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One-Electron Oxidation of 3-Substituted 2-Oxa-3-azabicyclo[2.2.2]octane Derivatives

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Abstract: $E^{\circ\prime}$ values measured by cyclic voltammetry and vIP values measured by photoelectron spectroscopy are reported for several 3-alkyl- and 3-acyl-2-oxa-3-azabicyclo[2.2.2]octane derivatives and some model compounds. The X-ray structure of **2**-CHO shows it to be in the *Z* conformation in the crystal, but both *Z* and *E* forms are observed in solution. ESR spectra are reported for several of the cation radicals, as well as the ENDOR spectrum of the 3-neopentyl cation radical. These results indicate that relaxation energies upon electron removal remain rather high even when the nitrogen is planar in both the neutral and cation radical forms in acylated compounds and that most of the N,C═O resonance of the neutral acylated compounds is gone in the cation radical.

Tetraalkylhydrazines (R_2NNR_2) have unusual conformational properties because of NN rotation angle dependent interactions between the lone pairs on their adjacent nitrogens.[1] In contrast to most saturated compounds, their cation radicals $R_2NNR_2^{\bullet+}$ are typically long-lived, allowing convenient study of their one-electron-oxidation properties, including measurement of the thermodynamics for electron transfer by measurement of the formal potential for oxidation ($E^{\circ\prime}$) using cyclic voltammetry (CV).[2] Unusually large effects on both the thermodynamics and kinetics of electron transfer are observed when the alkyl groups are changed, principally because of large changes in preferred geometry at the nitrogens in the two oxidation states. Dialkyl peroxides (ROOR) also have adjacent lone-pair-bearing atoms and show large effects on orbital energy level distributions as the OO rotational angle is changed by substituents.[3] Special alkyl groups are required for study of the one-electron oxidation of peroxides in the absence of following reactions because rapid decomposition of $ROOR^{\bullet+}$ usually occurs. Rather rapid OC cleavage for example with tertiary R groups appears to occur, because acyclic and four-membered-ring examples are only long-lived at −78 °C, where heterogeneous electron transfer is slow,[4] and even bicyclic examples show detectable decomposition at room temperature.[5] Extremely rapid CH cleavage occurs in most secondary R examples but is successfully inhibited by "Bredt's rule kinetic protection",[6] placing the α carbons at the bridgeheads of medium-ring bicyclic structures, which allows measurement of $E^{\circ\prime}$ and study of the solution ESR spectra of the cation radicals.[7]

In this work[8] we examine the electron-transfer properties of trisubstituted hydroxylamines (R_2NOR) including both alkyl substituents, which have only a rather weak electronic interaction with the nitrogen lone pair, and strongly interacting acyl substituents substituted on nitrogen. The effects of replacing alkyl by acyl substituents are easier to consider for hydroxylamines than they are for hydrazines (which are also being studied[9]) because the flattening at nitrogen which accompanies acyl group substitution causes substantially larger steric interactions for both oxidation states when the acyl groups are not linked into rings.

Results and Discussion

1-R

CV and PE Data. Most examples of R_2NOR do not give long-lived cation radicals in solution. The problem is not hydrogen loss from the carbons α to the nitrogen atom because **1**-OMe$^{\bullet+}$ does not even last the few milliseconds at −78 °C which are required to observe its reduction wave by CV.[6] The fact that **1**-Cl$^{\bullet+}$ is long-lived even at room temperature on the CV time scale (seconds) shows that the dialkylamino group of **1**-R is robust even when a poorer electron donator than OMe is present as R. Even **1**-O-*t*-Bu, which lacks an α proton next to O, proved to give a short-lived cation radical under CV conditions.[10] We turned to the 2-oxa-3-azabicyclo[2.2.2]octyl system **2**-R as one which ought to successfully protect the oxygen end of a hydroxylamine cation radical.[8] These compounds are readily available from **3**-H·HCl, which is available by the method of Arbuzov and Markovskaya,[11] who showed that reaction of 1,3-cyclohexadiene (**4**) with 1-chloro-1-nitrosocyclohexane (**5**) in alcohol produces **3**-H·HCl in good yield. Assignment of ESR splittings of the cation radicals required differentiation between the bridgehead positions, which was accomplished by using the 1-methyl com-

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(1) (a) Shvo, Y. *The Chemistry of Hydrazo, Azo, and Azoxy Groups*; Patai, S., Ed.; Interscience: New York, 1975, Part II, pp 1017–1095. (b) Nelsen, S. F. *Acc. Chem. Res.* **1978**, *11*, 14.

(2) (a) Nelsen, S. F. *Acc. Chem. Res.* **1981**, *14*, 131. (b) Nelsen, S. F. *Molecular Structures and Energetics*; Liebman, J. F., Greenberg, A., Eds.; VCH Publishers: Deerfield Beach, FL; Vol. 3, pp 1–86.

(3) (a) Brown, R. S. *Can. J. Chem.* **1975**, *53*, 3439. (b) Caughlin, D. J.; Brown, R. S.; Salomon, R. G. *J. Am. Chem. Soc.* **1979**, *101*, 1533. (c) Gleiter, R. T.; Schang, P.; Adam, W.; Eggelte, H. J.; Erden, I.; Bloodworth, A. J. *J. Electron Spectrosc. Relat. Phenom.* **1980**, *19*, 223. (d) Gleiter, R.; Dobler, W.; Eckert-Maksic, M.; Bloodworth, A. J.; Eggelte, H. J.; Cremer, D. *J. Org. Chem.* **1984**, *49*, 3716.

(4) Nelsen, S. F.; Kapp, D. L.; Gerson, F.; Lopez, J. *J. Am. Chem. Soc.* **1986**, *108*, 1027.

(5) Nelson, S. F.; Teasley, M. F.; Kapp, D. L.; Wilson, R. M. *J. Org. Chem.* **1984**, *49*, 1843.

