Acknowledgment. We are grateful to the National Institutes of Health, Grant GM 31958, for financial support.

Registry No. (–)-1, 617-12-9; (±)-3, 116130-11-1; 3 (isomer 1), 116257-37-5; 3 (isomer 2), 116183-36-9; (±)-4, 76947-23-4; 5 (isomer 1), 116183-37-0; 5 (isomer 2), 116183-38-1; (*E*)-6, 116130-12-2; (±)-6, 116183-39-2; 7, 116130-13-3; 8, 116130-14-4; 9, 116130-15-5; 10, 116130-16-6; 11 (isomer 1), 94903-41-0; 11 (isomer 2), 116183-40-5; 12 (isomer 1), 116130-17-7; 12 (isomer 2), 116183-41-6; 12 (2somer 3), 116130-18-8; 12 (isomer 4), 116130-19-9; (*E*)-13, 116130-20-2; (*Z*)-13, 116183-42-7; (*Z*)-14, 116130-21-3; (*E*)-14, 116183-43-8; (*Z*)-15, 116130-22-4; (*E*)-15, 116183-44-9; (*Z*)-16, 116130-23-5; (*E*)-16, 116183-45-0; (*Z*)-17, 116130-24-6; (*E*)-17, 116183-46-1; (*Z*)-18, 116130-25-7; (*E*)-18, 116183-47-2; (*Z*)-19, 116130-26-8; (*E*)-19, 116183-48-3; 20, 99-96-7; 21, 116130-27-9; 22, 116130-28-0; 23, 600-18-0; 27 (isomer 1), 116130-29-1; 27 (isomer 2), 116130-30-4; 27 (methyl ester, isomer 1), 91828-70-5; 27 (methyl ester, isomer 2), 116130-31-5; 28 (isomer 1), 116183-49-4; 28 (isomer 2), 116183-50-7; 29, 28645-07-0; (±)-29, 2328-26-9; (+)-30, 7782-24-3; (±)-30, 2328-24-7; (+)-31, 98819-68-2; trimethyl diazophosphonoacetate, 60190-78-5.

Supplementary Material Available: Table of the ^1H NMR chemical shift of the C_9 methyl group and the C_9 vinyl hydrogen of *Z* and *E* isomers (1 page). Ordering information is given on any current masthead page.

Formation of Polycyclic Dimers from Vinyl Nitroxides and Their Dissociation and Isomerization[1]

Hans Günter Aurich,* Otto Bubenheim, Wilfried Kessler, and Klaus-Dieter Mogendorf

Fachbereich Chemie, University of Marburg, Hans Meerwein-Strasse, D-3550 Marburg, Federal Republic of Germany

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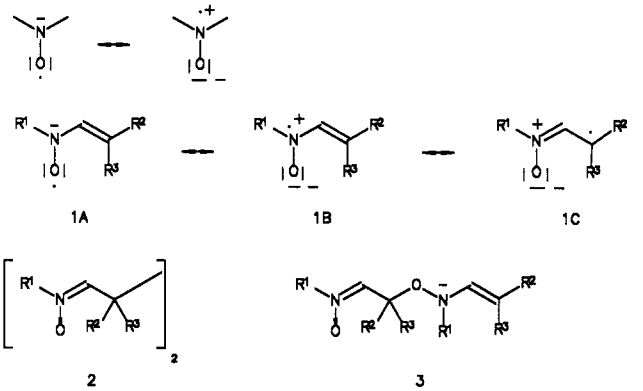
The ambiphilic vinyl nitroxides (VN) **6** dimerize, affording either tricyclic dimers (TRI-DI) **8** or bicyclic dimers (BI-DI) **7**. Formation of **8** is rationalized by C–C bond formation followed by an intramolecular (3 + 2 + 2) cycloaddition involving one nitrone and two carbonyl groups, whereas **7** must arise from O–C bond formation followed by an intramolecular (3 + 2) cycloaddition of nitrone and alkene moiety. Since the BI-DIs **7** are the thermodynamically more stable dimers, the course of the reaction depends on the question of whether it is possible to overcome the activation barrier for its formation. The crucial reaction step, the 1,3 dipolar cycloaddition involving the nitrone and alkene moiety, is favored by *N*-phenyl substitution and retarded by *N*-*tert*-butyl substitution of the nitrone group. Thus, BI-DIs **7** arise from *N*-phenyl-substituted VNs, whereas VNs with R^1 = *tert*-butyl yield TRI-DIs **8** at room temperature. Most of the TRI-DIs **8** dissociate at room temperature or slightly elevated temperatures. Dissociation is favored either by steric congestion of **8** or by enhanced stabilization of the acyl group R^3CO of the VNs **6**. Tetracyclic dimers (TET-DI) **12** arise from TRI-DIs **8** in refluxing methanol or in the presence of acids at room temperature. Isomerization in aprotic solvents in the absence of acids requires higher temperatures. Under these conditions formation of TET-DIs **12** is frequently accompanied by formation of BI-DIs **7** which must be formed via the VNs **6**.

The extraordinary thermodynamic stabilization of the nitroxide group by delocalization of the unpaired electron between nitrogen and oxygen atom is well documented.[2] Since the delocalization energy is in the order of 30 kcal/mol, dimerization by O–O bond formation is expected to be extremely unfavorable.[3] Thus, di-*tert*-alkyl nitroxides are persistent radicals that can be isolated in most cases. In contrast, vinyl nitroxides (VN) **1** are likely to be very reactive radicals. Since delocalization of the unpaired electron to the β-carbon atom of the vinyl group is possible (see mesomeric formula C), dimerization of these radicals with formation of C–C- or O–C-bonded dimers **2** or **3** is

Scheme I



anticipated to be energetically favorable (Scheme I).

Indeed, VNs formed by oxidation of the corresponding nitrones or hydroxylamines cannot generally be detected under standard conditions by ESR spectroscopy if they are only monosubstituted at the β-position (R^3 = H).[1a] Usually they are trapped rapidly by their precursor nitrones which are excellent spin traps.[4] If substituent R^2 is capable of conjugation (phenyl or an electron-acceptor group such as acyl or alkoxycarbonyl), dimers **2** or the corresponding dehydro dimers are formed in moderate to

(1) (a) Nitroxides (Aminyl Oxides). 39. For 38, see: Aurich, H. G., Eidel, J.; Schmidt, M. *Chem. Ber.* **1986**, *119*, 36. (b) Presented in part at the NATO Advanced Research Workshop on Substituent Effects in Radical Chemistry, Louvain-la-Neuve, Belgium, January 20–24, 1986 (Abstract: Nato ASI, Series C, Reidel: Dordrecht, 1986; Vol. 189, pp 195–198) and at the 8th IUPAC Conference on Physical Organic Chemistry 1986, Tokyo, Japan August 24–29, 1986 (Abstract: Studies in Organic Chemistry, Elsevier Science Publ.: Amsterdam, 1987; Vol. 31, pp 351–356).

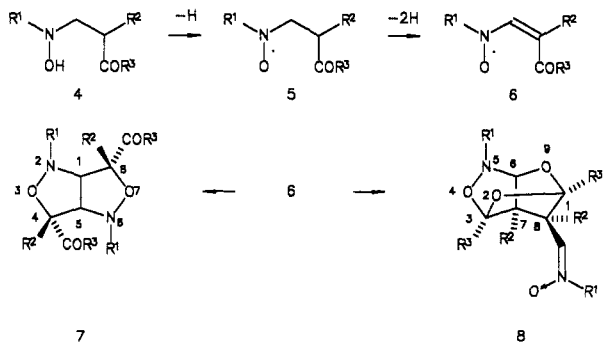
(2) (a) Forrester, A. R.; Hay, J. M.; Thomson, R. H. In *Organic Chemistry of Stable Free Radicals*, Academic Press: London and New York, 1968; p 190. (b) Rozantsev, E. G.; Sholle, V. D. *Synthesis* **1971**, 190 and 401. (c) Rozantsev, E. G. In *Free Nitroxyl Radicals*; Plenum Press: New York–London, 1970; p 125. (d) Aurich, H. G. In *The Chemistry of Functional Groups, Supplement F–Part 1, Chapter 14–Nitroxides*; Patai, S., Ed.; John Wiley & Sons: Chichester, 1982; p 566.

(3) (a) Bowman, D. F.; Gillan, T.; Ingold, K. U. *J. Am. Chem. Soc.* **1971**, *93*, 6555. (b) Mendenhall, G. D.; Ingold, K. U. *J. Am. Chem. Soc.* **1973**, *95*, 6390.

