Synthesis and Reactivity of Captodative Diradical Oligomers Incorporating the 3,5,5-Trimethyl-2-oxomorpholin-3-yl (TM-3) Unit[1]

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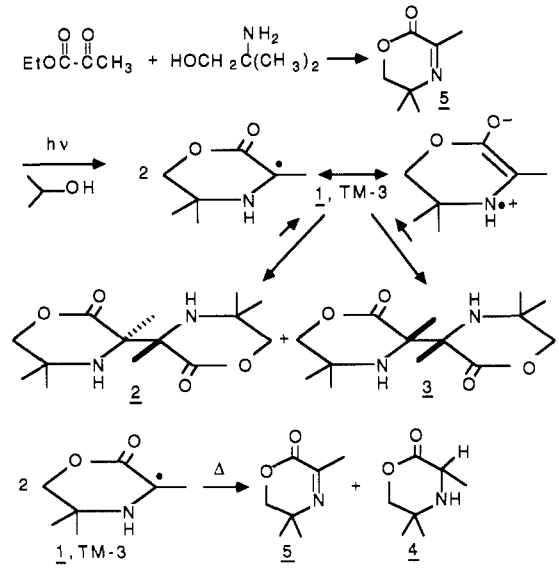
The synthesis and reactivity of macrocyclic oligomers of diradicals incorporating the 3,5,5-trimethyl-2-oxomorpholin-3-yl radical stabilizing unit are described, oligomers (**8** and **9**) of *dl*-6,6′-bi(3,5,5-trimethyl-2-oxomorpholin-3-yl) (**7**) and *dl*-1,3-propanediyl-6,6′-bis(3,5,5-trimethyl-2-oxomorpholin-3-yl) (**10**), respectively. The diradicals differ by zero and trimethylene bridges connecting oxomorpholinyl radicals at the 6-position. The oligomers of **7** are predominantly mixtures of stereoisomeric trimers and the oligomers of **10** are predominantly mixtures of stereoisomeric pentamers. The oligomers were formed by photoreduction in 2-propanol of the corresponding bisoxazinones, *dl*-6,6′-bi(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (**11**) and *dl*-1,3-propanediyl-6,6′-bis(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (**12**), prepared from diamino diols and pyruvoyl chloride. Warm degassed solutions of the oligomers showed doublet EPR signals characteristic of the 3,5,5-trimethyl-2-oxomorpholin-3-yl unit, indicating that the macrocycles undergo ring opening via bond homolysis. The oligomers are oxidatively cleaved by molecular oxygen, *N*-methylisatin (**26**), diphenylpicrylhydrazyl (DPPH), and daunomycin (**6**) to give back bisoxazinones **11** and **12**, in analogy with the oxidative cleavage of the dimers of 3,5,5-trimethyl-2-oxomorpholin-3-yl (**1**, TM-3). The kinetics of oxidative deoligomerization with DPPH as the oxidizing agent are first order in oligomer. The activation parameters for deoligomerization of **9** are consistent with those for cleavage of a model, monoradical dimer, bi(3,5,5,6-tetramethyl-2-oxomorpholin-3-yl) (**30**, **31**), suggesting that all weak bonds cleave at about the same rate and that the kinetics are actually first order in weak bonds. The activation parameters for deoligomerization of **8**, especially in benzene, were anomalous, suggesting a more complicated mechanism. A reversible first bond cleavage followed by a slow second bond cleavage is proposed. Metal ion binding ability of these highly functionalized macrocycles was also explored and found to be low except for the small alkali and alkaline-earth cations, Li^+, Mg^{2+}, and Ca^{2+}.

Introduction

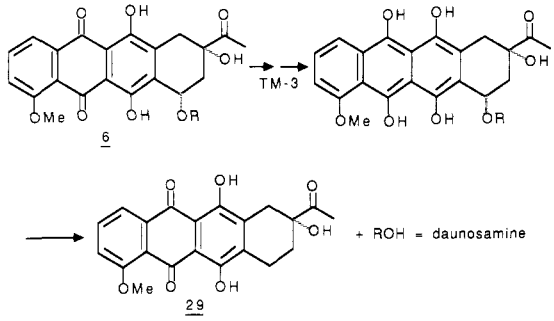
3,5,5-Trimethyl-2-oxomorpholin-3-yl (**1**, TM-3)[2] is one of the most persistent and stabilized[3] radicals in the class known as captodative,[4] push–pull[5] or merostabilized free radicals.[6] It exists in equilibrium with meso and *dl* dimers **2** and **3** (Scheme I) with equilibrium constants ranging from 1.3×10^{-9} to 5.8×10^{-16} M as a function of medium at 25 °C.[7] Free energies of activation for bond homolysis of **3** increase from 21 kcal/mol in ethanol to 26 kcal/mol in benzene at 25 °C.[7] X-ray crystallographic measurements[8] and substituent effect studies[9] indicate that both steric and electronic effects contribute to the facile bond homolysis. 2-Oxomorpholin-3-yl dimers are products of the photoreduction of 5,6-dihydro-1,4-oxazin-2-ones in 2-propanol solvent.[2,9]

TM-3 disproportionates to 3,5,5-trimethyl-2-oxomorpholine (**4**) and 5,6-dihydro-3,5,5-trimethyl-1,4-oxazin-2-one (**5**) very slowly at ambient temperature. It reacts as a mild one-electron reducing agent and is especially

Scheme I



effective for reduction of the quinone functional groups of anthracyclines such as daunomycin (**6**).[10] Reduction



of easily reducible substrates often occurs much faster than

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(2) Koch, T. H.; Olesen, J. A.; DeNiro, J. *J. Am. Chem. Soc.* **1975**, *97*, 7285.

(3) Leroy, G. *Adv. Quant. Chem.* **1985**, *17*, 1. Leroy, G.; Peeters, M. S.; Wilante, C. In *Substituent Effects in Radical Chemistry*; Viehe, H. G., Janousek, Z., Merényi, R., Eds.; Reidel: Boston, 1986; pp 1–48.

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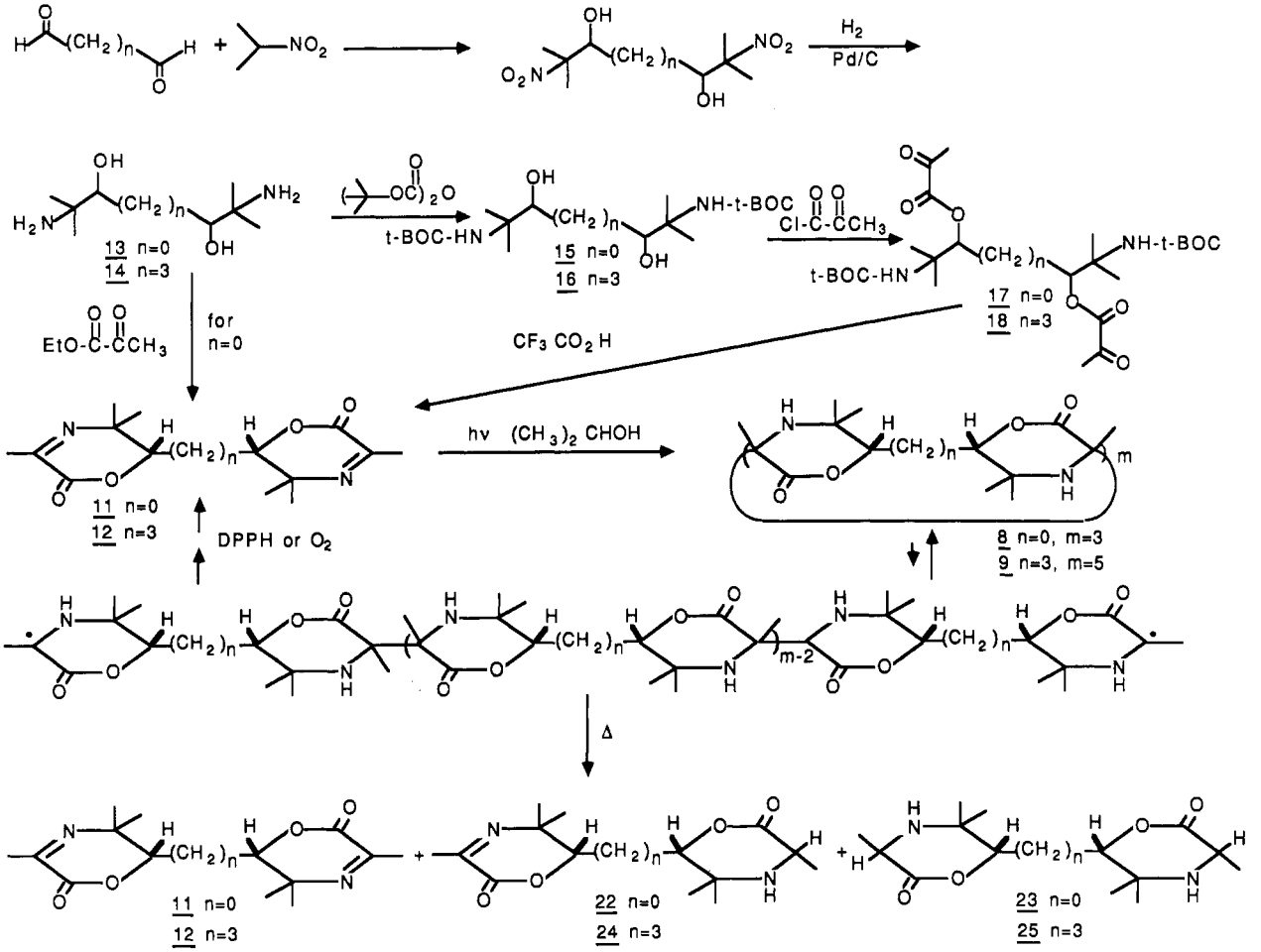
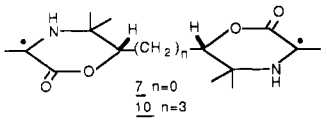
Scheme II



radical recombination and, hence, the rate of reduction is the rate of bond homolysis.[11] The mechanism for reduction appears to be one-electron transfer[12] except for the reduction of molecular oxygen. An intermediate in the reduction of oxygen to hydrogen peroxide has a covalent bond between oxygen and the 3-position of TM-3.[13]

The properties of TM-3 prompted the synthesis of diradicals based upon the 3,5,5-trimethyl-2-oxomorpholin-3-yl unit. The diradicals were conceived as compounds that might oligomerize reversibly and function as multiple electron reducing agents. In communication form we have reported the synthesis of oligomers of *dl*-6,6′-bi(3,5,5-trimethyl-2-oxomorpholin-3-yl) (**7**) and the characterization of the oligomers as macrocycles (**8**).[14] We now report the synthesis of macrocyclic oligomers (**9**) of *dl*-1,3-propanediyl-6,6′-bis(3,5,5-trimethyl-2-oxomorpholin-3-yl) (**10**) and kinetic measurements of the oxidative deoligomerization of both **8** and **9**.