(6) Nelsen, S. F.; Kessel, C. R.; Brien, D. J. *J. Am. Chem. Soc.* **1980**, *102*, 702.

(7) Nelsen, S. F.; Teasley, M. F.; Bloodworth, A. J.; Eggelte, H. J. *J. Org. Chem.* **1985**, *50*, 3299.

(8) For preliminary communication of these results, see: Nelsen, S. F.; Thompson-Colon, J. A. *J. Org. Chem.* **1983**, *48*, 3364.

(9) (a) Nelsen, S. F.; Blackstock, S. C.; Rumack, D. T. *J. Am. Chem. Soc.* **1983**, *105*, 3115. (b) Nelsen, S. F.; Blackstock, S. C.; Petillo, P. A.; Kaftory, M. *J. Am. Chem. Soc.* **1987**, *109*, 5724.

(10) Unpublished work of Daniel J. Steffek, Ph.D. Thesis, University of Wisconsin, 1986.

(11) (a) Arbuzov, Yu. A.; Markovskaya, A. *Bull. Akad. Sci. USSR., Div. Chem. Sci.* **1952**, 355. (b) For a review, see: Hamer, J.; Mushtaq, A. In *1,4-Cycloaddition Reactions*; Hamer, J., Ed.; Academic: New York, 1967; Chapter 12, p 419.

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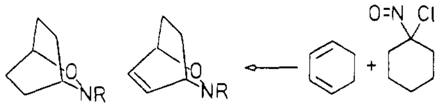
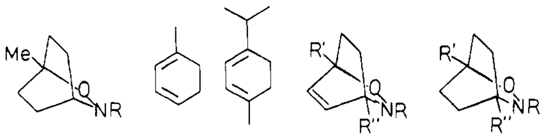


2-R 3-R 4 5

pounds **6**-R. Diels–Alder addition of **5** to 1-methyl-1,3-cyclohexadiene (**7**) gave only the regiochemistry shown for **6**, which is consistent with literature results[12] for 1-substituted butadienes, which also produce the isomer with the substituent adjacent to oxygen in the Diels–Alder product. The Diels–Alder reaction becomes too inefficient for 1,4-disubstituted 1,3-cyclohexadienes to add to **5** very successfully. With α-terpinene (**8**), aromatization to *p*-cymene with production of cyclohexanone oxime (isolated in 70% yield) was the principal reaction, but a 1.9% yield of **9**-CO_2Me was isolated after treatment with methyl chloroformate, allowing preparation of **10**-CO_2Me and **10**-Me by reduction; the regiochemistry of the addition was not established for **9** or **10** (R′, R″ = Me,*i*-Pr).



6-R 7 8 9-R 10-R

As we hoped, both *N*-alkyl and *N*-acyl examples of **2**-R and its analogues give cation radicals which are long-lived enough to allow $E°'$ measurement by CV. The lifetimes of the R = methyl compounds are significantly shorter than those of the ethyl compounds and increase when the solution is diluted, indicating that the cation radical is decomposed by the neutral compound, presumably by proton transfer. As expected[13] because CH bond alignment with the spin-bearing p orbital at nitrogen is sterically inhibited, **2**-*neo*-$Pe^{\bullet+}$ proved to be long-lived on the CV time scale, with no cation radical decomposition detected.

Most of the N-acylated species **2**-$COR'^{\bullet+}$ were long-lived on the CV time scale, although **2**-$COCF_3$, the compound studied which is hardest to oxidize, gave irreversible CV behavior in acetonitrile. Its oxidation is nearly as difficult as that of peroxides, which are also irreversible in acetonitrile, and like peroxides,[4,5,7] **2**-$COCF_3$ gave long-lived cations in CH_2Cl_2/TFAA. Both the 1-alkylated (**6** and **10**) and unsaturated (**3**) R = COR′ (R′ = H, alkyl, *O*-alkyl) cation radicals were noticeably shorter lived even though their oxidation potentials are in the range of their **2** analogues which gave long-lived cation radicals. Faster scan rates allowed determination of $E°'$ of the 1-alkylated compounds **6**-COMe, **6**-CHO, and **10**-COOMe at room temperature, but low temperature was required for the unsaturated compounds **3**-$CONMe_2$ and **3**-COMe (studied in CH_2Cl_2). Using the reduction/oxidation peak current ratio method of Nicholson and Shain[14] (assuming first-order decomposition for the cation radical) we estimate the reciprocal lifetime of **3**-$CONMe_2^{\bullet+}$ at 0.43 s^{-1} at −78 °C ($\Delta G^{\ddagger} \sim$ 12.3 kcal/mol) and of **3**-$CHO^{\bullet+}$ at 2.0 s at −65 °C ($\Delta G^{\ddagger} \sim$ 11.9 kcal/mol), significantly lower barriers than for **10**-$CO_2Me^{\bullet+}$ at 1.0 s^{-1} at 21 °C ($\Delta G^{\ddagger} \sim$ 17.6 kcal/mol). We suggest from the structural changes that lead to short lifetime (stability order: secondary C_1 > tertiary > allylic) that C_1–O cleavage is involved in cation radical decomposition.

Photoelectron spectra of several examples of **2**-R and of **6**-COOMe were determined to allow comparison of the gas-phase vertical ionization potential (vIP) with the solution-phase oxidation potential. Because the bicyclic system makes O,N lone-pair overlap large, the first PES ionization band, corresponding to the HOMO, is that dominated by the antibonding combination of the N_3 and $O_2(\pi)$ lone pairs, which is principally centered on N_3. The PES and CV data for **2**-R are summarized in Table I, and the CV data for **3**-R, **6**-R, and **10**-R appear in Table II.