(4) Janzen, E. G. *Acc. Chem. Res.* **1971**, *4*, 31.

0022-3263/88/1953-4997$01.50/0

Scheme II[a]



A:	R^1 = *t*Bu; R^2 = Ph R^3	**B:**	R^1 = *t*-Bu; R^3 = Ph R^2	**C:**	R^1 = *t*-Bu R^3 = PhOMe-4 R^2
a:	Ph	**a:**	PhOMe-4	**a:**	Ph
b:	$PhNO_2$-4	**b:**	Me	**b:**	PhOMe-4
c:	$PhCH_3$-2	**c:**	*i*-Pr	**c:**	$PhNO_2$-4
d:	2-thienyl				
e:	*i*-Pr				
f:	Me				
D:	R^2 = $PhNO_2$-4 R^3 = Ph R^1	**E:**	R^2 = R^3 = Ph R^1	**F:**	R^1 = PhMe-4 R^2 = Me R^3 = Ph
a:	*t*-Bu	**a:**	Ph		
b:	c-C_6H_{11}	**b:**	$Me_2C(CN)$		
c:	$PhCH_2$	**c:**	Me		
d:	Me				

[a] The following dimers were isolated: TRI-DI 8, **Aa–f**, **Ba–b**, **Ca–c**, **Da–b**, **Eb**; BI-DI 7, **Dc–d**, **Ea–b**, **F**.

good yield under the oxidative conditions.[5]

On the other hand, β-disubstituted VNs are more or less persistent radicals, particularly if one of the two substituents is an electron-attracting group capable of conjugation.[6] Such radicals are of special interest, since their dimers of the type **2** or **3** can undergo intramolecular reactions in which the nitrone group and the other functionalities are involved. We discovered that β-acyl-substituted VNs (R^3 = COR) form different types of polycyclic compounds of unexpected structures which are derived from the C–C-bonded dimers **2**[7] as well as from the O–C-bonded dimers **3**.[8] In this sense the VNs exhibit ambiphilic properties. Herein we describe the influence of the substitution pattern on the course of the dimerization as well as on the dissociation and isomerization of these dimers.

Results and Discussion

A. Formation of Vinyl Nitroxides. Oxidation of the hydroxylamines **4** by lead dioxide in chloroform or dichloromethane initially gives the nitroxides **5**, as was confirmed by ESR spectroscopy. The nitrogen coupling constants a^N of the dialkyl nitroxides **5** (R^1 = alkyl) fall in the range between 14.3 and 15.8 G, those of the alkyl aryl nitroxides **5** (R^1 = aryl) between 11.0 and 11.7 G.[9] Further oxidation affords the VNs **6A–F** via the intermediate formation of nitrones (Scheme II).

In the absence of lead salts the VNs **6** are relatively persistent in solution. For instance, the half-life time of a 10^{-3} M solution of **6Aa** is about 36 h. Furthermore, this radical could not be reduced by various hydrogen donors, not even by such a strong hydrogen donor as 9,10-dihydroanthracene[13] in refluxing tetrahydrofuran. Lead salts, however, catalyze the dimerization of VNs **6**, reducing their lifetime considerably. The ESR coupling constants of the parent radical **6Aa** (for the substitution pattern see Scheme II) in dichloromethane are as follows: a^N = 8.8 G, $a^H_{\alpha\text{-C}}$ = 2.85 G, $a^H_{R^2}$ = 1.7 G (3 H; ortho, para), $a^H_{R^2}$ = 0.65 G (2 H; meta). The values for most of the other *N*-alkyl-substituted VNs are very similar (a^N = 8.65–9.0 G).[9]

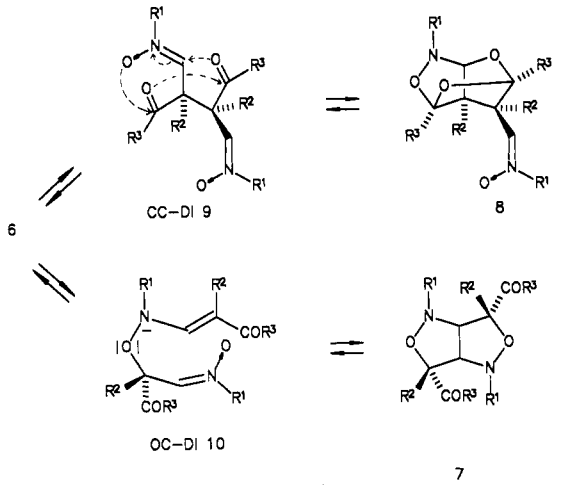
Due to the extended delocalization of the unpaired electron in VNs the nitrogen coupling constants of **6** are considerably smaller than those of dialkyl and alkylaryl nitroxides,[10] indicating a spin density ρ^N of approximately 0.26 to 0.27.[11] The coupling of the phenyl protons of R^2 indicates the delocalization of the unpaired electron into this phenyl group. Hence, the trans configuration of the nitroxide group and the phenyl group R^2 seems to be probable for steric reasons. As a consequence, the acyl group R^3CO should be more or less twisted against the plane of the vinyl group to avoid steric congestion. For **6Cc**, **6Da,b**, and **6Dd** (R^2 = $PhNO_2$-4) a^N is reduced to 8.0–8.1 G. This decrease is assumed to be due to a shift of spin density to the nitroxide oxygen (increasing importance of mesomeric formula **1A**) caused by the electron-attracting effect of the *p*-nitrophenyl group rather than by increased delocalization of the unpaired electron into the vinyl group and the aryl group R^2. Further exceptions are **6Bb** (a^N = 8.0 G, $a^H_{CH_3,R^2}$ = 8.95 G) and **6Bc** (a^N = 10.2 G). In the latter case the increase in a^N is due to the decreased delocalization. The decreased value of **6Bb**, however, points to a totally changed situation which may be caused by the decreased steric requirements of the methyl group. The coupling constant of 8.95 G for the methyl group of **6Bb** indicates a spin density of approximately 0.3 at the β-carbon atom.[12] The decreased values of **6Ea** (a^N = 8.1 G) and **6F** (a^N = 8.1 G) correspond to an additional delocalization into the aryl group R^1. Generally, the differences in the spin density distribution of the VNs **6** are not so large as to affect the way of their dimerization in a crucial manner.

B. Dimerization of Vinyl Nitroxides. The tricyclic dimers **8** (TRI-DI) and/or the bicyclic dimers **7** (BI-DI) were isolated from the reaction mixture after evaporation of the solvent in moderate to good yields (see Experimental Section) by performing the oxidation of hydroxylamines **4** on a preparative scale.

Upon oxidation of the *N*-arylhydroxylamines **4Ea**[8] and **4F**, only the BI-DIs **7** were formed. In contrast, oxidation of *N*-alkylhydroxylamines **4A–C** yielded the TRI-DIs **8** in most cases (see Scheme II). The VN **6Bc** does not dimerize, presumably for steric reasons. From its reaction mixture only decomposition products were isolated. Likewise neither **7Ec** nor **8Ec** could be isolated, although VN **6Ec** was detected by ESR. Obviously dimerization cannot compete with further oxidation of the methyl group of this VN.

(5) Aurich, H. G.; Schmidt, M.; Schwerzel, T. *Chem. Ber.* **1985**, *118*, 1105.
(6) Aurich, H. G.; Schmidt, M.; Schwerzel, T. *Chem. Ber.* **1985**, *118*, 1087.
(7) Aurich, H. G.; Baum, G.; Massa, W.; Mogendorf, K.-D.; Schmidt, M. *Chem. Ber.* **1984**, *117*, 2615.
(8) Aurich, H. G.; Mogendorf, K.-D.; Schmidt, M. *J. Org. Chem.* **1984**, *49*, 2654.
(9) For the spectral data of the individual compounds, see supplementary material.
(10) For comparison, see: Forrester, A. R. In *Landolt-Börnstein, Vol. 9, Magnetic Properties of Free Radicals, Part 1: Nitroxide Radicals*; Springer: Berlin, 1979; p 221 and 612, respectively.
(11) Using the first-order approximation, $a^N = Q^N_{NN}\rho^N$ with Q^N_{NN} = 33.1 G: Aurich, H. G.; Hahn, K.; Stork, K.; Weiss, W. *Tetrahedron* **1977**, *33*, 969.
(12) Using the equation $a^H_{CH_3} = Q^H_{CCH_3}\rho^C_{CCH_3}$ with $Q^H_{CCH_3}$ = −29 G: Fessenden, R. W.; Schuler, R. H. *J. Chem. Phys.* **1963**, *39*, 2147.
(13) Bockrath, B.; Bittner, E.; McGrew, J. *J. Am. Chem. Soc.* **1984**, *106*, 135.