Results and Discussion

Synthesis and Characterization of Diradical Oligomers.

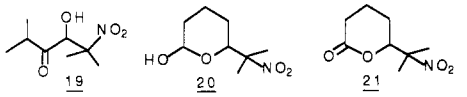
The oligomers of **8** and **9** were synthesized in 60% yield via sequential photoreduction of the carbon–nitrogen double bonds of the respective bisoxazinones, *dl*-6,6′-bi(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (**11**) and *dl*-1,3-propanediyl-6,6′-bis(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (**12**). The photoreduction was conducted at reduced temperature in 2-propanol solvent with excitation of the n–π^* band of the dihydrooxazinone chromophore. Oligomerization likely occurred as the carbon–nitrogen double bonds were reduced, and the actual diradicals **7** and **10** were probably not produced in significant amounts. The oligomers precipitated during the photolysis and were collected as a mixture of stereoisomers by filtration or centrifugation.

The bisoxazinones **11** and **12** were synthesized from the respective diamino diols **13** and **14** obtained from reaction of dialdehydes with 2 equiv of 2-nitropropane followed by catalytic hydrogenation of the nitro functional groups. The amino groups of the diamino diols were protected as *t*-BOC derivatives (**15** and **16**) with di-*tert*-butyl dicarbonate. Subsequently, the alcohol groups were acylated with pyruvoyl chloride to give bis-*t*-BOC bispyruvate intermediates **17** and **18**. Removal of the *t*-BOC groups with trifluoroacetic acid also resulted in cyclization to the desired bisoxazinones **11** and **12**. The yields of bisoxazinones from the diamino diols were in the range of 10%. Bisoxazinone **11** was also prepared in 18% yield from direct condensation of **13** as its bis acetic acid salt with ethyl pyruvate at elevated temperature. The syntheses are summarized in Scheme II.

A byproduct of the reaction of glyoxal with 2-nitropropane was 2,5-dimethyl-4-hydroxy-5-nitrohexan-3-one

(11) Bennett, R. W.; Wharry, D. L.; Koch, T. H. *J. Am. Chem. Soc.* **1980**, *102*, 2345.
(12) Burns, J. M.; Wharry, D. L.; Koch, T. H. *J. Am. Chem. Soc.* **1981**, *103*, 849.
(13) Gaudiano, G.; Koch, T. H. *J. Am. Chem. Soc.* **1986**, *108*, 5014.
(14) Gaudiano, G.; Sweeney, K.; Haltiwanger, R. C.; Koch, T. H. *J. Am. Chem. Soc.* **1984**, *106*, 7628.

(19, 38%), most likely resulting from E2 elimination of nitrous acid[15] from the intermediate 2-hydroxy-3-methylbutanal followed by a second condensation with 2-nitropropane. A byproduct of the reaction of glutaric dialdehyde with 2-nitropropane was a mixture of the diastereoisomers of 2-(2-hydroxytetrahydropyran-6-yl)-2-nitropropane (20, 75%), resulting from cyclization of the intermediate 5-hydroxy-6-methyl-6-nitroheptanal. The mixture of diastereoisomers of 20 was further characterized by oxidation to 2-nitro-2-(2-oxotetrahydropyran-6-yl)-propane (21) with lead tetraacetate in 63% yield.



19 20 21

The stereochemistry of the bisoxazinones 11 and 12 was established as *dl* by X-ray crystallography. Structure determinations were performed with single crystals of intermediate 13 and bisoxazinone 12. Details of the crystal structure analysis of 13 are reported as supplementary material to the earlier communication[14] and of 12 as supplementary material here.

The assignment of the structures to the products of photoreduction of bisoxazinones 11 and 12 as macrocyclic oligomers of diradicals 7 and 10 is based upon spectroscopic data, molecular weight determinations, combustion analysis, and chemical evidence. The average molecular weights of oligomers 8 and 9, determined by vapor pressure osmometry, were 850 and 1670 amu, respectively, indicating that 8 was predominantly a mixture of stereoisomeric trimers and 9, a mixture of stereoisomeric pentamers. Contrary to our earlier report, the size of 8 is trimeric, independent of batch.[14] The earlier observed variation from trimeric to pentameric might have resulted from problems with the 25-year-old osmometer available at that time. The fast atom bombardment mass spectrum of 8 showed a peak for trimer as well as fragment peaks for dimer and monomer, and of 9, for pentamer as well as fragment peaks for tetramer, trimer, dimer, and monomer. An N–H stretching band was observed at 3.01–3.03 μm in the infrared of both 8 and 9, indicative of the morpholinone structural unit. UV and IR analysis of 8 showed that peaks at 318 nm and 6.1 μm, respectively, characteristic of the conjugated carbon–nitrogen double bond of oxazinone, were absent. The presence of some oxazinone groups was observed by UV and ^{1}H NMR analysis of 9; however, HPLC indicated that these were all accounted for by a small contamination of the oligomers with bisoxazinone 12. ^{1}H NMR analysis of both 8 and 9 also indicated the absence of any protons characteristic of terminal morpholinone rings which might have resulted from disproportionation of intermediate radicals. The ^{1}H NMR and ^{13}C NMR spectra were complex but consistent with the proposed structures. Degassed solutions of the oligomers showed no EPR signals at ambient temperature but a weak 24-line signal characteristic of the trimethyloxomorpholinyl radical at elevated temperatures as summarized in Table I. No triplet EPR signal appeared at any temperature. The effect of polar solvent on the magnitude of the 3-methyl hyperfine coupling constant is consistent with dipolar character for the oxomorpholinyl radical unit as expressed by a zwitterionic resonance contributor as shown for TM-3 in Scheme I. Reaction of 8 and 9 with molecular oxygen gave back bisoxazinones 11 and 12. Heating of the diradical oligomers (8 and 9) in chloroform resulted in bond homolysis and disproportionation to bisoxazinone 11,

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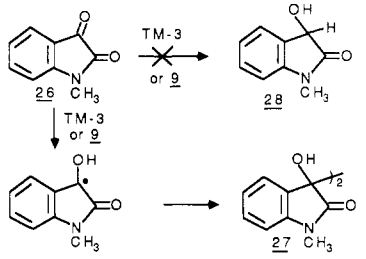
Table I. EPR Hyperfine Coupling Constants for the Oligomers of Diradicals 7 and 10

diradical	temp, °C	solvent	coupling constants (G) a_N	a_{NH}	a_{CH_3}
7	60	$CHCl_3$	6.25	3.50	11.46
10	61	$CHCl_3$	6.16	3.60	11.36
10	73	$CHCl_3$	6.18	3.52	11.52
10	86	$CHCl_3$	6.20	3.40	11.60
10	49	EtOH	6.40	5.28	10.00
10	60	EtOH	6.44	5.20	10.08
10	74	EtOH	6.52	5.04	10.20

6-(3,5,5-trimethyl-2-oxomorpholin-6-yl)-5,6-dihydro-3,5,5-trimethyl-1,4-oxazin-2-one (22), and 6,6′-bi(3,5,5-trimethyl-2-oxomorpholinyl) (23) from 8, and bisoxazinone 12, 1-(3,5,5-trimethyl-2-oxomorpholin-6-yl)-3-(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazin-6-yl)propane (24), and 1,3-bis(3,5,5-trimethyl-2-oxomorpholin-6-yl)propane (25) from 9 (see Scheme II). The disproportionation products 22, 23, 24, and 25 were identical with products obtained from incomplete and complete palladium on charcoal catalyzed hydrogenation of bisoxazinones 11 and 12, respectively. At ambient temperature in chloroform solvent, disproportioantion of 8 took almost 1 year to complete. The mixture of disproportionation products 11, 22, and 23 was also observed upon pyrolysis of 8 at 140 °C in a vacuum sublimer and at 200 °C in the injection port of a gas chromatograph. The osmometric molecular weights, the lack of EPR signals at ambient temperature, and the lack of oxazinone or morpholine end groups precludes the presence of substantial amounts of open-chain oligomers. This leads to the proposal of macrocyclic trimers and pentamers for structures of the products of photoreduction of bisoxazinones 11 and 12.

Reduction Reactions with Diradical Oligomer 9. Bond homolysis of the macrocyclic oligomers produces a diradical oligomer which in principle can deliver two electrons to a reducible substrate within an encounter complex. This possibility was examined with two reduction reactions observed previously with the TM-3 radical. TM-3 radical reduces *N*-methylisatin (26) to *meso*- and *dl*-*N*,*N*′-dimethylisatides (27) via single electron transfer



26 28 27

followed by radical combination of the resulting 2-hydroxy-1-methyl-3-oxo-2-indolyl radical. The transfer of two electrons within an encounter complex would give 3-hydroxy-1-methyl-2*H*-indol-2-one (28). In chloroform and ethanol solvents reduction with oligomer 9 gives only isatides 27, possibly because one-electron reduction of 2-hydroxy-1-methyl-3-oxo-2-indolyl is more difficult than one-electron reduction of 26.[16] TM-3 radical also reduces daunomycin to its 7-deoxyaglycon 29 via semiquinone and hydroquinone intermediates.[10] Molecular oxygen reacts rapidly with the semiquinone and prevents reductive glycosidic cleavage. Because of our interest in developing antidotes[17] and/or rescue drugs[18] for the anthracyclines