Table I. Summary of PES and CV Data[a] for **2**-R

compd	vIP, eV	$E°'$ ($\Delta E_{pp}{}^{b}$), V
2-Me	7.91	0.67 (0.09)[c]
2-Et	7.89	0.64 (0.08)
2-*neo*-Pe	7.75	0.60 (0.09)
20		0.62 (0.08)
2-$CONMe_2$	8.13	1.15 (0.07)
2-COMe	8.30	1.36 (0.07)
2-CO-*t*-Bu	8.06	1.34 (0.10)
2-COOMe	8.43	1.40 (0.07)
2-COOEt	8.39	1.38 (0.09)
2-COO-*t*-Bu		1.37 (0.08)
2-CHO	8.53	1.52 (0.07)
(**2**-CO)$_2$		1.61 (0.07)
2-COCl		1.76 (0.09)
2-$COCF_3$	8.83	2.16 (0.09)[d]
2-CN	9.13	1.83 (0.25)

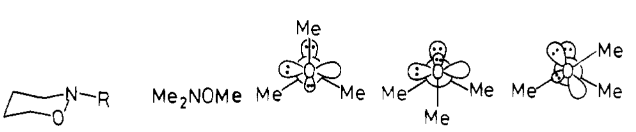
[a] Conditions: 2 mM in 0.1 M *n*-Bu_4NClO_4/CH_3CN, scan rate 0.2 V/s, at gold for R = alkyul, Pt for R = acyl, vs SCE, unless otherwise noted. [b] Difference between the oxidation and reduction peak potentials. [c] 0.5 mM, 0.5 V/s scan rate. [d] Solvent 20:1 CH_2Cl_2–CF_3CO_2H, scan rate 1 V/s.

Table II. Summary of CV Data[a] for **3**-R, **6**-R, and **10**-R

compd	$E°'$ ($\Delta E_{pp}{}^{b}$), V	compd	$E°'$ ($\Delta E_{pp}{}^{b}$), V
3-Me	0.78 (0.10)[c]	**6**-COMe	1.33 (0.06)[e]
3-Et	0.75 (0.09)	**6**-CHO	1.48 (0.08)[f,g]
3-$CONMe_2$	1.32 (0.07)[d]	**10**-Me	0.61 (0.10)[c]
3-COMe	1.53 (0.31)[d]	**10**-COOMe	1.40 (0.07)[h]
6-Me	0.76 (0.12)[c]		

[a] Conditions: 2 mM in 0.1 M *n*-Bu_4NClO_4/CH_3CN, scan rate 0.2 V/s, at gold for R = alkyl, Pt for R = acyl, vs SCE, unless otherwise noted. [b] Difference between the oxidation and reduction peak potentials. [c] 0.5 mM, 0.5 V/s scan rate. [d] −78 °C in CH_2Cl_2. [e] 5 V/s scan rate. [f] 10 V/s scan rate. [g] PES: vIP = 8.41 eV. [h] 1 V/s scan rate.

Conformations of Neutral R_2NOR'. Conformations of alkylated hydroxylamines have received considerable study.[15] The nitrogens of trialkylhydroxylamines are bent past tetrahedral; that of **11**-$CH_2C_6H_4$-*p*-CO_2H has α(av), the average of the bond angles for the substituents at nitrogen, 108.8° by X-ray crystallography,[16] and that of **12a** has been estimated to have α(av) = 105.6° by electron diffraction.[17] Although **12a** is the stablest conformation of **12**, an estimated 20% of a minor conformation suggested to be **12b** is present.



11-R 12 12a 12b 12c

Jones, Katritzky, and co-workers[18] measured the dipole moment μ for **12** at 0.88 D and concluded that **12c** is the major conformation in solution, a very different result from that found in the gas phase. As in all of their dipole moment work, Jones, Katritzky, and co-workers estimate μ by summing weighted increments for energy minima only. They estimated μ of 0.45, 1.81, and 0.98 D for **12a–c**, respectively, dismissed **12b** from consideration because its μ is so high and estimated a 75/25 mixture of **12c**/**12a** as being present in solution. This procedure is incorrect because rotational energy surfaces are flat enough that one really must sum over the entire energy surface to hope to generate the correct

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(12) Kresze, G.; Firl, J. *Fortschr. Chem. Forsch.* **1969**, *11*, 245.
(13) Nelsen, S. F.; Cunkle, G. T. *J. Org. Chem.* **1985**, *50*, 3701.
(14) Nicholson, R. S.; Shain, I. *Anal. Chem.* **1964**, *36*, 206.

(15) For a review, see: Riddell, F. G. *Tetrahedron* **1981**, *37*, 849.
(16) (a) Riddell, F. G.; Murray-Rust, P.; Murray-Rust, J. *Tetrahedron* **1974**, *30*, 1087. (b) ∠CNO = 108.0, ∠CNC = 113.7, ∠ONC = 104.8°.
(17) (a) Rankin, D. W. H.; Todd, M. R.; Riddell, F. G.; Turner, E. S. *J. Mol. Struct.* **1981**, *71*, 171. (b) The quality of this α(av) is not known, because ∠CNC had to be assumed and a value of 111.5° was chosen; this seems much too large from the X-ray data of ref 16, and the optimized ∠CNO obtained, 102.6 (7)°, seems much too small.
(18) Jones, R. A. Y.; Katritzky, A. R.; Saba, A.; Sparrow, A. J. *J. Chem. Soc., Perkin Trans. 2* **1974**, 1554.

answer. Furthermore, **12c** is not predicted to be an energy minimum by any level of molecular orbital calculations.[15] We suggest that **12c** was only considered as an energy minimum because these authors, like Riddell,[15] write two "sp^3-hybridized" oxygen lone pairs instead of pure p and s-rich lone pairs at oxygen, so that **12c** artificially appears "staggered"; it is not. We have carried out AM1[19] semiempirical calculations on **12** to allow a more reasonable estimation of the dipole moment expected for **12**. AM1 gives **12a** as the global NO rotation energy minimum, and a 5.0 kcal/mol higher energy NO rotational maximum, which occurs between the electronically most destabilized eclipsed N and O(p) lone-pair conformation and the sterically most destabilized eclipsed MeN,OMe conformation. A weighted Boltzmann average over this energy well gives a predicted μ of 0.58 D, not the 0.42 D of **12a**, because a significant fraction of the material is present in higher energy conformations which have higher μ. There is also a second energy minimum corresponding to **12b** (calculated μ = 2.65 D, energy 1.0 kcal/mol higher than **12a**). Including the whole energy surface in the Boltzmann averaging gives a calculated μ of 1.00 D. We do not doubt that the AM1 energy curve is not perfect even for the gas phase, that the AM1-calculated μ values might be slightly too large, or that the **12a**,**12b** energy gap would be slightly smaller in solution than in the gas phase; the calculations are not claimed to be highly accurate. We believe it is nevertheless clear that the μ observed for **12** provides no evidence for **12c** being an energy minimum.