Scheme III



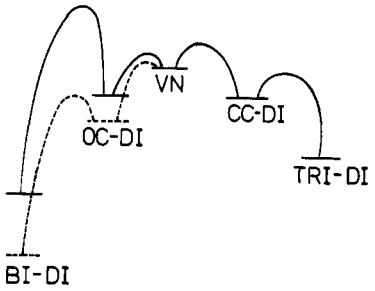
When the *tert*-butyl group R^1 in **6Aa** is replaced by the more electron-withdrawing 2-cyano-2-propyl group (**6Eb**), the TRI-DI **8Eb** is only formed to a small amount, BI-DI **7Eb** being the main product. Whereas oxidation of **4Da** and **4Db** yielded the TRI-DIs **8Da** and **8Db**, the BI-DIs **7Dc** and **7Dd** were the only products which could be isolated from oxidation of the corresponding hydroxylamines **4Dc** and **4Dd**.

The structures of the dimers **7** and **8** were elucidated with the aid of spectroscopic methods and confirmed by X-ray analyses of the parent compounds **7Ea**[14] and **8Aa**.[15] The characteristic NMR data are as follows.[9] TRI-DIs **8**: ^{13}C NMR C-1 and C-3 109.0–110.7 and 106.4–109.9 ppm, C-6 90.9–93.6 ppm (d, J = 170–180 Hz), C-7 and C-8 70.1–78.4 and 57.6–66.7 ppm, *C*-nitrone 129.3–132.0 ppm (d, J = 160–186 Hz); ^1H NMR H-6 δ 5.7–6.2 (exception **8Bb**). According to the appearance of two diastereomers **8Bb** exhibits two signals at 5.4 and 5.2 ppm. BI-DIs **7**: ^{13}C NMR C-1/C-5 72.5–80.8 ppm (d, J = 144–153 Hz), C-4/C-8 90.9–96.2 ppm, C=O 191.4–200.7 ppm; ^1H NMR H-1/H-5 δ 5.5–6.55. As the NMR spectra reveal, only one of the possible diastereomeric products is formed for all compounds **8** as well as **7**, with the exception of TRI-DI **8Bb**. In the case of **8Bb** the two diastereomers with different configuration at C-8 are formed in a ratio of approximately 1:1. The configurational assignment of the standard dimers **7Ea** and **8Aa** is based on X-ray analyses.[14,15] Presumably the stereochemistry does not vary within the two types of dimers.

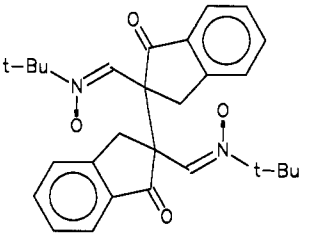
Since the partial formation of the BI-DIs **7** in the isomerization of the TRI-DIs **8** (vide infra) indicates that the former are thermodynamically more stable, formation of the TRI-DIs must be kinetically controlled.

The formation of three or four bonds in a single reaction step giving the BI-DIs **7** or the TRI-DIs **8**, respectively, is rather improbable. Therefore it is reasonable to assume that dimerization starts with formation of O–C single-bonded dimer **10** (OC-DI) or C–C single-bonded dimer **9** (CC-DI) (Scheme III). In the second reaction step the OC-DI undergoes an intramolecular (3 + 2) cycloaddition[16] of the nitrone group and the enaminoxy group giving the BI-DI **7**, whereas the TRI-DI **8** is formed by a (3 + 2 + 2) cycloaddition of CC-DI **9** involving one nitrone and two carbonyl groups.

Scheme IV. Schematic Presentation of the Dimerization Pathways of VNs 6



Indeed, such an OC-DI (**10**) could never be isolated, but a CC-DI (**11**) arose from dimerization of the corresponding VN **6** (R^2CCOR^3 = oxoindanylidene) as a 2:1 mixture of *d,l* and meso forms.[17] The separated diastereomers **11** equilibrated in solution after several hours, indicating that C–C dimerization is reversible.[18]



11

The CC-DIs **9** constitute hexasubstituted ethanes with considerable repulsive interactions. In one of the staggered conformations one of the nitrone groups and the two carbonyl groups are held tightly together at rather short distances. Obviously, this proximity effect[19] is responsible for the unusual intramolecular (3 + 2 + 2) cycloaddition.[20] Thus, once the CC-DI **9** is formed in the proper conformation, it easily undergoes the cycloaddition process. Merely for compound **11** this reaction is blocked by the rigidity of the molecule which would give rise to a severely strained TRI-DI.

From the formation of compound **11** the conclusion may be drawn that the C–C-bonded dimer is slightly favored over the corresponding O–C-bonded dimer, at least in this case. However, the enaminoxy group of **10** can be stabilized by more electronegative substituents as for instance R^1 = phenyl or 2-cyano-2-propyl[21] as well as R^2 = 4-nitrophenyl. At least with the *p*-nitrophenyl group R^2 the *N*-alkyl-substituted CC-DI and OC-DI should be energetically comparable since both BI-DI and TRI-DI are

(14) Aurich, H. G.; Baum, G.; Massa, W.; Mogendorf, K.-D., submitted to *Acta Crystallogr.*

(15) Aurich, H. G.; Baum, G.; Massa, W.; Mogendorf, K.-D. *Acta Crystallogr., Sect. C* **1985**, *C41*, 573.

(16) For reviews, see: (a) Houk, K. N. *Acc. Chem. Res.* **1975**, *8*, 361. (b) Padwa, A. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 123. (c) Oppolzer, W. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 10. (d) Tufariello, J. J. In *1,3 Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984, p 83, see p 116.

(17) Aurich, H. G.; Bubenheim, O.; Schmidt, M. *Chem. Ber.* **1986**, *119*, 2756.

(18) As only one of the two possible diastereomeric forms of the TRI-DI **8** is formed with the exception of **8Bb**, only one of the two diastereomeric forms of the CC-DIs **9** undergoes the (3 + 2 + 2) cycloaddition. Nevertheless, the yield of TRI-DI **8Aa**, arising from the *d,l*-configurated CC-DI, exceeds even 90%. This seems to be a further indication of the reversibility of the reaction step **6** ⇌ **9**.

(19) For a recent discussion of proximity effects on reactivity, see: Dorigo, A. E.; Houk, K. N. *J. Am. Chem. Soc.* **1987**, *109*, 3698 and references cited there.

(20) A similar reaction sequence with formation of four C–O bonds in the HCl-catalyzed dimerization of several 1,3-dicarbonyl compounds was recently described: Tsuboi, S.; Ono, T.; Takeda, A. *Heterocycles* **1986**, *24*, 2007.

(21) The strong electron-withdrawing effect of the 2-cyano-2-propyl group is reflected by its effect on the basicity of amines: Stevenson, G. W.; Williamson, D. *J. Am. Chem. Soc.* **1958**, *80*, 5943.