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Table II. Rate Constants for the Bond Homolysis of Diradical Oligomers 8 and 9

oligomer	solvent	temp, K	k, s^{-1}	temp, K	k, s^{-1}
8	PhH	313.1	$(6.20 \pm 0.02) \times 10^{-6}$	344.5	$(8.05 \pm 0.02) \times 10^{-5}$
		323.7	$(1.34 \pm 0.04) \times 10^{-5}$	355.0	$(2.54 \pm 0.09) \times 10^{-4}$
		333.9	$(3.41 \pm 0.08) \times 10^{-5}$		
8	EtOH	297.8	$(9.40 \pm 0.03) \times 10^{-5}$	320.6	$(1.46 \pm 0.03) \times 10^{-3}$
		310.4	$(5.30 \pm 0.02) \times 10^{-4}$	330.5	$(3.20 \pm 0.01) \times 10^{-3}$
9	PhH	323.7	$(1.49 \pm 0.03) \times 10^{-5}$	344.5	$(1.84 \pm 0.09) \times 10^{-4}$
		333.2	$(4.14 \pm 0.02) \times 10^{-5}$	355.5	$(7.99 \pm 0.02) \times 10^{-4}$
9	EtOH	298.3	$(1.70 \pm 0.02) \times 10^{-4}$	312.9	$(1.30 \pm 0.01) \times 10^{-3}$
		303.5	$(3.46 \pm 0.02) \times 10^{-4}$	317.8	$(2.56 \pm 0.08) \times 10^{-3}$
		310.6	$(8.98 \pm 0.08) \times 10^{-4}$	328.0	$(6.13 \pm 0.02) \times 10^{-3}$

Table III. Activation Parameters for Bond Homolysis of Diradical Oligomers 8 and 9

parameters	8 (PhH)	8 (EtOH)	9 (PhH)	9 (EtOH)
A, s^{-1}	2.0×10^{8}	3.6×10^{11}	3.8×10^{14}	7.0×10^{13}
E_a, kcal/mol	19.5 ± 1.1	21.2 ± 1.4	28.8 ± 3.0	24.0 ± 2.0
$\Delta H^{\ddagger}$, kcal/mol	18.8 ± 1.1	20.5 ± 2.0	28.1 ± 2.0	23.4 ± 2.0
$\Delta S^{\ddagger}$, cal/deg·mol	−22.7 ± 3.5	−7.7 ± 4.7	5.9 ± 2.2	2.8 ± 3.0
k, s^{-1}	1.34×10^{-5} [a]	2.1×10^{-4} [b]	1.49×10^{-5} [a]	3.5×10^{-4} [b]

[a] 50.6 °C. [b] 30.5 °C.

Table IV. Rate Constants for Bond Homolysis of the Radical Dimers of 3,5,5,6-Tetramethyl-2-oxomorpholin-3-yl (30 and 31) in Benzene

dimer	temp, K	k, s^{-1}	temp, K	k, s^{-1}
30	323.2	$(3.86 \pm 0.04) \times 10^{-5}$	344.5	$(6.95 \pm 0.08) \times 10^{-4}$
	333.3	$(1.41 \pm 0.02) \times 10^{-4}$	354.7	$(2.58 \pm 0.04) \times 10^{-3}$
31	323.7	$(2.00 \pm 0.02) \times 10^{-5}$	344.3	$(3.23 \pm 0.03) \times 10^{-4}$
	333.2	$(8.08 \pm 0.02) \times 10^{-5}$	354.7	$(1.10 \pm 0.01) \times 10^{-3}$

that operate by reducing the anthracyclines to their 7-deoxyaglycons, we compared the reactivity of oligomer **9** and TM-3 dimer with daunomycin in the presence of a low concentration of molecular oxygen. Oligomer **9** produced only traces of 7-deoxydaunomycinone (**29**), indicating that either oligomer **9** did not reduce daunomycin any faster to the hydroquinone state than TM-3 dimer or that the hydroquinone state reacted faster with the molecular oxygen present than it eliminated the amino sugar, daunosamine.

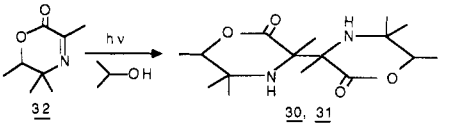
Kinetics of Bond Homolysis of the Diradical Oligomers 8 and 9. The rate of bond homolysis of diradical oligomers **8** and **9** was determined in both benzene and ethanol solvents by using 2,2-diphenyl-1-picrylhydrazyl (DPPH) as a radical trapping agent. DPPH is cleanly reduced to 2,2-diphenyl-1-picrylhydrazine by 2-oxomorpholin-3-yl radicals faster than the radicals recombine.[9] The reaction was followed spectroscopically at 516–522 nm, the absorption maximum of DPPH. The absorbance versus time data followed simple first-order kinetics with reactions carried to approximately 90% destruction of the stoichiometric amount of DPPH. The order of the reaction was further established from the observation that the first-order rate constant did not change when the concentration of the oligomer was halved. The rate constants as a function of temperature are reported in Table II and activation parameters are reported in Table III.

Measurements of the rates of bond homolysis of derivatives of TM-3 dimer modified at the 3- and 5-positions of the morpholine rings showed that the rates were sensitive to steric and electronic effects at these positions.[9] Diradical oligomers **8** and **9** bear additional substituents at the 6-position of the morpholine rings. The possible steric effect on the rates of bond homolysis of **9** arising from an acyclic carbon substituent at the 6-position was evaluated by comparison of the rates with those for bond homolysis of the two major stereoisomeric dimers (**30** and **31**) resulting from photoreduction of 5,6-dihydro-3,5,5,6-tetramethyloxazin-2-one (**32**). These rate constants as a function of temperature were also measured by using DPPH as a radical trapping agent and are reported in Table IV. Activation parameters are compared with those for the TM-3 dimers, measured earlier,[7] in Table V.

Table V. Activation Parameters for Bond Homolysis of the Radical Dimers of 3,5,5,6-Tetramethyl-2-oxomorpholin-3-yl (30 and 31) and *dl*-3,5,5-Trimethyl-2-oxomorpholin-3-yl (3)

parameters	30 (PhH)	31 (PhH)	3 (PhH)[a]	3 (EtOH)[a]
A, s^{-1}	3.1×10^{16}	1.4×10^{15}	4.1×10^{14}	3.1×10^{12}
E_a, kcal/mol	31.0 ± 1.0	29.4 ± 1.0	28.8 ± 2.3	21.0 ± 2.0
$\Delta H^{\ddagger}$, kcal/mol	30.3 ± 1.0	28.7 ± 1.0	28.1 ± 2.3	20.4 ± 2.0
$\Delta S^{\ddagger}$, cal/deg·mol	14.7 ± 3.0	8.5 ± 3.0	6.1 ± 6.8	−3.4 ± 6.4

[a] Taken from ref 7.

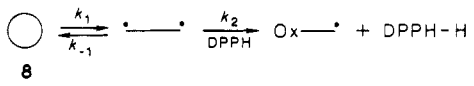


Considering that the macrocyclic oligomers **8** and **9** are mixtures of stereoisomers and are most likely not of uniform size, the observation of a simple first-order rate for the radical trapping experiments was surprising. In fact, prior to using a simple first-order rate law, we attempted to fit the kinetic data to more complicated consecutive first-order expressions. These efforts uniformly failed. One possible explanation for the first-order behavior is that the reactions are first order in weak bonds and that the rate of bond homolysis is independent of the various possible structural variations. Another possible explanation is that the first bond cleavage, which transforms the molecule from a cyclic to an acyclic molecule, occurs at a rate independent of the size and stereochemistry of the cycle and slow relative to subsequent bond cleavages. The first explanation seems to be the most generally applicable. Determining from model studies

(17) Averbuch, S. D.; Gaudiano, G.; Koch, T. H.; Bachur, N. R. *J. Clin. Oncol.* **1986**, *4*, 88.
(18) Averbuch, S. D.; Gaudiano, G.; Koch, T. H.; Bachur, N. R. *Cancer Res.* **1985**, *45*, 6200.

whether the first bond cleavage is slow relative to subsequent bond cleavages is near impossible because the variations in the activation parameters are not large enough relative to errors inherent in selecting the models and the experimental errors of the measurements. In support of weak bonds with identical connectivity cleaving at very similar rates is the observation that the activation parameters for cleavage of stereoisomers **30** and **31** in benzene solvent and **2** and **3**[11] in chloroform solvent are identical within 2 standard deviations. The diradical oligomer weak bonds differ in stereochemistry as do the weak bonds of **30** and **31**.

The one system that appears anomalous well beyond experimental error is the bond homolysis of diradical oligomer **8** in benzene solvent. The enthalpy of activation is less than expected and the entropy of activation is highly negative. Possibly, with this system and under these conditions, the first bond cleavage is reversible and the rate is controlled by the rate of trapping, the rate of bond homolysis, and the rate of recyclization. If the rate constant for recyclization (k_{-1}) is large relative to the rate constant for trapping (k_2) times the concentration of trapping agent, the rate law is first order in oligomer and first order in DPPH and the apparent rate constant is the rate constant for bond homolysis (k_1) times the rate constant for trapping divided by the rate constant for recyclization. A mechanism of this type might give an



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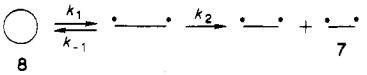
apparent enthalpy of activation less than expected and an apparent large negative entropy of activation.[7] Absorbance versus time data were consistent with an integrated bimolecular rate law when fit with a nonlinear least-squares algorithm; however, the fit was not as good as the fit of the data to the integrated unimolecular rate law, especially at the early stage of the reaction. A bimolecular rate law was ultimately rejected on the basis of the effect of halving the initial concentrations of the oligomer and DPPH on the initial rate. If the bimolecular mechanism were correct, the initial rate should have decreased by a factor of 4; it decreased by only a factor of 2, again consistent with a rate law first order in oligomer and zero order in DPPH. An alternate mechanism consistent with first-order kinetics and possibly with the anomalous activation parameters is a reversible first bond cleavage followed by a rate-controlling second bond cleavage. With this mechanism, if the rate constant for recyclization (k_{-1}) is large relative to the rate constant for the second bond cleavage (k_2), then the apparent rate constant is k_1k_2/k_{-1}, where k_1 is the rate constant for the first bond cleavage. The apparent E_a is



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$E_{a_1} + E_{a_2} - E_{a_{-1}}$ and the apparent A factor is A_1A_2/A_{-1}. A possible set of activation energies and A factors that would give the observed activation energy and preexponential factor is $E_{a_1} = 10$, $E_{a_2} = 20$, and $E_{a_{-1}} = 10$ kcal/mol and $A_1 = 1 \times 10^{11}$, $A_2 = 1 \times 10^{13}$, and $A_{-1} = 5 \times 10^{15}$ s^{-1}. E_{a_2} was selected on the basis of activation energies for bond homolysis of the TM-3 dimer in benzene solvent and the larger steric effect anticipated for cleavage of the weak bonds of acyclic oligomers of **7**. The predominant trimeric structure of **8** and the steric crowding resulting from directly binding the morpholine rings at the 6-position rationalize the small E_{a_1} and the large $E_{a_{-1}}$ relative to those determined for bond homolysis of TM-3 dimers. The small A_1 and large A_{-1} might result from less ordered solvent when the oligomer is cyclized.