In contrast, only the equatorial conformation has been observed by NMR for **11**-Me,[15] and **11**-CH$_2$C$_6$H$_4$-*p*-CO$_2$H is also equatorial in the crystal, with an oxygen p lone pair,N lone pair dihedral angle estimated from the X-ray data[16] at 37.9°. Although it has a more favorable lone pair,lone pair dihedral angle, the structural constraints of the oxazolidine ring clearly make axial **11**-R higher in energy than the equatorial form in solution.[20] Nitrogen inversion barriers are higher for trialkylhydroxylamines than for hydrazines of comparable substitution. $\Delta G^{\ddagger}$(25 °C) has been measured at 14.4 kcal/mol for **11**-Me, and 14.9 kcal/mol for **2**-Me,[15] while the corresponding numbers for hydrazines **13** and **14** are 12.5 and 12.2 kcal/mol,[21] despite higher steric contributions from the methyl on the noninverting nitrogen.

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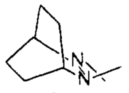

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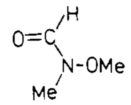

$O{=}C(H){-}N(Me){-}OMe$

15E

Less was known about conformations of acyldialkylhydroxylamines. Walter and Schaumann[22] found that **15** is a 3:1 mixture of *E*:*Z* isomers about the amide bond at −27.5 °C in CDCl$_3$ and measured a 14.6 kcal/mol N-CO rotational barrier at 19.5 °C by ^{1}H NMR, so the barrier is considerably lower than the 20–21 kcal/mol of dimethylformamide in various solvents.[23] In contrast, the N-CO rotational barrier of **2**-CHO is substantially higher than that of **15**, because no conformational broadening is seen at room temperature. Both steric and electronic factors are likely to be involved in making the rotational barrier of **15** lower than that of **2**-CHO; we shall not consider this complex issue here. The X-ray crystal structure of **2**-CHO was determined in this work, and it exists in the *Z* conformation shown in Figure 1, which summarizes the heavy-atom bond lengths and bond angles. The nitrogen atom is essentially planar (α(av) = 119.8(2)°), and the NO bond is 0.045 Å shorter than that of **11**-CH$_2$C$_6$H$_4$-*p*-CO$_2$H.[16] A shorter NO bond for **15** is expected because flattening at nitrogen increases s character in the NO bond, but the change observed seems rather large. For a series of tricyclic *N*,*N*′-diacylhydrazines in which changes in α(av) result from restriction of the NNC angles, *d*(NN) was found to be linear with α(av), shortening from ca. 1.458 to 1.407 Å (0.051) between α(av) of 109.5 and 120°.[24] The rehybridization at N is a little larger in comparing **11**-CH$_2$C$_6$H$_4$-*p*-CO$_2$H (a(av) = 108.8°) with **2**-CHO, but only one of the two atoms is flattening. The CON angle does increase from 108.0° for **11**-CH$_2$C$_6$H$_4$-*p*-CO$_2$H to 109.1° for **2**-CHO, but we lack data to tell how much this ought to decrease *d*(NO). The bicyclic ring has little twist ($\angle$CN,OC = −7.6°), and the C=O group is almost coplanar with the NO bond ($\angle$ON,CO = 1.5°); this leads to an unusually short O,O nonbonded distance of 2.691 Å, shorter than the van der Waals contact distance of 2.9 Å. N,C=O resonance is thus intact in **2**-CHO, as indicated by similar N—CO and C=O distances to those found in crystalline *N*,*N*′-diformylhydrazine[25] (1.320 (2)- vs 1.325 (4)-Å N—CO distances and 1.224 (2)- vs 1.214 (5)-Å C=O distances, respectively). As expected from work on acylated hydrazines,[9b] semiempirical calculations do a comparably poor job on the structure of **2Z**-CHO, although AM1 does somewhat better than MNDO.

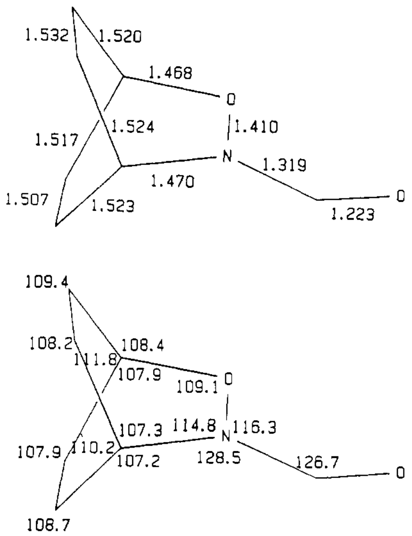

Figure 1. Bond lengths and angles for crystalline **2**-CHO. Statistical errors in the XC bond lengths are ±0.003 Å, and ±0.004 for the CC bond lengths; statistical errors in bond angles are ±0.2°.

Dissolving solid **2**-CHO at low temperature gives the NMR spectrum of only **2Z**-CHO, which is stable for over 4 h at −78 °C, but at room temperature, **2**-CHO exists as a mixture of the *Z* and *E* forms, as do **2**-COMe and **2**-COCF$_3$. We have been unable to find any evidence for different PE spectra or CV curves for *Z* and *E* conformations of **2**–COR′; large differences in behavior are not expected.