Table I. Dissociation of TRI-DIs 8 at 49 °C (10^{-2} M in THF)

8, R^1 = *t*-Bu	R^2	R^3	10^4[R•] (mol L^{-1})	$10^2\alpha$[a]	10^6K (mol L^{-1})	ΔG (kcal mol^{-1})
8Aa	Ph	Ph	2.5	1.25	6.4	7.7
8Ab	Ph	$PhNO_2$-4	1.8	0.9	3.1	8.1
8Ac	Ph	$PhCH_3$-2	18.1	9.05	360	5.1
8Ad	Ph	2-thienyl	7.8	3.9	63.5	6.2
8Af	Ph	Me	<0.05	<0.025	<0.0025	>12.7
8Ba	PhOMe-4	Ph	2.8	1.4	7.8	7.55
8Ca	Ph	PhOMe-4	6.8	3.4	47.9	6.4
8Cb	PhOMe-4	PhOMe-4	6.3	3.15	41.0	6.5
8Cc	$PhNO_2$-4	PhOMe-4	2.3	1.15	5.2	7.8
8Da	$PhNO_2$-4	Ph	1.0	0.5	1.0	8.85

[a] The values given in the preliminary reports[1b] for the dissociation of some of the dimers 8 were much too high because of several inaccuracies caused by the equipment.

formed, depending on the nature of R^1 (**7Dc/7Dd** versus **8Da/8Db**). A comparison of the two single-bonded intermediates CC-DI and OC-DI shows that the former is much more sterically hindered. In contrast to the CC-DI **9**, the OC-DI **10** is a more flexible molecule which must adopt an energetically less favorable conformation to undergo the intramolecular (3 + 2) cycloaddition giving the BI-DI **7**. With the assumption that the formation of OC-DI **10** is also reversible, the intramolecular (3 + 2) cycloaddition of **10** to afford **7** is the crucial step in this reaction. Since *N*-phenyl-substituted nitrones exhibit a higher reactivity in 1,3-dipolar cycloaddition as compared to *N*-alkyl-substituted nitrones,[22,23] the activation barrier for the conversion OC-DI **10** → BI-DI **7** can be overcome for the *N*-phenyl-substituted VNs **6Ea** and **6F**, whereas this pathway is blocked for all the *N*-*tert*-butyl-substituted VNs **6** at room temperature. The latter form instead the TRI-DIs **8** by a kinetically controlled reaction. In this case formation of OC-DI **10** is only part of an unproductive equilibrium (see Scheme IV). The different products from **6Da,b** on the one hand and from **6Dc,d** on the other hand may also be rationalized by the different reactivity of the corresponding nitrone groups in intramolecular 1,3-dipolar cycloaddition.[24]

C. Dissociation of Dimers. Generally, the TRI-DIs **8** dissociate in solution to give VNs **6** (exception **8Bb**). However, the conditions under which dissociation is observed are quite different. Most TRI-DIs dissociate even at room temperature, albeit very slowly. On the other hand, several radicals could be detected only at elevated temperatures. For instance, in a 10^{-3} M solution of **8Aa** the radical **6Aa** was detected at room temperature after about half an hour, whereas its ESR signal was immediately observed when the solution was warmed up to 40 to 50 °C. The situation is similar for most of the TRI-DIs **8**. In contrast, the instantaneous dissociation of **8Eb**, **8Da**, and **8Af** can be observed only at much higher temperatures (**Eb**: 100 °C in toluene; **Da** and **Af**: 120–130 °C in mesitylene). Accordingly, dissociation of **8Da** in tetrahydrofuran (THF) at 50 °C occurs so slowly that it takes several hours until equilibrium concentration is reached. TRI-DI **8Bb** does not dissociate at all up to 160 °C.

Table I gives a comparison of the radical concentrations arising from 10^{-2} M solutions of TRI-DIs **8** in THF at 49 °C and the corresponding α, K, and ΔG values for the equilibrium **8** ⇌ 2 **6**. (Degree of dissociation (α) = percentage of dimer which is dissociated.)

On the basis of the determination of K at 49 °C the concentration of radical **6Aa** was determined from the height of the amplitudes of a selected ESR line at various temperatures.[25] The plot of ln K vs $1/T$ gave a straight line for two independent series of measurements. From the slope of the line the dissociation enthalpy $\Delta H°_{diss}$ = 22.3 ± 2 kcal·mol^{-1} [26] was determined according to the van't Hoff equation (1). From eq 2 the entropy $\Delta S°_{diss}$ was evaluated to 45.5 ± 3 eu at 49 °C.

$$\frac{d \ln K}{dT} = \frac{\Delta H_{diss}}{RT^2} \quad (1)$$

$$\Delta G = -RT \ln K = \Delta H - T\Delta S \quad (2)$$

The steric effect of substituent R^3 which destabilizes the dimer is revealed by the high degree of dissociation of TRI-DI **8Ac**. Steric effects of substituents R^2, of course, play a far more important role. Thus, dimerization of radical **6Bc** is even prevented by the larger steric requirement of the isopropyl group R^2 as compared to methyl (**6Bb**). Since **8Bb** does not dissociate up to 160 °C, the stabilization of VNs **6** by the phenyl group R^2 seems to be essential for the dissociation of the TRI-DIs. As formation of VNs **6** from TRI-DIs **8** is accompanied by development of conjugation between substituent R^3 and the carbonyl group (exception: **6Ae** and **6Af**) dissociation increases with increasing electron-donating power of R^3 (**Ab** < **Aa** < **Ca** < **Ad**).

The VN **6Aa** is also formed by dissociation of the BI-DI **7Aa** and the TET-DI **12Aa** (vide infra); however, much higher temperatures are required in these cases (90 °C in toluene and 120 °C in mesitylene, respectively). However, **6Aa** could not be detected when a solution of BI-DI **7Aa** in THF was kept at 50 °C for several hours. On the other hand, the *N*-phenyl-substituted BI-DI **7Ea** does not dissociate at all, not even when its solution in mesitylene is heated up to 160 °C for a short period.

D. Isomerization of the Dimers. The TRI-DIs **8Aa**, **8Ac–f**, **8Ba,b**, and **8Ca,b** isomerize either at room tem-

(22) (a) Huisgen, R.; Seidl, H.; Brüning, I. *Chem. Ber.* **1969**, *102*, 1102. (b) Dolbier, W. R., Jr.; Wicks, G. E.; Burkholder, C. R. *J. Org. Chem.* **1987**, *52*, 2196. (c) Liguori, A.; Ottana, R.; Romeo, G.; Sindona, G.; Uccella, N. *Tetrahedron* **1988**, *44*, 1247.

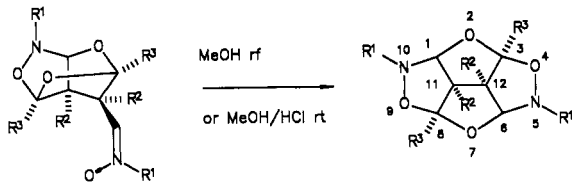
(23) Application of frontier molecular orbital theory to the cycloaddition between nitrones and alkenes leads to the conclusion that the LUMO(nitrone)–HOMO(alkene) as well as the HOMO(nitrone)–LUMO(alkene) interaction is important: see ref 16d, p 101. As was calculated for *C*-phenylnitrones (see ref 22c) substitution of the *N*-methyl group by *N*-phenyl lowers the LUMO and raises the HOMO of the nitrone, thus diminishing the gap for both types of interactions. If this is generally true for nitrones, the question of which type of interaction is dominant would be irrelevant in the case under consideration.

(24) There are several examples where the reactions of *N*-*tert*-butylnitrones differ markedly from those of the corresponding *N*-methylnitrones: De Sarlo, F.; Brandi, A.; Guarna, A. *J. Chem. Soc., Perkin Trans. 1* **1982**, 1395. Padwa, A.; Kline, D. N.; Koehler, K. F.; Matzinger, M.; Venkatramanan, M. K. *J. Org. Chem.* **1987**, *52*, 3909. Aurich, H. G.; Kesselheim, H.-P.; Schmidt, M. *Tetrahedron Lett.* **1988**, *29*, 307.

(25) Vincow, G.; Dauben, H. J., Jr.; Hunter, F. R.; Volland, W. V. *J. Am. Chem. Soc.* **1969**, *91*, 2823.

(26) An estimation of $\Delta H°_{diss}$ by measurement of the spin concentration at various temperatures was kindly performed by Prof. W. P. Neumann and Dr. U. Stewen, University of Dortmund. The value of $\Delta H°$ = 20.9 kcal mol^{-1} found by them agrees with our value.

Scheme V[a]



8 12

[a] MeOH reflux or MeOH/HCl rt: **Aa**, **Ac–f**, **Ba–b**, **Ca–b**. MeOH/HCl reflux: **Ab**, **Da–b**. Aprotic solvents: 8 $\overset{\Delta}{\rightarrow}$ 12 + 7.