Deoligomerization of **8** in benzene might logically differ from the deoligomerization of **9** in benzene and ethanol and possibly deoligomerization of **8** in ethanol because the oligomers of **7** are predominantly trimers and the oligomers of **10** are predominantly pentamers. The trimer in benzene might undergo reversible first bond cleavage because of the proximity of the radical sites and the inability of benzene to solvate captodative radicals.

Metal Ion Binding. Inspection of CPK models of macrocyclic diradical oligomer **8** suggested that it might in part exist as a coronand structure[19] with the methyl substituents on the outside of the macrocycle and the amino and lactone functional groups on the inside, possibly available for binding metal cations. Formation of metal ion binding sites in the large macrocycle **9** would require a certain amount of molecular folding. Metal ion binding properties of these materials were examined by using the oligomers to dissolve metal picrates in methylene chloride. Diradical oligomer **8** dissolved 1.0Li^+/oligomer, 0.4Mg^{2+}/oligomer and other alkali and alkaline-earth metal picrates to a lesser extent at ambient temperature, and diradical oligomer **9** dissolved 1.2Li^+/oligomer, 0.9Mg^{2+}/oligomer, 0.6Ca^{2+}/oligomer, 0.2Sr^{2+}/oligomer, and 0.1Ba^{2+}/oligomer in methylene chloride at ambient temperature. Methylene chloride solutions of the oligomers were not capable of extracting metal picrates from aqueous solutions or dissolving highly polar organic molecules such as sucrose or methylene blue.

Other relevant captodative diradical systems that have been described include the transition state in the thermal isomerization of 1,2-bis(4-methoxyphenyl)-1,2-bis(4-cyanophenyl)ethylene,[20] the product of two-electron reduction of linked paraquat units,[21] 1,1′-trimethylenebis-[4-carbomethoxypyridinyl],[22] 1,1′-ethylenebis[4-(methoxycarbonyl)pyridinyl],[23] and 1,1′-ethylenebispyridinyl.[24] The latter four systems appear to cyclize intramolecularly rather than oligomerize. Oligomerization of diradicals based upon the triarylmethyl radical unit has also been proposed.[25]

Experimental Section

General Remarks. Melting points were measured with a Thomas-Hoover Unimelt apparatus and are uncorrected. Infrared spectra were determined on a Perkin-Elmer Model 337 or 727B spectrophotometer. UV–vis spectral data were collected with a Hewlett-Packard Model 8450 diode array spectrometer. ^{1}H NMR spectra were recorded with a Varian EM-390, Bruker WM-250, or Chemagnetics A200 spectrometer and ^{13}C NMR spectra with a Bruker WM-250 spectrometer. Chemical shifts are reported in parts per million on the δ scale from internal tetramethylsilane or 3-(trimethylsilyl)propanesulfonic acid sodium salt, and coupling constants are reported in hertz. EPR spectra were recorded with a Varian 109E spectrometer and coupling constants are reported in gauss. Mass spectral data were obtained with a VG Instruments 7070EQ-HF spectrometer. X-ray crystallographic data were collected with a Nicolet Analytical Instruments P3F autodiffractometer. Analytical gas chromatography was performed with a Varian Aerograph 1700 gas chromatograph equipped with a thermal conductivity detector or with a Hewlett-Packard 5790 A capillary gas chromatograph equipped with a flame ionization

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detector. High pressure liquid chromatography was performed with a Hewlett-Packard 1090 liquid chromatograph equipped with a diode array detector and low-temperature HPLC with a Spectra Physics 740 pump equipped with a Model 220 UV detector. Vapor pressure osmometry was conducted with a Mechrolab 310A or a Wescan 233 osmometer; average molecular weights were determined from a calibration curve obtained with standard solutions of benzil in chloroform. Microanalyses were performed by Atlantic Microlab, Atlanta, GA, and Galbraith Labs, Knoxville, TN.

The experiments describing the synthesis and reactions of the oligomers of **7** and **10** were essentially identical. Consequently, those experiments related to **10** are reported here. Physical and spectroscopic properties of **8**, synthetic intermediates leading to **8**, and products of disproportionation of **8** were reported earlier.[14] The preparation of bisoxazinones by direct condensation of diamino diols with ethyl pyruvate was accomplished in the synthesis of **11**, and the experiment is reported here. The reduction of **11** and the disproportionation of **8** were established in more detail than the corresponding experiments with **12** and **9**, respectively, and are reported here.

Solvents were reagent grade, HPLC grade, or spectroanalyzed grade. All solvents used for flash chromatography were distilled prior to use.

The flash chromatography technique was essentially that described by Still, Kahn, and Mitra.[26] Various columns from 1.0 to 5.0 cm o.d. were packed with 15 cm of Merck silica gel 60 (40–63 μm) and were eluted at a flow rate of 5 cm/min. Volumes of 5 to 20 mL were collected for each fraction based on the size of the column. Fractions were analyzed by analytical TLC using Merck PF254 silica gel plates. A dry column flash chromatography technique was also utilized as described by Harwood.[27] Various sizes of coarse, sintered glass funnels were packed with Merck silica gel 60 to within 1 cm of the top rim of the funnel while suction was applied with an aspirator. The columns were eluted with a series of solvent mixtures that were progressively more polar. Volumes of 10 to 50 mL were collected for each fraction on the basis of the size of the funnel.

Kinetic data were collected by visible spectroscopic measurements on solutions prepared in two-compartment cells with one compartment a Pyrex cuvette. The cells and the freeze–thaw degassing procedure are described elsewhere.[28] The two compartments were needed to isolate reagents during degassing.

***dl*-2,8-Dimethyl-2,8-dinitro-3,7-nonanediol.** To a magnetically stirred solution of 400 mL of 2-nitropropane in 400 mL of reagent-grade methanol and 40.0 g of potassium hydroxide was added 228 g (0.57 mol) of 25% glutaric dialdehyde in water dropwise over 19 h. After completion of the addition, the solution was allowed to stir at ambient temperature for an additional 28 h. The solution was poured into a separatory funnel containing 300 mL of ice and water. The phases were separated and the aqueous phase was extracted (2 × 100 mL) with diethyl ether. The combined organic phases were washed with 50 mL of water, dried over anhydrous magnesium sulfate, and filtered. The solvent was removed by rotary evaporation, and the viscous residue was diluted with 75 mL of ethyl acetate and cooled in an ice bath. A white precipitate gradually formed and was collected by suction filtration. The yield after drying in vacuo was 31.7 g (23%) of dinitro diol. This material was sufficiently pure for use in subsequent reactions. A sample recrystallized twice from ethanol formed colorless needles with mp 145–146 °C and had the following spectral properties: ^{1}H NMR (DMSO-d_6) δ 1.43 (br s, 18 H), 3.83 (m, 2 H), 5.3 (d, J = 7.5, 2 H); IR (KBr) 2.91, 3.39, 6.56, 6.85, 7.14, 7.27, 7.41, 7.94, 8.77, 9.26 μm; mass spectrum (70 eV), m/z (rel intensity) 185 (3), 143 (2), 142 (3), 141 (3), 125 (6), 89 (27), 71 (32), 57 (41), 43 (100). Anal. Calcd for $C_{11}H_{22}N_2O_6$: C, 47.47; H, 7.97; N, 10.07. Found: C, 47.52; H, 7.98; N, 10.06.

The balance of the product mixture was identified as a diastereoisomeric mixture of 2-nitro-2-(2-hydroxytetrahydropyran-6-yl)propanes (**20**). The isomers were purified by silica gel dry column flash chromatography, eluting successively with 50%, 60%, 70%, 80%, and 90% ethyl acetate/hexanes (v/v) but could not be sufficiently separated for adequate spectral characterization. On silica gel TLC the isomers had an R_f of 0.43, eluting with 50% ethyl acetate/hexanes (v/v). The ^{1}H NMR spectrum in DMSO-d_6 displayed two doublets at 6.13 and 6.37 ppm that disappeared upon exchange of the acidic protons with D_2O, characteristic of secondary alcohols. The IR spectrum (thin film) showed peaks at 2.93, 3.39, 3.49, 5.48, 6.49, 6.87, 6.96, 7.17, 7.44, 8.44, and 9.75 μm. Anal. Calcd for $C_8H_{15}NO_4$: C, 50.78; H, 7.99; N, 7.40. Found: C, 50.52; H, 8.04; N, 7.35.

2-Nitro-2-(2-oxotetrahydropyran-6-yl)propane (21). Oxidation of **20** was accomplished with lead tetraacetate, adapting a procedure described by Partch.[29] A 500-mL round-bottom flask was charged with 12 g (0.063 mol) of a purified mixture of the diastereoisomers of 2-nitro-2-(2-hydroxytetrahydropyran-6-yl)-propane (**20**), 30 g (0.068 mol) of lead tetraacetate, and 300 mL of pyridine. The mixture was magnetically stirred for 18 h at ambient temperature. The mixture was gravity filtered and the residue triturated with diethyl ether and filtered. The combined filtrates were concentrated by rotary evaporation and the remaining pyridine was removed by high vacuum rotary evaporation at 50 °C, 0.1 Torr. The viscous yellow oily residue was partially dissolved in ethyl acetate with heating. Upon cooling the product precipitated. The solvent was decanted and the light yellow solid residue was dissolved in ethanol with warming. Gradually a white precipitate formed that was collected by suction filtration and air-dried to yield 7.5 g (63%) of **21**. A sample recrystallized from ethanol had the following physical and elemental properties: mp 76–77 °C; ^{1}H NMR ($CDCl_3$) δ 1.56 (s, 3 H), 1.65 (s, 3 H), 1.77–2.17 (m, 4 H), 2.43–2.70 (m, 2 H), 4.82 (ddd, J = 11.8, 2.9, 1.1, 1 H); IR ($CHCl_3$) 3.42, 3.48, 5.75, 6.45, 6.85, 7.14, 7.27, 7.41, 8.1, 9.3, 9.48 μm; mass spectrum (CI, isobutane), m/z (rel intensity) 188 (14, M + 1), 158 (12), 141 (63), 113 (78), 99 (54), 71 (72), 55 (64), 43 (100). Anal. Calcd for $C_8H_{13}NO_4$: C, 51.33; H, 7.00; N, 7.48. Found: C, 51.27; H, 7.03; N, 7.45.