ESR Splittings of R$_2$NOR$^{\bullet+}$. The ESR spectra of **2**-R$^{\bullet+}$ and its analogues provide the most direct experimental evidence for the nature of these cation radicals, and considerable effort was put into assigning these very complex spectra. Although the **2**-alkyl cations showed nearly uniform line widths throughout the spectrum, all of the **2**-acyl cations exhibited nonuniform line widths, with the high-field, $\bar{M}_N$(N) = −1 lines more noticeably broadened compared to the low-field lines; compare the spectra of **2**-Me$^{\bullet+}$ and **2**-CHO$^{\bullet+}$ in Figures 2 and 3. We only used the most resolved, low-field branch of the spectra in estimating the

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[19] Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.

[20] AM1 predicts axial **11**-Me to be 1.4 kcal/mol stabler than the equatorial form in the gas phase, which is unlikely to be correct, given the large energy gap in the opposite direction in solution.

[21] Nelsen, S. F.; Weisman, G. R. *J. Am. Chem. Soc.* **1976**, *98*, 1842, 3281.

[22] Walter, W.; Schaumann, E. *Liebigs Ann. Chem.* **1971**, *743*, 154.

[23] (a) Stewart, W. E.; Siddall, T. H. III. *Chem. Rev.* **1970**, *70*, 517. (b) Jackson, L. M. *Dynamic Nuclear Magnetic Resonance Spectroscopy*; Jackson, L. M., Cotton, F. A., Eds.; Academic: New York, 1975; Chapter 7, p 203.

[24] Kaftory, M.; Agmon, I. *J. Am. Chem. Soc.* **1984**, *106*, 7785.

[25] Tomiie, Y.; Koo, C. H.; Nitta, I. *Acta Crystallogr.* **1958**, *11*, 774.

Table III. ESR Splitting Constants (G) for $\mathbf{2}\text{-R}^{\bullet +}$ and Its Analogues

compd	*T*, K	N (1 N)	$H_{5x,8x}$ (2 H)	$H_{6x,7x}$ (2 H)	$H_{5n,8n}$ (2 H)	H_1 (1 H)	other	LW[a]
2-Me	210	19.90	4.30	1.65	1.03	0.90	19.90 (3 H)	0.5
6-Me	214	19.90	4.30	1.65	1.03		19.90 (3 H)	1.0
10-Me	207	19.7	4.4	1.6			19.7 (3 H)	2.0
2-Et	187	19.94	4.40	1.70	0.99	0.74	15.43 (2 H)	0.5
2-*neo*-Pe[b]	207	18.65	4.48	1.67	*b*	−0.93	11.48 (2 H)	1.3
2-COMe	245	14.35	4.14	2.35	0.71	0.61	0.69 (3 H)[c]	0.3
6-COMe	228	14.14	3.95	2.56	0.35		0.72 (3 H)	0.25
2-CHO	218	13.43	4.11	2.63	0.72	0.56	0.56 (1 H)	0.37
6-CHO	205	13.36	3.80	2.90	unobsd		unobsd	1.3
2-CO-*t*-Bu	209	14.62	4.51	2.31	0.53	0.55	unobsd	0.3
2-CO_2Me	234	14.66	4.35	2.51	0.67	0.65	0.65 (3 H)[d]	0.5
2-CO_2-*t*-Bu	212	14.88	4.35	2.55	0.68	0.65	unobsd	0.43
($\mathbf{2}$-CO)$_2$	186	13.25	4.00	2.75				1.8
2-COCl	205	13.75	4.07	2.75				2.5
2-$COCF_3$	195	12.8	4.1	3.1				1.7
2-$CONMe_2$	208	~17.0						

[a] Line width (G) used in simulating the spectrum with the splittings listed. [b] These splittings are from the ENDOR experiment at 220 K. A splitting of 0.29 G, presumably caused by $a(H_{6n,7n})$, was also observed, but the $H_{5x,8x}$ splitting was not resolved from that of H_1; see experimental section for details. [c] **2**-$COCD_3$ was successfully fit with a(3 D) = 0.1, LW = 0.45 G, and the other parameters listed. [d] **2**-CO_2CD_3 was successfully fit with a 1 H splitting of 0.67 G and a line width of 0.5 G.

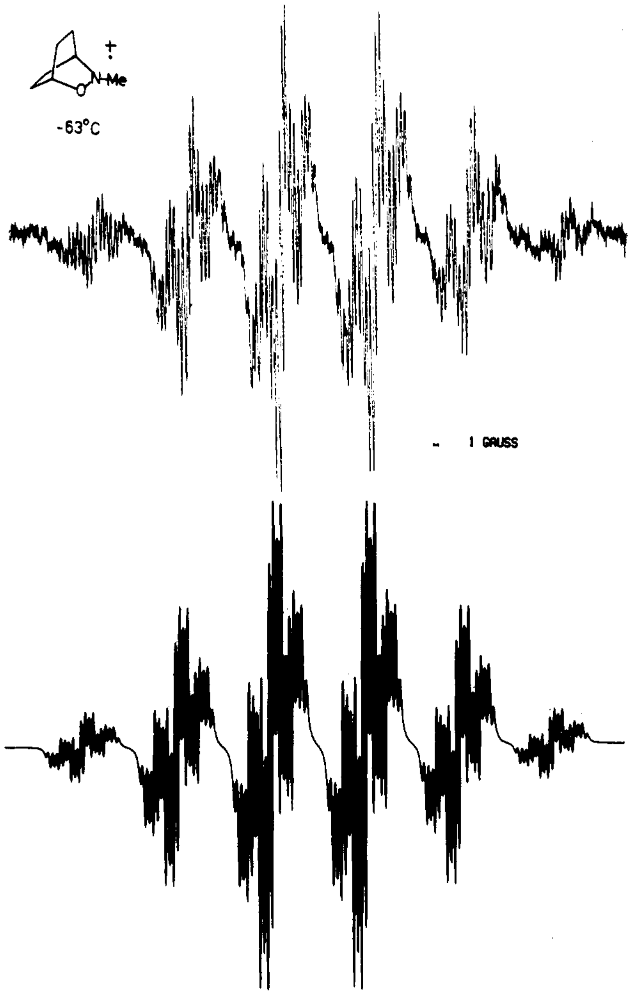


Figure 2. ESR spectrum of $\mathbf{2}\text{-Me}^{\bullet +}$ compared with a simulation using the splittings of Table III.