Table II. Isomerization of TRI-DIs 8 in Aprotic Solvents

	reactn time (h)	product yield, % 12	7
8Aa[a]	20	36	21[d]
8Ad[b]	18	0	95
8Ba[a]	18	48	7[e]
8Ca[a,f]	18	17	50
8Cb[a]	20	30	35
8Cc[c]	3	0	76
8Af[a]	8	>80	0
8Bb[a]	8	>80	0

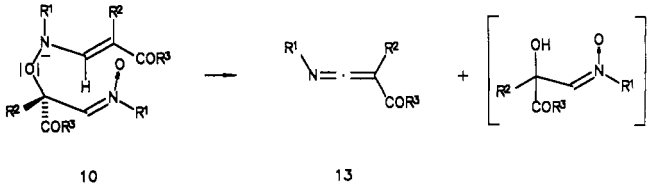
[a] In benzene at 80 °C. [b] In THF at 65 °C. [c] In toluene at 110 °C. [d] In addition 15% ketene imine **13Aa** was formed. [e] In addition 40% ketene imine **13Ba** was formed. [f] Both products were formed in almost the same yields after 15 min reflux in toluene at 110 °C.

perature in methanol in the presence of hydrochloric acid or in the absence of acid in refluxing methanol to give the TET-DIs **12** as the sole products. The *p*-nitrophenyl-substituted TRI-DIs **8Ab** and **8Da,b** undergo this isomerization in refluxing methanol in the presence of hydrochloric acid, whereas **8Cc** is decomposed under these conditions.

The rearrangement to the TET-DIs **12** is thought to proceed directly by breaking the bond between O-2 and C-1 followed by formation of two new bonds on the one hand between O-2 and the nitrone carbon and on the other hand between C-1 and the nitrone oxygen. In this case the dissociation of **8** seems to be only part of an unproductive equilibrium (Scheme V). In aprotic solvents, however, the behavior of most of the TRI-DIs is quite different. For instance, **8Aa**, which is isomerized to give **12Aa** in 93% yield after refluxing in methanol for 3 h, could be recovered almost quantitatively from refluxing at the same temperature in THF after 18 h. Likewise, isomerization of most of the other TRI-DIs **8** occurs in refluxing THF only to a negligible degree. There is one exception, however. From **8Ad** the BI-DI **7Ad** is formed in 95% yield after 18 h. In higher boiling aprotic solvents such as benzene or toluene isomerization of most of the TRI-DIs **8** takes place (see Table II). Under these conditions either the corresponding BI-DIs **7** are formed in addition to the TET-DIs **12** or the BI-DIs are the sole isomerization products. The isomerization is frequently accompanied by decomposition reactions, thus **8Ac** decomposes completely. However, those TRI-DIs which dissociate either under more drastic conditions or not at all do not form BI-DIs **7**. Whereas the TET-DIs **12** are the sole isomerization products from **8Af** and **8Bb**, no isomerization is found when **8Ab**, **8Da**, and **8Db** are heated in aprotic solvents.

The structures of the TET-DIs **12** were elucidated by their spectroscopic data[9] as well as those of the BI-DIs **7** (vide supra) and were additionally confirmed by X-ray analyses of **12Aa**[7] and **7Aa**.[14]

Scheme VI



10 13

The characteristic ^{13}C NMR data of TET-DIs **12** are as follows:[9] C-1/C-6 97.9–104.1 ppm (d, J = 165–169 Hz), C-3/C-8 114.8–119.5 ppm, C-11/C-12 69.6–84.5 ppm.

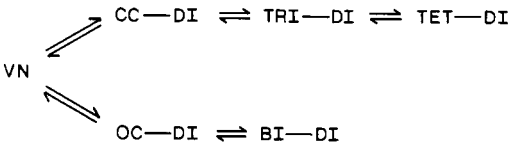
The isomerization of the TRI-DIs **8** to the BI-DIs **7** occurs via the VNs **6** and the OC-DIs **10**. At higher temperatures the reaction path to the thermodynamically more stable BI-DIs **7** is no longer blocked for the *N-tert*-butyl-substituted VNs **6**. Thus, the formation of BI-DIs **7** under these reaction conditions confirms the suggestion that the height of the activation barrier for the reaction step **10** → **7** determines the dimerization pathway of the VNs **6**.

Since the compounds **8Da** and **8Db** do not isomerize at all in the absence of acids, the *p*-nitrophenyl group R^2 seems to stabilize the TRI-DIs **8** considerably.

Conjugation between aryl groups R^3 and the carbonyl group which is lost in TRI-DIs **8** and TET-DIs **12** is retained in the BI-DIs **7** just as in the VNs **6**. Thus formation of BI-DIs **7** is increased with enhanced donor properties of R^3 (**7Ad**, **7Ca–c**). In particular, the behavior of the TRI-DI **8Cc** is interesting. Whereas the *p*-nitrophenyl group R^2 prevents the formation of the TET-DI **12Cc** by its stabilizing effect, the *p*-methoxyphenyl group R^3 lowers the activation barrier for the alternative reaction path.

Even several of the more stable isomers, the BI-DIs **7** and the TET-DIs **12**, can undergo isomerization under more drastic conditions. However, their isomerizations are accompanied by decomposition reactions. Thus, heating of the BI-DI **7Aa** in toluene for 5 h at 110 °C gave the TET-DI **12Aa** and the ketene imine **13a**, both in 15% yield, along with unchanged **7Aa** (60%).

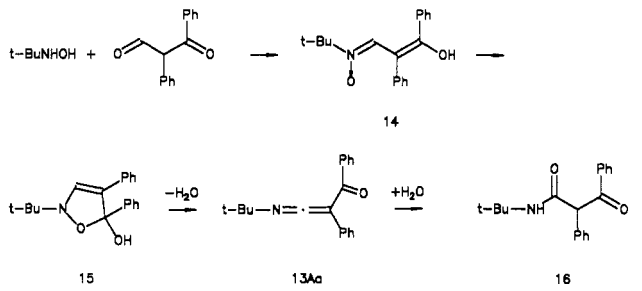
Prolonged heating increased the yield of **13a** as well as those of other unidentified decomposition products. In contrast, the *N*-phenyl-substituted BI-DI **7Ea** neither rearranges nor decomposes in refluxing toluene within 6 h. When the TET-DI **12Aa** was refluxed in mesitylene, formation of small amounts of BI-DI **7Aa** and ketene imine **13a** along with a larger quantity of decomposition products was detected.



Thus, all reaction steps are reversible in principle, however, the higher the temperatures the more isomerization is accompanied by decomposition reactions. Obviously, the formation of the ketene imine **13** is the key step in the decomposition of the dimers (Scheme VI). They can arise along with other products by disproportionation of the OC-DIs **10**.[27]

(27) It cannot be excluded that VNs **6** are reduced by the solvent at higher temperatures to afford the corresponding nitrones which then eliminate water, yielding finally the ketene imines **13**. However, this seems to be less probable since at least at 65 °C the VN **6Aa** being in equilibrium with the TRI-DI **8Aa** is not reduced in the presence of the extremely strong hydrogen donor 9,10-dihydroanthracene (See: A. Formation of Vinyl Nitroxides).

Scheme VII



The structure of **13a** was confirmed by an independent synthesis starting from *tert*-butylhydroxylamine and benzoylphenylacetaldehyde in chloroform in the presence of magnesium sulfate at room temperature. The initially formed nitrone **14**[28] presumably undergoes cyclization, affording the 3-isoxazoline **15** which eliminates water to yield **13a**. Hydrolysis of **13a** affords the amide **16** (Scheme VII).

Experimental Section

^{1}H NMR spectra were obtained on a Varian T60, JEOL FX-100, or Bruker WH 400 spectrometer. ^{13}C NMR spectra were recorded on a JEOL FX-100, Varian XL-100, or Bruker WH 400 spectrometer. Chemical shifts are reported with reference to tetramethylsilane. MS spectra were determined with Varian CH7 (EI) and 711 (FD) spectrometer. ESR measurements were performed with Varian EE9 and EE12 spectrometers.

ESR Spectra of Radicals 5 and 6. PbO_2 was added to a 10^{-3} to 10^{-4} M solution of the hydroxylamine **4** in an ESR tube. Alternatively, a probe of the reaction mixture was diluted. After several freezing/degassing cycles the tube was sealed and the spectrum was recorded.

Quantitative ESR Measurements. These measurements were performed in a dual cavity with a pitch sample as normalization standard. A special ESR tube was equipped with a chromel–alumel thermocouple which allowed temperature determination with an accuracy of ±0.05 °C. The thermocouple was dipped into the radical solution and the ESR tube was so adjusted that the thermocouple was put in the upper half of the cavity.