***dl*-2,8-Diamino-2,8-dimethyl-3,7-nonanediol (14).** A 500-mL Parr medium pressure reaction bottle was charged with 20 g (0.072 mol) of *dl*-2,8-dimethyl-2,8-dinitro-3,7-nonanediol, 8 g of 10% palladium on charcoal, 40 mL of glacial acetic acid, and 250 mL of absolute ethanol. The mixture was hydrogenated at 90 psi at ambient temperature until the theoretical uptake of hydrogen was achieved. The mixture was filtered through Celite and the filtrate concentrated to approximately one-fifth of its original volume by rotary evaporation and poured into 600 mL of cold ethyl acetate. The white precipitate that formed was collected by suction filtration and dried in vacuo at ambient temperature, yielding 24.3 g (92%) of the bis acetic acid salt of **14**: mp 223–224 °C; ^{1}H NMR (D_2O) δ 1.26 (s, 6 H), 1.32 (s, 6 H), 1.37–1.76 (m, 6 H), 1.91 (s, 6 H), 3.49–3.62 (m, 2 H). The precipitate (1.0 g) was dissolved in 10 mL of a saturated sodium hydroxide solution and extracted (2 × 20 mL) with chloroform. The combined organic layers were dried over anhydrous magnesium sulfate and filtered. Rotary evaporation of the solvent yielded 600 mg of the free amine (mp 115–116 °C). The diamino diol **14** gave the following spectral data: ^{1}H NMR ($CDCl_3$) δ 1.03 (s, 6 H), 1.13 (s, 6 H), 1.23–1.73 (m, 2 H), 1.73–2.06 (s, br, 6 H, exchanged with D_2O), 3.17–3.37 (m, 2 H); IR ($CHCl_3$) 2.94, 3.33, 6.33, 6.80, 7.19, 7.30, 9.26, 11.24 μm; fast atom bombardment mass spectrum (glycerin, positive ion), m/z (rel intensity) 219 (15, M + 1), 218 (100, M). Anal. Calcd for $C_{11}H_{26}N_2O_2$: C, 60.52; H, 12.00; N, 12.83. Found: C, 60.26; H, 11.94; N, 12.67.

***dl*-2,8-Dimethyl-2,8-bis((*tert*-butoxycarbonyl)amino)-3,7-nonanediol (16).** The procedure of Tarbell, Yamamoto, and Pope[30] was modified as follows. A solution of 27 g (0.12 mol) of di-*tert*-butyl dicarbonate in 160 mL of chloroform was added to a magnetically stirred mixture of 20 g (0.059 mol) of diamino diol **14** acetic acid salt, 10 g of sodium hydroxide, and 30 g of sodium chloride in 200 mL of water. The mixture was stirred at reflux under a nitrogen atmosphere for 18 h. The phases were separated and the aqueous layer was extracted with 50 mL of chloroform. The combined organic phases were dried over anhydrous magnesium sulfate and filtered. The filtrate was concentrated by rotary evaporation to approximately one-tenth of its original

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volume, poured into 300 mL of cold diethyl ether, and placed in a freezer. A white precipitate slowly formed and was collected by suction filtration and dried in vacuo at ambient temperature, yielding 21 g (85%) of **16** (mp 139–140 °C). The di-*t*-BOC diamino diol **16** had the following properties: ^{1}H NMR ($CDCl_3$) δ 1.19 (s, 6 H), 1.35 (s, 6 H), 1.43 (s, 18 H), 1.50–2.17 (m, 6 H), 3.46 (m, 2 H), 4.03 (m, 2 H, D_2O exchanged), 4.65 (s, br, 2 H); IR ($CHCl_3$) 2.92, 3.36, 5.56, 5.92, 6.67, 6.87, 7.17, 7.30, 7.87, 8.58, 9.22 μm; fast atom bombardment mass spectrum (glycerin, positive ion), m/z (rel intensity) 419 (100, M + 1), 363 (10), 319 (20), 263 (71), 245 (11), 215 (7); silica gel TLC R_f 0.20 (40% ethyl acetate/hexanes (v/v)). Anal. Calcd for $C_{21}H_{42}N_2O_6$: C, 60.26; H, 10.11; N, 6.69. Found: C, 60.41; H, 10.06; N, 6.52.

***dl*-2,8-Dimethyl-2,8-bis((*tert*-butoxycarbonyl)amino)-3,7-bis(pyruvoyloxy)nonane (18).** A flame-dried, 1000-mL, three-neck, round-bottom flask equipped with a mechanical stirrer was charged with 120 g of vacuum oven dried (120 °C, 0.2 Torr) dibasic sodium hydrogen phosphate, 600 mL of dried (4-Å molecular sieves) dichloromethane, and 22 g (0.053 mol) of di-*t*-BOC diamino diol **16**. The flask was submerged into an ice bath and the mixture stirred under a nitrogen atmosphere. Pyruvoyl chloride[31] (90%, 18.4 g, 0.156 mol) was added dropwise to the stirred mixture over 15 min and the mixture was stirred at 0 °C for 2 h. The ice bath was removed and the mixture was stirred at ambient temperature for 1 h. The flask was resubmerged into the ice bath and the mixture was stirred for an additional hour. The reaction was followed by silica gel TLC, monitoring the disappearance of the di-*t*-BOC diamino diol **16**, eluting with 30% dichloromethane/ethyl acetate (v/v). The mixture was filtered and the solid residue was washed (2 × 100 mL) with anhydrous diethyl ether. The filtrate was washed with 200 mL of 2 M pH 7 phosphate buffer. The organic phase was dried over anhydrous magnesium sulfate in the freezer. Silica gel TLC analysis of the ethereal layer displayed only one spot, R_f 0.7, eluting with 30% dichloromethane/ethyl acetate (v/v). The di-*t*-BOC dipyruvate **18** was not sufficiently stable for purification for combustion analysis or for determination of its melting point. The crude reaction product was used in the subsequent step in the synthesis of **12**. The structure of the di-*t*-BOC dipyruvate **18** was determined from its relatively simple spectral characteristics: ^{1}H NMR ($CDCl_3$) δ 1.27 (s, 6 H), 1.32 (s, 6 H), 1.42 (s, 18 H), 1.53–1.77 (m, 6 H), 2.48 (s, 6 H), 4.55 (s, br, 2 H), 5.37–5.52 (m, 2 H); IR (thin film) 2.98, 3.36, 5.76, 6.62, 7.19, 7.33, 7.87, 8.73, 9.3 μm; fast atom bombardment mass spectrum (glycerin, negative ion), m/z (rel intensity) 559 (30, M + 1), 558 (100, M), 557 (59).

***dl*-1,3-Propanediyl-6,6′-bis(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (12).** The solvent was removed from the crude di-*t*-BOC dipyruvate **18** by rotary evaporation. The resulting viscous residue was dissolved in 50 mL of dichloromethane, and 25 mL of trifluoroacetic acid was added dropwise with stirring. Upon completion of the addition of the trifluoroacetic acid, the solution was stirred for 2 h at ambient temperature. The solvent was removed by rotary evaporation, and the resulting residue was dissolved in 100 mL of triethylamine followed by 100 mL of water. After cooling, 200 mL dichloromethane was added. The phases were separated and the organic phase was washed successively with 0.5 N hydrochloric acid and water until the aqueous layer tested acidic to litmus. The organic phase was washed with 50 mL of 5% aqueous sodium bicarbonate and dried over anhydrous magnesium sulfate. The mixture was filtered and the solvent was removed by rotary evaporation. The resulting residue was diluted with 30 mL of diethyl ether and placed in the freezer. A light amber precipitate gradually formed. Purification of the precipitate and the residue remaining from the rotary evaporation of the solvent was accomplished by dry column flash chromatography, eluting successively with dichloromethane, 5% acetone/dichloromethane, and 10% acetone/dichloromethane (v/v). The yield was 2.05 g (12%) of **12** after air drying. A sublimed (124–126 °C at 0.2 Torr) sample (mp 141–142 °C) had the following spectral properties: ^{1}H NMR ($CDCl_3$) δ 1.07 (s, 6 H), 1.32 (s, 6 H), 1.50–1.86 (m, 6 H), 2.25 (s, 6 H), 3.92–4.13 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 19.89, 21.08, 26.38, 30.21, 57.36, 84.32, 156.45, 156.91; IR ($CHCl_3$) 5.79, 6.13 μm; mass spectrum (70 eV), m/z (rel intensity) 322 (22, M), 238 (10), 237 (61), 96 (13), 83 (16), 82 (100), 81 (31), 74 (16), 69 (11), 59 (26), 45 (15), 43 (13), 42 (60), 41 (20), 31 (33), 29 (15); silica gel TLC R_f 0.4 (10% acetone/dichloromethane (v/v)); UV (95% EtOH) λ_{max} 324 nm, ϵ 209 L mol^{-1} cm^{-1}. Anal. Calcd for $C_{17}H_{26}N_2O_4$: C, 63.33; H, 8.13; N, 8.69. Found: C, 63.30; H, 8.16; N, 8.68. Crystals for single-crystal X-ray crystallography were grown from 50% dichloromethane/isooctane (v/v) by slow evaporation of the solvent. The stereochemical configuration of **12** was assigned on the basis of the X-ray crystal structure.

