that from the ESR studies[5,6] or some stereochemical studies,[7–10] suggesting a linear π radical for the α-phenyl vinylic radical. In this paper, however, we will report our finding that the absolute rate constants for the addition reactions of the benzenethiyl radicals to phenylacetylene estimated by flash photolysis are intermediate between styrene and 1-pentyne. We will discuss the relation between the rate constants and the structures of the vinylic radicals after examining the polar effects in the transition state of the addition reactions.

Results and Discussion

The para-substituted benzenethiyl radicals were produced by xenon flash decomposition of the corresponding disulfides; transient absorption bands at ca. 500 nm were ascribed to the thiyl radicals.[11–13] They decayed with second-order kinetics, suggesting recombination (k_r) to produce the disulfides; from the slopes of the second-order plots ($2k_r/\epsilon$, where ϵ refers to the molar extinction coefficient of the thiyl radical), the concentrations of the thiyl radicals produced by one flash exposure were estimated to be ~10^{-7}–10^{-6} M on the basis of the assumption of the diffusion-

(1) Mayo, F. R.; Walling, C. *Chem. Rev.* **1940**, *27*, 351.
(2) Simamura, O. *Top. Stereochem.* **1969**, *4*, 21.
(3) Doak, K. W. *J. Am. Chem. Soc.* **1950**, *72*, 4681.
(4) Gazith, M.; Szwarc, M. *J. Am. Chem. Soc.* **1957**, *79*, 3339.
(5) Bennett, J. E.; Howard, J. A. *Chem. Phys. Lett.* **1971**, *9*, 460.
(6) Neilson, G. W.; Symones, M. C. R. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1405.
(7) Kopchik, R. M.; Kampmeier, J. A. *J. Am. Chem. Soc.* **1968**, *90*, 6733.
(8) Singer, L. A.; Chen, J. *Tetrahedron Lett.* **1969**, 4849.
(9) Ohnuki, T.; Yoshida, M.; Simamura, O.; Fukuyama, M. *Chem. Lett.* **1972**, 999.
(10) Panek, E. J.; Kaiser, L. R.; Whitesider, G. M. *J. Am. Chem. Soc.* **1977**, *99*, 3708.
(11) Thyrion, F. C. *J. Phys. Chem.* **1973**, *77*, 1478.
(12) Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1979**, *101*, 1815.
(13) Nakamura, M.; Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1980**, *102*, 698.

0002-7863/82/1504-3934$01.25/0