The degree of dissociation (α) and the dissociation constant (K) for the equilibrium TRI-DI **8Aa** ⇌ 2 VN **6Aa** in THF at 49 °C were determined as follows: The ESR signal of a 10^{-1} M solution of **8Aa** was measured without exclusion of oxygen. The line width of the three broad ESR lines was comparable to that of the diphenylpicrylhydrazyl (DPPH), a 10^{-3} M solution of which was used as reference. The first integration of the ESR signals was performed with the aid of the Varian spectro system 100 using the program parts MSAV (multi scan average) and SECI (second integral). The corresponding curve was plotted on graph paper and the second integration was performed by summing up the area under the curve. A comparison of the signal area of the VN with the area of the DPPH standard, normalized against the pitch, gave the radical concentration [R•]. The dissociation constant K and the degree of dissociation (α) were evaluated according to eq 3.

$$K = \frac{[R^\bullet]^2}{[R\text{–}R]} = \frac{4\alpha^2}{1-\alpha}C^\circ \qquad (3)$$

C° = concentration related to the total amount of dimer

Since the coupling constants of the *tert*-butyl β-aryl-β-aroylvinyl nitroxides **6** do not differ at first approximation, the line widths of the three broad ESR lines from nondegassed samples of 10^{-2} M solutions of the dimers **8** at 49 °C are equal. Thus the radical concentrations of the samples from substituted VNs **6** at 49 °C could be determined by measuring the amplitude height of their signals using the amplitude height of the signal of a 10^{-2} M solution of **8Aa** as a standard. The values for α, K, and ΔG at 49 °C in THF (Table I) were derived in this manner.

Temperature Dependence of the Concentration of VN 6Aa. Two solutions (2.44×10^{-3} and 1.49×10^{-3} M) of dimers **8Aa** in THF were carefully degassed; subsequently ESR measurements were performed under argon at various temperatures (from 37.6 to 58.6 °C). Well-resolved ESR spectra with sharp lines were obtained. Since the line widths are temperature-independent in the small temperature range, the height of the amplitudes is proportional to the radical concentration [R•].[25] [R•] at 49 °C is evaluated from the dissociation constant K and the dimer concentration. With use of this value as a standard, the radical concentration at all temperatures could be determined. According to the van't Hoff equation (1) the value of ΔH°_{diss} was determined from the slope of a plot of ln K_{equ} vs $1/T$.[29]

Preparation of Hydroxylamines 4. A solution of 25 mmol of hydroxylamine R^1NHOH in 10 mL of dichloromethane was added to a solution of 25 mmol of 1,2-disubstituted 2-propen-1-one $CH_2{=}CHR^2COR^3$ in 10 mL of dichloromethane. After 24 h the solvent was removed and 20 mL of diethyl ether was added to the residue. The hydroxylamines **4** crystallize after standing in the refrigerator for some days. Several of the compounds exist as cyclic semiketals in the solid state; however, in solution the ring opens to afford the tautomer **4**, as was indicated by their IR spectra in CCl_4.

The hydroxylamines **4** listed in Table III were prepared by this procedure. **4Aa**[7] and **4Ae**[8] are known; **4F** was directly oxidized.

Oxidation of Hydroxylamines 4. A solution of 10 mmol of **4** in 100 mL of dichloromethane or chloroform was dropped at 0 °C into a suspension of 20 g of PbO_2 in 300 to 500 mL of dichloromethane or chloroform, respectively, within 2 h. The reaction mixture was stirred for additional 15 h at room temperature. After separation from the solid residue the solvent was removed at room temperature. The remaining oil was dissolved

Table III

	yield (%)	mp (°C)	Anal. C, H, N	MS, m/e (M^+, relative intensity)
4Ab	35	104–106	$C_{19}H_{22}N_2O_4$	342 (7, EI)
4Ac	91	oil	*a*	311 (2, EI)
4Ad	71	102–103	$C_{17}H_{21}NO_2S$	303 (9, EI)
4Ae	82	46–48	$C_{16}H_{25}NO_2$	263 (3, EI)
4Af	57	84	$C_{14}H_{21}NO_2$	235 (7, EI)
4Ba	70	111–112	$C_{20}H_{25}NO_3$	327 (4, EI)
4Bb	91	73	$C_{14}H_{21}NO_2$	235 (100, FD)
4Bc	65	oil	*b*	263 (9, EI)
4Ca	74	109	$C_{20}H_{25}NO_3$	327 (2, EI)
4Cb	35	96–97	$C_{21}H_{27}NO_4$	357 (100, FD)
4Cc	52	oil	*c*	271 (M^+ – 101; 100, EI)
4Da	94	131–132	$C_{19}H_{22}N_2O_4$	342 (6, EI)
4Db	73	105	*d*	368 (100, FD)
4Dc	64	213–214	*e*	376 (100, FD)
4Dd	70	81	$C_{16}H_{16}N_2O_4$	300 (100, FD)
4Eb	24	105–106	$C_{19}C_{20}N_2O_2$	308 (6, EI)
4Ec	62	112–113	$C_{16}H_{17}NO_2$	255 (12, EI)

[a] $C_{20}H_{25}NO_2$ (311.4): MS (EI), m/e (relative intensity) 311 (M^+, 2); ^{1}H NMR ($CDCl_3$) 1.1 δ (s, 9 H, $C(CH_3)_3$), 2.4 (s, 3 H, CH_3), 2.5–4.0 (two br m, 2 H, CH_2), 5.8 (m, 1 H, CH), 6.6 (s, 1 H, OH), 7.0–7.6 (m, 9 H, Ar). [b] $C_{16}H_{25}NO_2$ (263.4): MS (EI), m/e (relative intensity) 263 (M^+, 9); ^{1}H NMR ($CDCl_3$) δ 0.9 (d, J = 7 Hz, 6 H, $CH(CH_3)_2$), 1.1 (s, 9 H, $C(CH_3)_3$), 1.7–3.8 (several br m, 4 H), 5.6 (s, 1 H, OH), 7.3–8.0 (m, 5 H, Ar). [c] Ready decomposition; $C_{20}H_{24}N_2O_5$ (372.4): ^{1}H NMR ($CDCl_3$) δ 1.2 (s, 9 H, $C(CH_3)_3$), 2.9–3.0 (m, 1 H, CH_2), 3.5–3.6 (m, 1 H, CH_2), 3.9 (s, 3 H, OCH_3), 4.9–5.2 (m, 2 H, CH + OH), 7.0–8.1 (m, 8 H, Ar). [d] Anal. Calcd for $C_{21}H_{24}N_2O_4$: C, 68.46; H, 6.56; N, 7.60. Found: C, 67.97; H, 6.71; N, 7.38. [e] Anal. Calcd for $C_{22}H_{20}N_2O_4$: C, 70.20; H, 5.35; N, 7.44. Found: C, 70.35; H, 4.87; N, 7.41.

(28) Nitrone **14** was isolated in the absence of magnesium sulfate. It exists in equilibrium with the keto-nitrone form in $CDCl_3$. In solution it undergoes easily conversion to ketene imine and other products. The corresponding *N*-phenylnitrone reacts in an analogous manner as was found by De Sarlo and Renzi: De Sarlo, F.; Renzi, G. *J. Chem. Soc., Perkin Trans. 1* **1978**, 1113.

(29) The values of [R•], α, K, and ΔG° for various temperatures are given in the supplementary material.

Table IV

	yield (%)	mp (°C)	Anal. C, H, N	MS, *m/e* (M^+, relative intensity)
8Aa[a]	91	163–164		
8Ab	61	152–153	$C_{38}H_{38}N_4O_8$	678 (100, FD)
8Ac	20	155	$C_{40}H_{44}N_2O_4$	616 (2, EI)
8Ad	70	132–133	$C_{34}H_{36}N_2O_4S_2$	600 (2, EI)
8Ae	47	135	$C_{32}H_{44}N_2O_4$	520 (4, EI)
8Af	40	134–135	$C_{28}H_{36}N_2O_4$	464 (20, EI)
8Ba	82	158–159	$C_{40}H_{44}N_2O_6$	648 (1, EI)
8Bb[b]	65	129–131	$C_{28}H_{36}N_2O_4$	464 (57, EI)
8Ca	85	129–130	$C_{40}H_{44}N_2O_6$	648 (6, EI)
8Cb	70	114–115	$C_{42}H_{48}N_2O_8$	708 (100, FD)
8Cc	72	170–171	*c*	738 (100, FD)
8Da	90	171–172	$C_{38}H_{38}N_4O_8$	678 (100, FD)
8Db	72	159–161	$C_{42}H_{42}N_4O_8$	729 (100, FD)

[a] See ref 7. [b] Two stereoisomers - fractionated crystallization from $CHCl_3/Et_2O$ (1:1) gave almost pure isomers. [c] Anal. Calcd for $C_{40}H_{42}N_4O_{10}$: C, 65.03, H, 5.73, N, 7.58. Found: C, 64.48, H, 5.66, N, 7.50.