***dl*-6,6′-Bi(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (11) from Direct Condensation of Diamino Diol 13 with Ethyl Pyruvate.** To a stirred suspension of 11.8 g (40 mmol) of *dl*-2,5-diamino-3,4-dihydroxy-2,5-dimethylhexane (**13**) diacetate in 150 mL of mesitylene at reflux was added 11.6 g (100 mmol) of ethyl pyruvate dropwise over a period of 30 min. The reaction was conducted under a nitrogen atmosphere, and a Dean–Stark trap was used to remove the water formed. The mixture was then refluxed for 15 h. Monitoring by GLC (7% SE30 on 60/80-mesh Chromosorb W in a 0.6 cm × 3 m column at 200 °C with a helium flow rate of 1 mL/s) showed that *dl*-6,6′-bi(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (**11**) (retention time, 4 min) reached its maximum concentration after ca. 13 h. After cooling, the light brown solution was decanted from a dark insoluble portion sticking on the walls of the flask, and the solvent was rotary evaporated at 0.2 Torr at 50 °C. Flash chromatography of the residue was performed with a 5.5 cm × 18 cm column of Merck 40–63-μm silica gel, eluting with ethyl acetate. Bisoxazinone **11** was collected after ca. 600 mL of solvent had passed through the column. The combined fractions containing **11**, for a total of ca. 500 mL, upon evaporation of the solvent gave a vitreous residue that crystallized upon addition of 25 mL of ether. The crystals (1.83 g, 18%) were collected and washed with ether. The product had mp 179–181 °C and appeared pure by TLC (R_f 0.25, ether; 0.5, ethyl acetate). An analytically pure sample, mp 186–188 °C, obtained by sublimation at 140–150 °C at 0.1 Torr, gave the following spectral absorptions: IR (KBr) 5.78, 6.10, 7.70, 8.60, 8.70, 9.40, 10.3, 12.3, 13.1, 17.8 μm; ^{1}H NMR ($CDCl_3$) δ 1.29 (s, 6 H), 1.37 (s, 6 H), 2.21 (s, 6 H), 4.33 (s, 2 H); ^{13}C NMR ($CDCl_3$) δ 21.22, 22.97, 27.13, 56.94, 80.03, 154.8, 156.9; mass spectrum (70 eV), m/z (rel intensity) 280 (4, M), 111 (8), 84 (8), 83 (100), 71 (11), 42 (31); UV (95% EtOH) λ_{max} 318 nm, ϵ 235 L mol^{-1} cm^{-1}. Anal. Calcd for $C_{14}H_{20}N_2O_4$: C, 59.99; H, 7.18; N, 9.99. Found: C, 60.13; H, 7.23; N, 9.95.

When the reaction was run using the free amino alcohol **13** instead of its diacetate, the same results were obtained except maximum product formation occurred after refluxing for 24 h.

Photoreduction of *dl*-1,3-Propanediyl-6,6′-bis(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazinyl) (12). Bisoxazinone **12** (200 mg) dissolved in 50 mL of 2-propanol was degassed with nitrogen and irradiated with a 400-W mercury street lamp through a Pyrex immersion well under a nitrogen atmosphere. Throughout the irradiation the photochemical apparatus was immersed in a cold bath thermostated at −40 °C. The reaction was followed by monitoring the disappearance of the absorbance at 324 nm. After 18 h, the irradiation was stopped, the immersion well was removed, and the flocculent white mixture was diluted with 10 mL of diethyl ether. The reaction vessel was stoppered and returned to the cold bath for an additional hour. The mixture was transferred to 50-mL screwtop Nalgene centrifuge tubes and centrifuged at 15000 rpm at −20 °C for 5 min. The supernatant was decanted, and the white residue was dried in vacuo at ambient temperature. The solvent of the supernatant was rotary evaporated under high vacuum (0.1 Torr), and 50 mL of diethyl ether was added, producing a white precipitate. This ethereal mixture was transferred to the Nalgene centrifuge tubes and centrifuged at 15000 rpm at −20 °C for 5 min. The supernatant was again decanted, and the residue was dried in vacuo at room temperature. The ^{1}H NMR spectra of the two crops of photolysis products were essentially identical. The combined yield was 132 mg (66%), mp 139–144 °C. Vapor pressure osmometry at 37 °C in chloroform indicated that the average molecular weight was 1670 amu, which implied an average of five molecules of starting material per product molecule. The diradical oligomer structure **9** was assigned on the basis of chemical properties and the following spectroscopic properties: ^{1}H NMR ($CDCl_3$) δ 0.9–1.9 (br m, 10 H), 3.8–4.6 (br m, 1 H); IR ($CHCl_3$) 3.34, 5.80 μm; fast atom bombardment mass

(31) Ottenheijm, H. C. J.; Tijhuis, M. W. *Org. Synth.* **1983**, *61*, 1.

spectrum (thiodiethanol, positive ion) showed peaks clustered at m/z (rel intensity) 1623 (<1), 1297 (<1), 976 (12), 650 (52), 325 (100). Anal. Calcd for $C_{85}H_{140}N_{10}O_{20}$: C, 62.94; H, 8.70; N, 8.63; O, 19.73. Found: C, 60.77; H, 8.96; N, 7.85; O, 22.19. The analysis is most correct for a trihydrate; calcd for $C_{85}H_{146}N_{10}O_{23}$: C, 60.91; H, 8.78; N, 8.36; O, 21.95.

Kinetics of Bond Homolysis of Diradical Oligomers 9. In a typical experiment, 2.42 mg (6.13×10^{-6} mol) of diphenylpicrylhydrazyl (DPPH) in a 50-mL volumetric flask was dissolved in 50 mL of nitrogen-purged, 95% ethanol or spectrograde benzene. A 25-mL volumetric flask was charged with 1.25 mg (3.85×10^{-6} mol of monomeric units) of the diradical oligomer **9** and 25 mL of spectrograde dichloromethane. A syringe was used to transfer 0.6 mL (0.925×10^{-7} mol of monomeric units) of the diradical oligomer solution to the spectral cell compartment of a two compartment cell cooled to 0 °C in ice. The dichloromethane was evaporated with a stream of nitrogen before 2.0 mL to 3.2 mL (2.45×10^{-7} to 3.92×10^{-7} mol) of the DPPH solution was injected into the second compartment of the cell. The solution was freeze–pump–thaw degassed, and the cell was sealed with a torch. The compartment containing the DPPH solution was wrapped in aluminum foil to assist in heat transfer before being placed into the thermostated cell holder. After 7 min for temperature equilibration, the DPPH solution was vigorously mixed with the diradical oligomer. The cell holder was placed into the spectrophotometer where the decrease in the average absorbance from 516 to 522 nm was followed versus time. A plot of the natural logarithm of the difference between the absorbance at any time t and the absorbance at infinity ($A_t - A_\infty$) versus time gave a straight line with a slope equal to the first-order rate constant for bond homolysis. The absorbance data were also subjected to a nonlinear least-squares regressional analysis using the following equation,

$$A_t - A_\infty = (A_0 - A_\infty)e^{-kt}$$

where k is the first-order rate constant for bond homolysis, A_0 is the absorbance at time zero, and t is the time. This entire procedure was repeated for a total of six different temperatures. The kinetic data obtained are summarized in Table II. By plotting $\ln(k/T)$ versus $1/T$ where T is the temperature in degrees Kelvin, the enthalpy of activation was calculated from the slope $= -\Delta H^*/R$, where R is the gas constant. The entropy of activation was calculated from the intercept $(\ln(R/Nh) + \Delta S^*/R)$, where N is Avogadro's number and h is Planck's constant (see Table III). The kinetics of bond homolysis of **8** in benzene and ethanol were determined similarly.

Effects of DPPH Concentration on the Kinetics of Bond Homolysis of the Diradical Oligomers 9. A 1.35×10^{-4} M ethanolic solution of DPPH was used to study this effect at 25.4 °C. The same procedure described in the preceding section was used except that the concentration of the diradical oligomer (expressed in monomeric units) was halved. The concentration effect was also determined for the oligomer in benzene at 82.5 °C. Linear least-squares regressional analysis of the data showed that the rate constant was not affected by the change in the concentration of the diradical oligomers **9**.

Air Oxidation of the Diradical Oligomers 9. The diradical oligomers **9** (20 mg) were refluxed in 30 mL of ethanol for 1 h in the presence of air. The solvent was removed by high vacuum rotary evaporation (0.1 Torr), and the residue was taken up in deuteriochloroform. The ^{1}H NMR spectrum was identical with that of the bisoxazinone **12**. No other products were observed.

Reduction of the Bisoxazinone 12. A 500-mL medium pressure Parr bottle was charged with 400 mg of the bisoxazinone **12**, 200 mg of 10% palladium on charcoal, and 75 mL of ethyl acetate. The mixture was hydrogenated at 60 psi for 18 h and then filtered through Celite. The solvent was removed by rotary evaporation. The ^{1}H NMR spectrum in $CDCl_3$ showed complete reduction of the carbon–nitrogen double bonds as evidenced by the absence of the 3,3′-methyl peak at 2.25 ppm. The products (**25**) of this reaction were formed, as two out of a possible three diastereoisomers, in approximately a ratio of 2.5 to 1 on the basis of the integration of the quartets at 3.60 and 3.74 ppm, respectively. The major isomer displayed two singlets at 1.03 and 1.15 ppm, a doublet at 1.31 ppm (J = 6.7), and a quartet at 3.60 ppm (J = 6.7). The minor isomer displayed two singlets at 1.09 and 1.12 ppm, a doublet at 1.41 ppm (J = 7), and a quartet at 3.74 ppm (J = 7). The mixture had broad complex multiplets at 1.48–1.80 ppm and 3.90–4.10 ppm.

Disproportionation of the Diradical Oligomers 9. An NMR tube attached to a 10-cm length of 9-mm Pyrex tubing was charged with 50 mg of the diradical oligomer **9** and 0.5 mL of deuteriochloroform. The solution was freeze–pump–thaw degassed through three cycles and sealed under vacuum. The tube was placed in a constant temperature bath thermostated at 60.8 ± 0.1 °C. The reaction was monitored periodically by ^{1}H NMR, following the increase in the absorption of the peak at 2.25 ppm. After 160 h the final spectrum was taken. The spectrum indicated what appeared to be the production of a mixture of two products, the bisoxazinone **12** and the bismorpholine, 1,3-bis(3,5,5-trimethyl-2-oxomorpholin-6-yl)propane (**25**). Silica gel TLC of the mixture eluting with 40% acetone/ethyl acetate (v/v) was more complex than the NMR spectrum indicated. Silica gel TLC showed that the mixture contained the bisoxazinone **12**, the isomers of the bismorpholine 1,3-bis(3,5,5-trimethyl-2-oxomorpholin-6-yl)propane (**25**), and a third product presumed to be 1-(3,5,5-trimethyl-2-oxomorpholin-6-yl)-3-(5,6-dihydro-3,5,5-trimethyl-2-oxo-1,4-oxazin-6-yl)propane (**24**), based upon its chromatographic and spectroscopic properties and in analogy with the products from disproportionation of **8**. The same products were identified by silica gel TLC and ^{1}H NMR analysis of the mixture resulting from partial hydrogenation of **12** at atmospheric pressure.