splitting constants. We were unfortunately unable to obtain a well-resolved spectrum of $\mathbf{2}\text{-CN}^{\bullet +}$. The splittings used in simulations of the observed spectra are shown in Table III, and the assignments given to the splittings observed will be discussed first. All spectra which showed significant resolution also showed two 2 H splittings, in the range 4–4.5 and 1.6–3.1 G. The ring methylene hydrogens which are exo to the heteroatoms and in W plan with the spin-bearing p-rich orbitals at these heteroatoms, are known to show much larger splittings than the ones endo, and

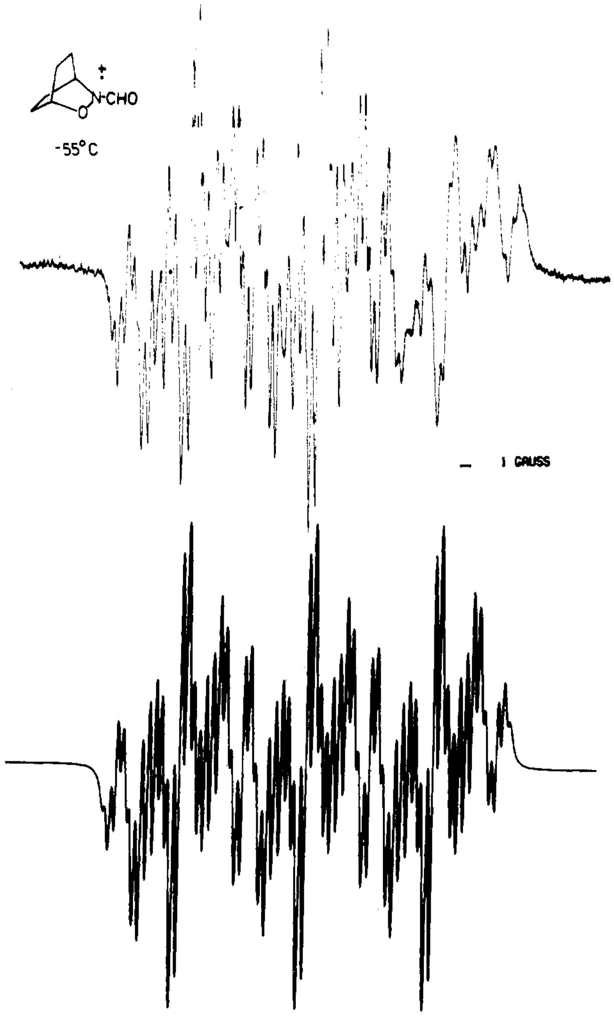


Figure 3. ESR spectrum of $\mathbf{2}\text{-CHO}^{\bullet +}$ compared with a simulation using the splittings of Table III.

Table IV. ESR Splitting Constants (G) for Some Symmetrical 2,3-Diheteroatom-Substituted Bicyclo[2.2.2]octane Derivatives

compd	hetero	a(2 N)	a(4 H_x)	a(4 H_n)	others
$14^{\bullet +}$	NMe	13.75	2.53	0.58	12.60 (6 H)
$16^{\bullet +}$	$NCHR_2$	15.24	2.87	0.55	unobsd (<0.2)
$17^{\bullet +}$	$NCOCH_2$	9.6	2.9	unres	unres
$18^{\bullet +}$	O		4.70	0.27	1.20 (2 H)

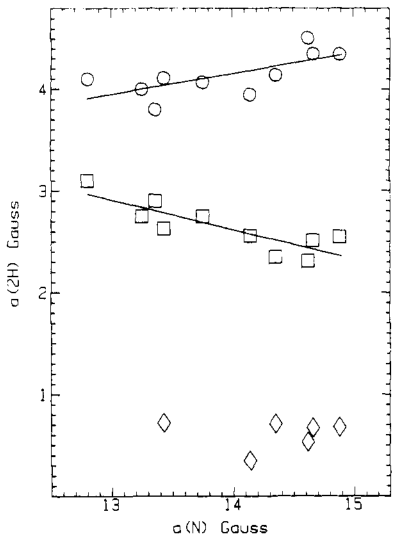
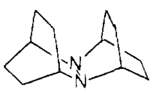


Figure 4. Plot of a(2 H) vs a(N) for **2**-COR$'^{\bullet+}$. The larger splittings (circles) are assigned to $a(H_{5x,8x})$, and the intermediate ones (squares) to $a(H_{6x,7x})$ from their a(N) dependence.

the ESR spectra of some symmetrical models for **2**-R$^{\bullet+}$, including the cations from **16**,[26] **17**,[9a] and **18**[7] are summarized in Table IV.