Table V

	yield (%)	mp (°C)	Anal. C, H, N	MS, *m/e* (M^+, relative intensity)
7Dc	90	204–205	$C_{44}H_{34}N_4O_8$	746 (100, FD)
7Dd	42	195–196	*a*	594 (100, FD)
7Ea	93	199–200	$C_{42}H_{32}N_2O_4$	628 (100, FD)
7Eb	55	205–209	$C_{38}C_{34}N_4O_4$	610 (16, EI)
7F	52	194–195	*b*, *c*	532 (15, EI)

[a] ^1H NMR: 2.5 (s, 6 H, 2 x CH_3), 5.52 (s, 2 H, H-1/H-5), 7.3–8.3 (m, 18 H, Ar). ^{13}C NMR: 47.0 (q, J = 137 Hz, CH_3), 80.8 (d, J = 149 Hz, C-1/C-5); 94.4 (s, C-4/C-8), 123.1–147.6 (3s + 5d, Ar), 197.3 (s, C=O). [b] ^1H NMR: 1.5 (s, 6 H, 2 x CH_3), 1.8 (s, 6 H, 2 x CH_3Ph), 6.0 (s, 2 H, H-1/H-5), 6.8–8.1 (m, 18 H, Ar). ^{13}C NMR: 20.5 and 20.6 (q, J = 131 Hz, CH_3 at C-4/C-8 and CH_3Ph), 72.5 (d, J = 153 Hz, C-1/C-5), 90.9 (s, C-4/C-8), 116.7–145.2 (8 signals, Ar), 200.7 (s, C=O). [c] Formed along with 24% of 2-methyl-*N*-(4-methylphenyl)-3-oxo-3-phenylpropanamide, mp 150–152 °C. The two compounds were separated by thin layer chromatography (PSC silica gel $60F_{254}$, Merck).

in a small quantity of ether and kept at −35 °C until crystallization occurred.

In the case of **4Ac** and **4Eb**, reaction was performed at −10 °C and between −20 and −30 °C, respectively. The [(2,4,9-trioxa-5-azatricyclo[4.2.1.$0^{3,7}$]non-8-yl)methylene]amine *N*-oxides **8** listed in Table IV were isolated.

From the oxidation of **4Eb** a mixture of **7Eb** and **8Eb** was obtained. **7Eb** was separated from **8Eb** by fractionated crystallization in ether. **8Eb** was not obtained pure. **8Eb**: approximate yield 12%; ^1H NMR δ 1.1 (s, 3 H, CH_3), 1.5 (s, 3 H, CH_3), 1.75 (s, 6 H, CH_3), 6.2 (s, 1 H, H-1), 6.7–7.5 (m, 20 H, Ar), 8.0 (s, 1 H, nitrone); ^{13}C NMR 24.4 and 24.9 (q, J = 131 Hz, CH_3), 28.0 (q, J = 131 Hz, 2 × CH_3), 55.6 (s, $C(CN)(CH_3)_2$), 67.8 (s, $C(CN)(CH_3)_2$), 66.7/78.4 (s, C-7/C-8), 91.8 (d, J = 179 Hz, C-6), 109.3/110.5 (s, C-1/C-3), 118.7 (s, CN), 121.0 (s, CN), 121.7–134.9 ppm (17 signals, *C*-nitrone + phenyl).

The 3,7-dioxa-2,6-diazabicyclo[3.3.0]octanes **7** listed in Table V were isolated.

Isomerizations of TRI-DIs 8. (a) In Methanol. Concentrated hydrochloric acid (2 mL) was added to a solution of 0.5 g of TRI-DI **8** in 50 mL of methanol. After 1 h the solution was neutralized by sodium carbonate and extracted with dichloromethane. After washing with water and drying with magnesium sulfate, the dichloromethane was evaporated and the residue was treated with diethyl ether. Crystallization occurred between 0 °C and −40 °C. The TET-DIs **12** include solvent which could not be completely removed in some cases. The TET-DIs **12Ab**, **12Da**, and **12Db** could only be obtained when the acid solution was refluxed; **8Cc** decomposed under these conditions.

The isomerization of the other TRI-DIs also takes place when they are refluxed in methanol in the absence of acids for some hours.

Table VI

	yield (%)[a]	mp (°C)	Anal. C, H, N	MS, *m/e* (M^+, relative intensity)
12Aa[b]	95 (93)	215–217		
12Ab[c]	59	270	$C_{38}H_{38}N_4O_8$	678 (100, EI)
12Ac	93	118	*d*	616 (10, EI)
12Ad	50 (90)	201	*e*	600 (100, FD)
12Ae	89	213	*f*	520 (31, EI)
12Af	90	145	$C_{28}H_{36}N_2O_4$	464 (81, EI)
12Ba	45 (53)	192–193	$C_{40}H_{44}N_2O_6$	648 (100, FD)
12Bb	86	147	*g*	464 (2, EI)
12Ca	72 (61)	162–163	$C_{40}H_{44}N_2O_6$	648 (100, FD)
12Cb	66 (50)	217–218	$C_{42}H_{48}N_2O_8$	708 (100, FD)
12Da[c]	30	233–234	$C_{38}H_{38}N_4O_8$	678 (100, FD)
12Db[c]	30	260–261	$C_{42}H_{42}N_4O_8$	730 (100, FD)

[a] In brackets are given the yields in refluxing methanol in the absence of acid. [b] See ref 7. [c] In refluxing methanol in the presence of HCl. [d] ^1H NMR: 1.6 (s, 18 H, $C(CH_3)_3$), 1.8 (s, 6 H, CH_3), 6.2–8.0 (m, 20 H, H-1/H-6 + Ar). ^{13}C NMR: 21.6 (q, J = 118 Hz, CH_3), 27.3 (q, J = 127 Hz, $C(CH_3)_3$), 58.1 (s, $C(CH_3)_3$), 81.2 (s, C-11/C-12), 98.2 (d, J = 166 Hz, C-1, C-6), 119.5 (s, C-3/C-8), 125.0–139.4 (10 signals, Ar). [e] Anal. Calcd for $C_{34}H_{36}N_2O_4S_2$: C, 67.97; H, 6.04; N, 4.66. Found: C, 67.33; H, 6.11; N, 4.36. [f] ^1H NMR: 0.4 (d, J = 7 Hz, 6 H, $CH(CH_3)_2$), 0.9 (d, J = 7 Hz, 6 H, $CH(CH_3)_2$), 1.3 (s, 18 H, $C(CH_3)_3$), 1.6 (septet, J = 7 Hz, 2 H, $CH(CH_3)_2$), 6.3 (s, 2 H, H-1/H-6), 6.7–7.3 (m, 10 H, Ar). ^{13}C NMR: 1.1 (q, J = 118 Hz, $CH(CH_3)_2$), 17.9 (q, J = 118 Hz, $CH(CH_3)_2$), 27.4 (q, J = 125 Hz, $C(CH_3)_3$), 35.8 (d, J = 123 Hz, $CH(CH_3)_2$, 57.1 (s, $C(CH_3)_3$), 82.8 (s, C-11/C-12), 97.9 (d, J = 166 Hz, C-1/C-6), 117.9 (s, C-3/C-8), 126.0–136.4 (4 signals, Ar). [g] ^1H NMR 0.7 (s, 6 H, CH_3), 1.4 (s, 18 H, $C(CH_3)_3$), 5.2 (s, 2 H, H-1/H-6), 7.3–7.5 (m, 10 H, Ar). ^{13}C NMR: 17.7 (q, J = 124 Hz, CH_3), 26.4 (q, J = 127 Hz, $C(CH_3)_3$), 57.2 (s, $C(CH_3)_3$), 69.6 (s, C-11/C-12), 104.1 (d, J = 165 Hz, C-1/C-6), 118.4 (s, C-3/C-8), 126.8–139.2 (4 signals, Ar).

Table VII

	yield (%)	mp (°C)	Anal. C, H, N	MS, *m/e* (M^+/FD)
7Aa	20[a]	204–206	$C_{38}H_{40}N_2O_4$	588
7Ad	80[b]	219–220	$C_{34}H_{36}N_2O_4S_2$	600
7Ca	40[a]	202–203	*d*	648
7Cb	25[a]	196	$C_{42}H_{48}N_2O_8$	708
7Cc	70[c]	182–183	*e*	738

[a] In benzene. [b] In THF. [c] In toluene. [d] Anal. Calcd for $C_{40}H_{44}N_2O_6$: C, 74.05; H, 6.84; N, 4.32. Found: C, 73.56; H, 7.06; N, 4.13. [e] Anal. Calcd for $C_{40}H_{42}N_4O_{10}$: C, 65.03; H, 5.73; N, 7.58. Found: C, 64.56; H, 5.62; N, 7.40.