Reduction of the Bisoxazinone 11. Bisoxazinone **11** (0.10 g, 0.35 mmol) was dissolved in 3 mL of ethyl acetate and hydrogenated in the presence of 27 mg of Kodak 10% palladium on charcoal at ambient temperature and 1 atm. Two molar equivalents of hydrogen were taken up in about 1 h. After filtration and solvent rotary evaporation, a vitreous residue (0.1 g) which slowly solidified into crystals of 6,6′-bi(3,5,5-trimethyl-2-oxomorpholinyl) (**23**) was obtained. GLC (0.6 cm × 3 m column of 7% SE-30 on 60/80 mesh Chromosorb W at 200 °C with a helium flow rate of 1 mL/s) showed a peak with retention time of 8 min. After washing the crystals with a little ethyl ether and air drying, the melting point was 136–138 °C (yield 90%). The material was characterized as 6,6′-bi(3,5,5-trimethyl-2-oxomorpholinyl) (**23**) from the following spectral data: IR (KBr) 3.02, 5.80, 7.25, 8.10, 8.45, 9.15, 9.50, 12.3, 12.6 μm; ^{1}H NMR ($CDCl_3$) δ 1.21 (s, 6 H), 1.35 (s, 6 H, overlapped with the upfield portion of a 6-H doublet at 1.39, J = 7), 3.65 (q, J = 7, 2 H), 4.34 (s, 2 H); mass spectrum (70 eV), m/z (rel intensity) 284 (M^+, 12), 197 (13), 114 (10), 110 (16), 86 (12), 85 (100), 84 (29), 83, (13), 70 (11), 44 (13), 42 (17). Anal. Calcd for $C_{14}H_{24}N_2O_4$: C, 59.14; H, 8.51; N, 9.85. Found: C, 59.08; H, 8.51, N, 9.82.

When the hydrogenation was stopped after only 1.2 molar equiv had been absorbed, GLC showed three major peaks with retention times of 4, 6, and 8 min. Preparative GLC showed that the 4-min peak was due to unreacted **11** and the 8-min peak was due to **23**. The compound with retention time of 6 min, mp 142–145 °C, proved to be one of the two possible diastereoisomers of 6-(3,5,5-trimethyl-2-oxomorpholin-6-yl)-5,6-dihydro-3,5,5-trimethyl-1,4-oxazin-2-one (**22**) on the basis of the following data: IR (KBr) 3.03, 5.76, 5.81, 6.08, 7.27, 8.40, 8.50, 8.70, 9.10, 9.90, 12.4, 13.1, 17.4 μm; ^{1}H NMR ($CDCl_3$) δ 1.21 (s, 3 H), 1.27 (s, 3 H), 1.36 (two overlapping singlets, 6 H), 1.48 (d, J = 7, 3 H), 1.77 (br s, 1 H), 2.21 (s, 3 H), 3.70 (q, J = 7, 1 H), 4.26 (s, 1 H), 4.41 (s, 1 H); mass spectrum (70 eV), m/z (rel intensity) 282 (M, 4), 112 (12), 110 (19), 86 (11), 85 (100), 84 (35), 83 (62), 70 (13), 44 (12), 42 (30); UV (95% EtOH) 318 nm (ε 129 M^{-1} cm^{-1}). Anal. Calcd for $C_{14}H_{22}N_2O_4$: C, 59.55; H, 7.85; N, 9.92. Found: C, 59.27; H, 7.92; N, 9.85.

A minor peak in the gas chromatogram, retention time 10 min, gave the following spectral data: ^{1}H NMR ($CDCl_3$) a series of partially overlapping sharp peaks at δ 1.18, 1.21, 1.37, 1.45, 1.47, 1.56, seven small peaks between 3.57 and 4.00 (possibly two partially overlapping quartets), and two singlets at 4.14 and 4.47. Comparison with the ^{1}H NMR spectrum of **23**, together with the lack of any feature in the UV spectrum above 250 nm and a mass spectral molecular ion at m/z 284, suggests that the GLC peak was due to a mixture of the other two diastereoisomers of **23**.

Disproportionation of Diradical Oligomers 8. Diradical oligomers **8** (16 mg) were dissolved in 1 mL of $CDCl_3$ in an NMR

tube. The solution was freeze–thaw degassed over four cycles at 10^{-5} Torr and sealed under vacuum. The tube was then kept in a thermostated bath at 60 °C. ^{1}H NMR spectral changes were monitored until, after 31 h, no more starting material appeared in the spectrum and no more meaningful changes were observed. At this moment the NMR spectrum showed the presence of bisoxazinone **11** and morpholinyloxazinone **22** as major species plus minor peaks possibly corresponding to diastereoisomers of **22** and bimorpholine **23**. GLC analysis (0.6 cm × 3 m column of 7% SE-30 on 60/80 mesh Chromosorb W at 200 °C with a He flow of 1 mL/s) showed two main peaks with retention times of 4 min (**11**) and 6 min (**22**). Minor peaks with retention times of 7 min, 8 min (**23**), and 10 min (br) also appeared. The UV spectrum in 95% ethanol showed a maximum at 318 nm with an intensity in agreement with ca. 90% disproportionation having occurred. Another experiment showed that disproportionation took almost 1 year to occur at ambient temperature.

Diradical oligomer **8** (13 mg) was also pyrolyzed in a vacuum sublimer at 140 °C for 30 min at 0.1 Torr, during which time 6 mg of a semisolid mixture was collected on the cold finger. Both ^{1}H NMR ($CDCl_3$) spectroscopic and GLC (vide supra) analyses showed that the composition of the mixture was very similar to that observed when the disproportionation was conducted in solution. Direct pyrolysis in the heated inlet of the GLC also gave the same five-peak pattern observed by GLC after solution disproportionation. Preparative GLC of **8**, accounting for 70% of the injected material, showed by ^{1}H NMR spectroscopy that the peak with retention time 4 min was **11**, the peak at 6 min was **22**, and the peak at 8 min was **23**. The ^{1}H NMR spectrum of material with retention time 7 min showed peaks at δ 1.20 (s, 3 H), 1.32 (two overlapping singlets, 6 H), 1.37 (s, 3 H), 1.44 (d, J = 7, 3 H), 2.21 (s, 3 H), 3.82 (q, J = 7, 1 H), 4.24 (s, 2 H), 4.41 (s, 2 H), suggestive of a stereoisomer of **22**. The ^{1}H NMR spectrum of the material that appeared as a broad peak with retention time of 10 min was identical with that obtained for material which gave the minor peak in the gas chromatogram of the mixture obtained from partial hydrogenation of **11**. The peak width and the spectrum suggested that this product was a mixture of two diastereoisomers of **23**; accordingly the mass spectrum (70 eV) showed the following peaks: m/z (rel intensity) 284 (14, M), 130 (13), 110 (8), 87 (24), 86 (7), 85 (100), 84 (19), 83 (96), 82 (10), 70 (8), 49 (16), 48 (19), 47 (43), and 43 (15).

Synthesis of 3-Hydroxy-1-methyl-2*H*-indol-2-one (28). A 25-mL, round-bottom flask was charged with 1.0 g (0.0062 mol) of 1-methylisatin (**26**) and 10 mL of absolute ethanol. To this mixture was added 100 mg (0.0132 mol) of sodium borohydride. The resulting solution was heated on a steam bath for 5 min. The solvent was removed by rotary evaporation. The resulting residue was dissolved in 5 mL of water. The light yellow precipitate that formed was collected by gravity filtration and washed with 5 mL of water. The precipitate was air-dried to yield 550 mg (57%) of **28**. A sample was recrystallized from ethanol to give pure **28** with mp 154–155 °C (lit.[32] mp 149–151 °C). The reduced isatin **28** had the following spectral properties: ^{1}H NMR ($CDCl_3$) δ 3.18 (s, 3 H), 4.13 (d, J = 5, 1 H, exchanged with D_2O), 5.1 (d, J = 5, 1 H), 6.8–7.6 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ 23.14, 69.81, 108.33, 123.12, 125.07, 127.29, 129.62, 143.85, 177.23; mass spectrum (70 eV), m/z (rel intensity) 163 (100, M), 146 (6), 135 (13), 118 (14), 106 (86), 91 (13), 77 (29), 65 (11).

Reduction of 1-Methylisatin (26) with the Diradical Oligomers 9 in Chloroform. An NMR tube equipped for evacuation was charged with 7.5 mg (4.66×10^{-5} mol) of 1-methylisatin, 15 mg (4.63×10^{-5} mol of monomeric units) of the diradical oligomers **9**, and 0.5 mL of deuteriochloroform. The solution was freeze–pump–thaw degassed through three cycles, sealed, and placed in a constant temperature bath thermostated at 35.0 ± 0.1 °C. The reaction was monitored by ^{1}H NMR until no further reaction was apparent (380 h). The 1-methylisatin was reduced to the *dl* and *meso* isatides **27** on the basis of the peaks observed at 3.03 and 3.20 ppm.[11]

Reduction of 1-Methylisatin with the Diradical Oligomers 9 in Ethanol. A 9-mm Pyrex tube was charged with 1.0 mg (0.62×10^{-5} mol) of 1-methylisatin (**26**), 50 mg (15.5×10^{-5} mol of monomeric units) of the diradical oligomers **9**, and 0.5 mL of absolute ethanol. The tube was freeze–thaw degassed as previously described and sealed. The tube was placed in a 35.0 ± 0.1 °C thermostated bath for 3 min. The reaction was quenched with liquid nitrogen and the solvent removed by rotary evaporation. The ^{1}H NMR spectrum of the residue indicated that the isatides **27** were the only products formed from **26**.

Reduction of 1-Methylisatin by the Morpholinyl Radical Dimers 2 and 3. A 9-mm Pyrex tube was charged with 1.7 mg (1.1×10^{-5} mol) of 1-methylisatin (**26**), 15 mg (5.3×10^{-5} mol) of the mixed radical dimers (**2** and **3**), and 0.5 mL of absolute ethanol. The solution was freeze–thaw degassed and sealed as previously described. The mixture was reacted at 35.0 ± 0.1 °C for 3 min ($^1/_5$ life of **2** and **3**) followed by quenching with liquid nitrogen. The ^{1}H NMR spectrum of the residue from solvent rotary evaporation indicated that the isatides **27** were formed exclusively.

Attempted Reduction of Daunomycin (6) with the Diradical Oligomers 9. A 100-mL volumetric flask was charged with 9.8 mg (1.73×10^{-5} mol) of daunomycin (**6**) hydrochloride, 12.3 mg (1.0×10^{-4} mol) of tris(hydroxymethyl)aminomethane (Tris Base), 15.9 mg (1.0×10^{-4} mol) of tris(hydroxymethyl)-aminomethane hydrochloride (Tris·HCl), and 100 mL of methanol degassed with technical grade nitrogen. The mixture was sonicated to assist in mixing. A 25-mL, two-neck, round-bottom flask was charged with 10 mL (1.73×10^{-6} mol) of this solution and an acid-washed magnetic stir bar. To the stirred solution was added 3.1 mg (9.6×10^{-6} mol) of the diradical oligomers **9**. The solution was stirred at ambient temperature under technical grade nitrogen for 5 h. Only traces of 7-deoxydaunomycinone (**29**) formation were observed by silica gel TLC (R_f 0.88; 20% methanol/dichloromethane (v/v)).