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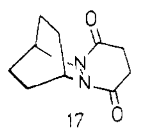

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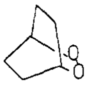

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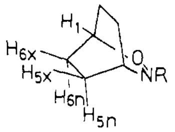


We have assigned the larger 2 H splittings by comparing them with the nitrogen splitting for the series of acylated compounds, as shown in Figure 4. The largest 2 H splitting (circles in Figure 4) increases when a(N) increases, while the intermediate one (squares) decreases. Because the spin distribution at the NO three-electron π bond should be polarized by the COR′ group, R′ groups which increase the spin density at nitrogen should decrease that at oxygen. We assign the largest splitting to that caused by the hydrogens in W plan with the nitrogen p orbital, $H_{5x,8x}$, and the intermediate one (squares) as that in W plan with the oxygen p orbital, $H_{6x,7x}$. The smaller splittings proved both ill-resolved and confusing. The methyl group was deuteriated in both **2**-COMe and **2**-CO$_2$Me to make sure that small bicyclic ring splittings of about the same size as the methyl splittings were present. **2**-*neo*-Pe$^{\bullet+}$ proves stable enough to allow its ENDOR spectrum to be obtained; see Experimental Section for details. A splitting of 0.93 G was observed by ENDOR, and the ESR spectrum indicates that both a 2 H and a 1 H splitting about this size are present. The 1-G 2H splitting must be an endo splitting, and we assign it as that γ to nitrogen, $H_{5n,8n}$, from its size relative to the exo splitting for **2**-Me$^{\bullet+}$ and **2**-Et$^{\bullet+}$ of 23–24%, compared with 23 and 19% for the alkylated hydrazines, **14**$^{\bullet+}$ and **16**$^{\bullet+}$, respectively. The acylated examples of **2**$^{\bullet+}$ show smaller resolved small 2 H splittings, 11–18% the size of $a(H_{5x,8x})$, but still larger than the 6% observed for peroxide **18**$^{\bullet+}$. The small size of the endo splitting of **18**$^{\bullet+}$ is consistent with our not being able to resolve a splitting for the hydrogens endo to oxygen in **2**-R$^{\bullet+}$ and its analogues; it is expected to be too small to resolve by ESR; we suspect that the 0.29-G splitting observed in the ENDOR spectrum of **2**-*neo*-Pe$^{\bullet+}$ corresponds to this splitting. We can confidently assign the observed bridgehead splitting as that next to oxygen, $a(H_1)$, because it is absent in the 1-methyl-substituted compounds **6**-Me$^{\bullet+}$ and **6**-COMe$^{\bullet+}$. It should also be noted that a higher bridgehead splitting was observed for the symmetrical peroxide cation radical **18**$^{\bullet+}$, but no bridgehead splitting was resolved for the hydrazine cation radicals. We presume that interaction with the spin density on the nonadjacent atom leads to cancellation, because for **16**$^{\bullet+}$ the nitrogens are known to be bent enough that a positive contribution to the bridgehead splitting of about 1 G should have resulted from interaction with the adjacent nitrogen.[26] The ENDOR spectrum of **2**-*neo*-Pe$^{\bullet+}$ showed a negative splitting near 1 G; it is not certain whether this is caused by the bridgehead H$_1$ or an endo 2 H splitting, but the bridgehead splitting seems most likely, as the other three 2 H splittings are positive.

The important information to be derived from the ESR spectra of these radicals is their spin distribution. These species are clearly related to protonated nitroxides, R$_2$NOH$^{\bullet+}$, which have received considerable work trying to quantitatively evaluate the π spin densities at N and O. Aurich and co-workers[27] interpreted their ^{14}N and ^{17}O splittings in terms of simple, one-term McConnell equations, with $a(\mathrm{N}) = 33.1\rho_\mathrm{N}$ and $a(\mathrm{O}) = 35.3\rho_\mathrm{O}$, but Cohen and Hoffman[28] employed a more complex treatment in which cross Q terms are used, as shown in eq 1 and 2. This leads to a different

$$a(\mathrm{N}) = Q_{\mathrm{NN}}{}^{\mathrm{N}}\rho_\mathrm{N} + Q_{\mathrm{OO}}{}^{\mathrm{N}}\rho_\mathrm{O} \qquad (1)$$

$$a(\mathrm{O}) = Q_{\mathrm{OO}}{}^{\mathrm{O}}\rho_\mathrm{O} + Q_{\mathrm{NN}}{}^{\mathrm{O}}\rho_\mathrm{N} \qquad (2)$$

form for the splittings than the simple McConnell equation, and they used eq 3 but also allowed for spin delocalization onto the

$$a(N) = 20.4\rho_\mathrm{N} + 3.8 \quad [\text{for } \rho_\mathrm{N} + \rho_\mathrm{O} = 1.00] \qquad (3)$$

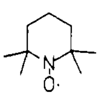
alkyl groups, employing eq 4 in place of a simple approximation of eq 3 that the spin densities at N and O would sum to one, where ρ_{ON} represents the cross terms, evaluated at −0.16, and ϵ represents

$$\rho_\mathrm{N} + \rho_\mathrm{O} + \rho_{\mathrm{ON}} = 1 - \epsilon \qquad (4)$$

the fraction of spin leaking off the NO group and was evaluated at 0.07. A best fit to their data gave $Q_{\mathrm{NN}}{}^{\mathrm{N}}$ = 23.9 G, $Q_{\mathrm{OO}}{}^{\mathrm{N}}$ = 3.6, $Q_{\mathrm{OO}}{}^{\mathrm{O}}$ = 31.7, and $Q_{\mathrm{NN}}{}^{\mathrm{O}}$ = 4.7; these constants give eq 5

$$a(\mathrm{N}) = 20.3\rho_\mathrm{N} + 3.92 \quad [\rho_\mathrm{N} + \rho_\mathrm{O} = 1.09] \qquad (5)$$

for a(N). Both Aurich and Hoffman point out that bending at the nitrogen of nitroxides increases s character at the N, and hence a(N), so that ρ_N does not quite have the pure p character implied by the form of eq 1–3. They incorporate an average of such effects into the experimentally derived Q values they use. The fact that the observed splitting is a time average over the energy surface makes consideration of a(N) somewhat complex, however. If the nitrogen is bent very much at equilibrium, increasing the temperature will lower a(N), which has been observed for several hydrazine cations which are known to be bent substantially.[26] The energy surface for nitroxides is very flat, and Griller[29] has pointed out that the very small temperature dependence of a(N) for di-*tert*-butyl nitroxide is solvent sensitive (−0.77 (11) mG/°C in cyclohexane, −0.65 (80) mG/°C in ethanol, −1.5 (15) mG/°C in acetone) and may be more influenced by solvent,nitroxide interactions than by the bending energy surface. Nevertheless, Bullock and Howard[30] have found that **19** and its 4-hydroxy-