The 2,4,7,9-tetraoxa-5,10-diazatetracyclo[4.4.2.$0^{3,12}$.$0^{8,11}$]dodecanes **12** listed in Table VI were isolated.

(b) In Aprotic Solvents. TRI-DI **8** (0.5 g) was heated in 100 mL of benzene, toluene, or THF under reflux. (The solvents were dried and distilled from Na.) After evaporation of the solvent the residue was treated with diethyl ether, affording crystallized products. From **8Aa**, **8Ca**, and **8Cb** only mixtures of BI-DIs **7** and TET-DIs **12** arose. These were separated by fractionated crystallization from toluene/*n*-hexane (TET-DIs **12** crystallize first).

In this way the 3,7-dioxa-2,6-diazabicyclo[3.3.0]octanes **7** listed in Table VII were isolated.

The ratios of the isomerization products in Table II were determined by the ratio of the *tert*-butyl signals in the ^1H NMR spectra of the reaction mixture. The *tert*-butyl signals are as follows. TRI-DI **8Aa**, 1.05 and 1.30; BI-DI **7Aa**, 1.00; TET-DI **12Aa**, 1.55; ketene imine **13Aa**, 1.22 ppm. The signals of the other compounds correspond to these values. The appearance of the products was additionally checked by the characteristic signals in the ^{13}C NMR spectra of the mixture. The same method was used to determine the products formed by isomerization of **7Aa** in toluene and **12Aa** in mesitylene.

The BI-DI **7Aa** was prepared in a more convenient way as follows: A suspension of 4 g of PbO_2 in 30 mL of toluene was refluxed and a solution of 1 g of hydroxylamine **4Aa** in 20 mL of toluene was added. The mixture was heated for 1.5 h. After

removal of the solid residue the solvent was evaporated. When the oily mixture was treated with diethyl ether BI-DI **7Aa** was obtained in 20% yield.

1,2-Diphenyl-3-(*tert*-butylimino)-2-propen-1-one (13Aa). A mixture of 1 g of *tert*-butylhydroxylamine and 2.2 g of 1,2-diphenylpropane-1,3-dione in 50 mL of $CHCl_3$ was stirred in the presence of $MgSO_4$ for 24 h. After filtration and evaporation of the solvent **13Aa** was obtained as an oil in 61% yield: MS (EI), *m/e* (relative intensity) 277 (M^+, 4); IR (film) ν 2080 and 1650 cm^{-1}; ^1H NMR δ 1.2 (s, 9 H, $C(CH_3)_3$), 7.1-7.7 (m, 10 H, Ar); ^{13}C NMR 30.0 (q, J = 127 Hz, $C(CH_3)_3$), 62.5 (s, $C(CH_3)_3$), 107.9 (s, C-2), 126.1-141 (8 C, Ar), 168.0 (s, C-3), 193.0 (s, C-1).

***N*-*tert*-Butyl-2,3-diphenyl-3-oxopropanamide (16)** was formed from **13Aa** in refluxing aqueous ethanol: mp 178-180 °C; MS (EI), *m/e* (relative intensity) 295 (M^+, 4). Anal. Calcd for $C_{19}H_{21}NO_2$: C, 77.26; H, 7.17; N, 4.74. Found: C, 76.71; H, 7.41; N, 4.68.

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Supplementary Material Available: Listing of the ESR coupling constants of nitroxides **5** and **6**, of the characteristic NMR data of compounds **8**, **7**, and **12**, and of the values of $[R^\bullet]$, α, K, and ΔG for the equilibrium **8Aa** $\rightleftharpoons$ 2 **6Aa** at various temperatures (7 pages). Ordering information is given on any current masthead page.

Chemistry of Oxaziridines. 10.[1] Selective Catalytic Oxidation of Sulfides to Sulfoxides Using *N*-Sulfonyloxaziridines

Franklin A. Davis* and Sankar G. Lal

Department of Chemistry, Drexel University, Philadelphia, Pennsylvania 19104

H. Dupont Durst

Research Directorate, Chemical Research, Development and Engineering Center, Aberdeen Proving Ground, Maryland 2101-5423

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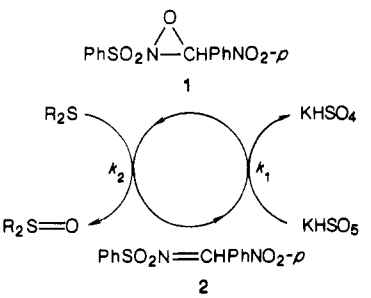
The chemoselective catalytic oxidation of aliphatic and aromatic sulfides to sulfoxides (90-95%) using a buffered potassium peroxymonosulfate (Oxone) generated *N*-sulfonyloxaziridine is described. This oxidizing system is rapid and relativily insensitive to the reaction parameters and the structure of the sulfide.

Sulfoxides are widely used synthons in organic synthesis and are commonly prepared by oxidation of sulfides.[2] The number of oxidizing reagents used for this purpose are many and varied because few, individually, have general or broad application.[2-9] Many of these oxidizing reagents are too reactive, resulting in significant overoxidation of sulfoxides to sulfones, particularly when the reagent is present in excess.[2b,3] With other reagents the chemoselectivity is poor, or they give undesirable side reactions such as cleavage of C-C and C-S bonds.[2b,3] Additional limitations include slow reaction rates, the necessity for careful control of the reaction parameters, instability, and expense.

Scheme I



A number of these limitations can be avoided by using *N*-sulfonyloxaziridines **1**, aprotic and neutral oxidizing reagents developed in our laboratories.[10,11] These reagents quantitatively and selectively oxidize most sulfides to

(1) Davis, F. A.; Chattopadhyay, S.; Towson, J. C.; Lal, S.; Reddy, T. *J. Org. Chem.* **1988**, *53*, 2087.

(2) For reviews of on the chemistry of sulfoxides, see: (a) Durst, T. In *Comprehensive Organic Chemistry*, Jones, D. N., Ed.; Pergamon Press, Ltd.: Oxford, 1979, Chapter 6. (b) Oae, S. In *Organic Chemistry of Sulfur*, Oae, S., Ed.; Plenum Press: New York, 1977; Chapter 8.

(3) For reviews on the oxidation of sulfides to sulfoxides, see: (a) Drabowicz, J.; Mikolajczyk, M. *Org. Prep. Proc. Int.* **1982**, *14*, 45. (b) Madesclaire, M. *Tetrahedron* **1986**, *42*, 5459. (c) Block, E. In *The Chemistry of Ether, Crown Ether, Hydroxyl Groups and Their Sulphur Analogues*; Patai, S., Ed.; Jonn Wiley & Sons: New York, 1980; Supplement E, Part 1, Chapter 13.

(4) Ho, T. L.; Wong, C. M. *Synthesis* **1972**, 561.

(5) Drabowicz, J.; Mikoilajczyk, M. *Synthesis* **1978**, 758.

(6) Ueno, Y.; Inoue, T.; Okawara, M. *Tetrahedron Lett.* **1977**, 2413.

(7) Torrini, I.; Paradisi, M. P.; Zecchini, G. P.; Agrosi, F. *Synth. Commun.* **1987**, *17*, 515.

(8) Drabowicz, J.; Midura, W.; Mikolajczyk, M. *Synthesis* **1979**, 39.

(9) Gasparrini, F.; Giovannoli, M.; Maresca, L.; Natile, G.; Palmieri, G. *Synth. Commun.* **1984**, *14*, 1111.

(10) For a review on the oxygen-transfer reactions of oxaziridines, see: Davis, F. A.; Haque, S. M. "Oxygen Transfer Reactions of Oxaziridines", *Advances in Oxygenated Process*; Baumstark, A. L., Ed; JAL Press: Greenwich, CT, Vol. 2, in press.

(11) The α-azo hydroperoxides, developed by Baumstark and coworkers, are also reported to be highly selective reagents for the oxidation of sulfides to sulfoxides; see: Baumstark, A. L.; Vasquez, P. C. *J. Org. Chem.* **1983**, *48*, 65.

0022-3263/88/1953-5004$01.50/0