Complexation of Various Metal Picrate Salts with the Diradical Oligomers 9. A 25-mL volumetric flask was charged with 5.93 mg (1.83×10^{-5} mol of pentamer units) of the diradical oligomers **9** and 25 mL of spectralgrade dichloromethane. A 1-cm path length Pyrex cuvette equipped with a screw cap top was charged with an excess of the metal picrate salt, 1 mL of the diradical solution, and 2 mL of spectral-grade dichloromethane. The cell was capped and shaken vigorously 100 times. The cell was allowed to sit for 5 to 10 min to allow for settling and the spectrum was taken from 300 to 800 nm. The concentration of the metal dissolved in the dichloromethane was determined by using the extinction coefficient of 18 000 L mol^{-1} cm^{-1} for the picrate anion.[33]

Synthesis of 3-Methyl-3-nitro-2-butanol. A magnetically stirred solution of 400 mL of 2-nitropropane, 400 mL of methanol, and 40 g of potassium hydroxide was cooled to 0 °C in an ice bath. To this stirred solution was added dropwise 45 mL (0.80 mol) of acetaldehyde over 30 min. Upon completion of the addition, the solution was stirred at 0 °C for 3 h. The solution was poured into a separatory funnel containing 200 mL of water. The layers were separated and the aqueous phase was extracted (2 × 100 mL) with diethyl ether. The combined organic phases were washed with 25 mL of water, dried over anhydrous magnesium sulfate, and filtered. The solvent was removed from the filtrate by rotary evaporation yielding 86 g (80%) of the crude nitro alcohol as a colorless oil. The crude nitro alcohol was sufficiently pure for subsequent reactions. It had the following spectral properties: ^{1}H NMR ($CDCl_3$) δ 1.21 (d, J = 6, 3 H), 1.55 (s, 3 H), 1.57 (s, 3 H), 2.52 (br, 1 H), 4.25 (q, J = 6, 1 H); IR (thin film) 2.71–3.28 (br), 3.36, 6.49, 6.85, 7.09, 7.27, 7.38, 8.97 μm; mass spectrum (70 eV), m/z (rel intensity) 89 (38), 87 (47), 69 (35), 59 (43), 45 (97), 43 (60), 41 (100), 32 (31). Anal. Calcd for $C_5H_{11}NO_3$: C, 45.10; H, 8.33; N, 10.52. Found: C, 45.22; H, 8.42; N, 10.40.

Synthesis of 3-Amino-3-methyl-2-butanol. A 500-mL Parr medium pressure reaction bottle was charged with 32 g (0.24 mol) of 3-methyl-3-nitro-2-butanol, 8 g of 10% palladium on charcoal, 50 mL of glacial acetic acid, and 200 mL of absolute ethanol. The mixture was hydrogenated at 96 psi at ambient temperature until the theoretical uptake of hydrogen was achieved. The mixture was filtered through Celite and the residue was washed with 25 mL of water. The filtrate was concentrated by rotary evaporation

(32) Colman, H. G. *Ann.* **1888**, *248*, 121.

(33) Pederson, C. J. *Fed. Proc.* **1968**, *27*, 1305.

until a viscous residue remained. The residue was poured into 600 mL of cold ethyl acetate and placed in a freezer. The white precipitate that formed was collected by suction filtration and dried in vacuo at ambient temperature, yielding 25 g (64%) of the amino alcohol acetic acid salt (mp 150–152 °C). Anal. Calcd for $C_7H_{17}NO_3$: C, 51.51; H, 10.50; N, 8.58. Found: C, 51.50; H, 10.51; N, 8.52. A portion of the white precipitate (1 g) was dissolved in 10 mL of a saturated sodium hydroxide solution. The basic mixture was extracted (2 × 10 mL) with chloroform. The combined organic extracts were dried over anhydrous magnesium sulfate and filtered. The solvent was removed by rotary evaporation, yielding 400 mg of the free amine as a colorless oil. The amino alcohol had the following spectral properties: ^{1}H NMR (DMSO-d_6) δ 1.74 (s, 3 H), 1.77 (s, 3 H), 1.80 (d, J = 6, 3 H), 3.86–4.4 (m, br, 4 H); IR (thin film) 2.74–3.31 (br), 3.36, 3.65, 6.31, 6.85, 7.25, 8.33, 8.97 μm; mass spectrum (70 eV), m/z (rel intensity) 104 (100), 87 (7), 86 (7), 58 (43).

Synthesis of 3,5,5,6-Tetramethyl-1,4-oxazin-2-one (32). A 250-mL, round-bottom flask was charged with 20 g of 3-amino-3-methyl-2-butanol acetic acid salt, 20 mL of ethyl pyruvate, and 200 mL of *m*-xylene. This mixture was magnetically stirred and became homogeneous upon heating. The solution was brought to reflux and the water formed was removed by means of a Dean–Stark trap. The reaction was halted after 5 h, and the solvent was removed by high vacuum (0.1 Torr) rotary evaporation. The residue was distilled (80–82 °C at 10 Torr). The distillate was dissolved in diethyl ether and cooled to −27 °C. The crystals that formed were collected by gravity filtration conducted in the freezer. The filtrate was concentrated and rediluted with ether and cooled to −27 °C. The procedure was repeated successively until no further crystallization occurred. The white crystals were air-dried, yielding 4 g (21%) of **32** (mp 48–49 °C). The tetramethyloxazinone had the following spectral properties: ^{1}H NMR ($CDCl_3$) δ 1.09 (s, 3 H), 1.31 (s, 3 H), 1.36 (d, J = 6, 3 H), 2.26 (s, 3 H), 4.29 (q, J = 6, 1 H); IR ($CHCl_3$) 3.38, 5.78, 6.12, 7.25, 7.3, 7.63, 8.47, 8.62, 9.0, 9.26 μm; mass spectrum (70 eV), m/z (rel intensity) 156 (7, M + 1), 155 (29, M), 111 (12), 83 (61), 70 (56), 55 (34), 42 (100); UV (95% EtOH) λ_{max} 324 nm (ϵ 105 L mol^{-1} cm^{-1}). Anal. Calcd for $C_8H_{13}NO_2$: C, 61.91; H, 8.44; N, 9.03. Found: C, 61.99; H, 8.46; N, 9.00.

Photoreduction of 3,5,5,6-Tetramethyl-1,4-oxazin-2-one (32). Oxazinone **32** (1.0 g) was dissolved in 130 mL of 2-propanol, and the solution was degassed with nitrogen and irradiated with a 400-W mercury street lamp in a Pyrex immersion well. Throughout the irradiation, the photochemical apparatus was immersed in a bath thermostated at −40 °C. The reaction was followed by monitoring the decrease of the absorbance at 324 nm. After 18 h, the irradiation was halted, and the solvent was removed by high vacuum (0.1 Torr) rotary evaporation, yielding 0.64 g (63%) of the crude dimers **30** and **31**. Silica gel TLC conducted at 7 °C, eluting with 5% acetone/dichloromethane (v/v), showed two spots (R_f 0.26 and 0.38), although formation of six stereoisomeric dimers was possible. The dimers were cleanly separated by using dry column flash chromatography, eluting successively with 1%, 2%, 3%, 4%, and 5% acetone/dichloromethane (v/v). The eluting solvents were cooled to 0 °C prior to elution. Two equal fractions (15 to 30 mL) were collected for each of the eluting concentrations. The dimer with the higher R_f was designated as *dl* (**30**, mp 139–141 °C) and the dimer with the lower R_f was designated as *meso* (**31**, mp 128–131 °C). These arbitrary designations were based on the comparison of the ^{1}H NMR chemical shifts of the protons in the 6- and 6′-positions and the methyl groups in the 3- and 3′-positions with the chemical shifts of comparable protons in the *dl* and *meso* dimers **2** and **3**. The tetramethyloxomorpholinyl radical dimers showed the following spectral properties: *dl* ^{1}H NMR ($CDCl_3$) δ 1.05 (s, 6 H), 1.14 (s, 6 H), 1.23 (d, J = 6, 6 H), 1.65 (s, 6 H), 4.63 (q, J = 6, 2 H); mass spectrum (CI, isobutane), m/z (rel intensity) 314 (33), 313 (100, M + 1); *meso* ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 6 H), 1.17 (s, 6 H), 1.20 (d, J = 6, 6 H), 1.52 (s, 6 H), 4.45 (q, J = 6, 2 H); mass spectrum (CI, isobutane), m/z (rel intensity) 314 (37), 313 (100, M + 1); IR for mixture of *meso* and *dl* dimers, ($CHCl_3$) 3.38, 5.85, 6.85, 7.25, and 8.2 μm. Anal. Calcd for $C_{16}H_{28}N_2O_4$: C, 61.51; H, 9.03; N, 8.97. Found: C, 61.28; H, 9.01; N, 8.77.

Kinetics of Bond Homolysis of the Tetramethyloxomorpholinyl Radical Dimers 30 and 31. In a typical experiment, 2.42 mg (6.13×10^{-6} mol) of diphenylpicrylhydrazyl (DPPH) in a 50-mL volumetric flask was dissolved in 50 mL of nitrogen-degassed, spectral-grade benzene. A 25-mL volumetric flask was charged with 1.25 mg (4.0×10^{-6} mol) of dimer and 25 mL of spectral-grade dichloromethane. A syringe was used to transfer 0.6 mL (0.96×10^{-7} mol) of the dimer solution to the spectral cell compartment of a two compartment cell cooled to 0 °C in ice. The dichloromethane was evaporated with a stream of nitrogen before 3.2 mL (3.92×10^{-7} mol) of the DPPH solution was injected into the second compartment of the cell. The solution was freeze–pump–thaw degassed as previously described. The experiment was conducted and the data were reduced as previously described for the diradical oligomers **9**. This procedure was repeated for a total of four different temperatures for each of the isomers. The results are summarized in Tables IV and V.

Supplementary Material Available: Details of the crystal structure analysis, tables of atomic parameters, tables of derived results, an ORTEP drawing showing the atomic number scheme, a stereodrawing, and a unit cell drawing for bisoxazinone **12** (8 pages). Ordering information is given on any current masthead page.