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substituted analogue, which are known from X-ray work to be significantlly bent at N in the crystals, have negative temperature coefficients (−2.1 and −2.2 mG/°C in CCl$_4$), while five nitroxides which are flat at N by X-ray (4-keto-**19** and four five-membered-ring analogues) have positive temperature coefficients ranging from +1.1 to +2.2 mG/°C in several solvents. Mono-

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(26) (a) Nelsen, S. F.; Blackstock, S. C.; Frigo, T. B. *J. Am. Chem. Soc.* **1984**, *106*, 3356. (b) Nelsen, S. F.; Blackstock, S. C.; Haller, K. J. *Tetrahedron* **1986**, *42*, 6101.

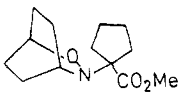
(27) (a) Aurich, H. G.; Hahn, K.; Stork, K.; Weiss, W. *Tetrahedron* **1977**, *33*, 969. (b) Aurich, H. G.; Czepluch, H.; Hahn, K. *Tetrahedron Lett.* **1977**, 4373. (c) Aurich, H. G.; Czepluch, H. *Tetrahedron Lett.* **1978**, 1313.

(28) Cohen, A. H.; Hoffman, B. M. *J. Phys. Chem.* **1974**, *78*, 1313.

(29) Griller, D. *J. Am. Chem. Soc.* **1978**, *100*, 5240.

(30) Bullock, A. T.; Howard, C. B. *J. Chem. Soc., Faraday Trans. 1* **1980**, *76*, 1296.

tert-butyl nitroxide has been shown to have a temperature coefficient for a(N) of +2.3 mG/°C in toluene, suggesting that it also is planar or nearly planar at nitrogen.[31] In this work we found that as expected from its low a(N) value, $\mathbf{14}^{\bullet+}$ is flat enough at nitrogen that it shows a positive temperature coefficient of +1.4 mG/°C (from measured nitrogen splittings (G) [T (K)] of 13.70 [1991, 13.70 [219], 13.75 [237], 13.78 [258]) and also that the temperature coefficient for **2**-COMe$^{\bullet+}$ is +3.7 mG/°C (14.15 [203], 14.20 [216], 14.25 [229], 14.30 [244]). The presence of a large proton splitting β to nitrogen and spectral complexity precluded accurate determination of the temperature dependence of a(N) for the methyl, ethyl, and neopentyl cases, but the tertiary N-alkyl analogue of **2**-R, $\mathbf{20}^{\bullet+}$, showed a positive temperature coefficient of +1.9 mG/°C (18.37 [188], 18.39 [209], 18.42 [230], 18.45 [249], 18.55 [254]; only the N splitting could be measured). These data indicate that both **2**-alkyl and **2**-acyl cation radicals are planar or nearly planar at equilibrium.



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Detailed consideration of the splittings observed (see Supplementary Material, which contains eq 6–9, used in estimating π spin densities, and tables of estimated spin densities for alkyl and acyl compounds) leads us to the conclusion that if $\rho_N + \rho_O = 1$,[32] $(\mathbf{2}\text{-R})^{\bullet+}$ has ρ_N of about 0.75 (3) and ρ_O of about 0.18. Cohen and Hoffman[28] estimated ρ_N at about 0.87 for $\mathbf{19}\text{-H}^{\bullet+}$, and replacement of its OH group by an O-alkyl group ought to polarize spin toward the oxygen atom. Similarly, we estimate ρ_N at 0.50 (2) for the $(\mathbf{2}\text{-COR}')^{\bullet+}$ examples and ρ_O at about 0.27 (2), with only a slight increase as R′ becomes more electron withdrawing. An increased ρ_O in the acylated cation radicals is reasonable because the carbonyl group stabilizes the nitrogen lone pair orbital, making its energy closer to that of the oxygen lone pair. It is also consistent with the slightly higher g factors observed for the acylated species. About 20–25% of the spin density is estimated not to appear at the NO π system of the acylated cation radicals, suggesting that it is delocalized onto the carbonyl group, which is consistent with the small R′ substituent splittings observed.

Oxidation Potentials and Relaxation Energies. The magnitude of the relaxation energy upon electron removal is critical for determining electron-transfer thermodynamics. Although it has been common to compare gas-phase ionization potentials with solution oxidation potentials and linear correlations are often seen, compounds containing amino nitrogen atoms are distinctly easier to oxidize in solution than their vertical ionization potentials would suggest.[33] Detailed studies of R_2NNR_2 oxidations have demonstrated that their relaxation energies are both unusually high and very dependent upon the NN rotational angle imposed by the substituents.[2]

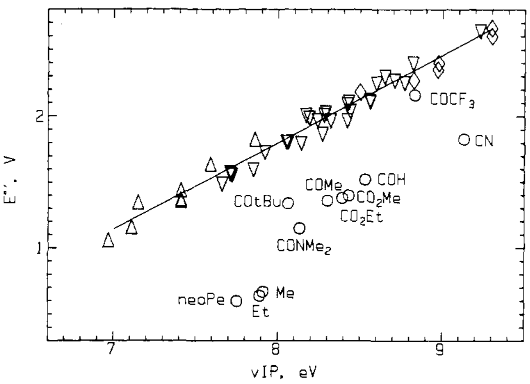


Figure 5. Plot of $E^{\circ\prime}$ vs vIP. The triangles correspond to fused-ring aromatic hydrocarbons, the inverted triangles to alkylated benzenes, and the diamonds to bicyclic peroxides;[7] the line shown is that of eq 10. The circles show **2**-R data from this work.

Table V. $\delta\Delta G_e$ Values (kcal/mol) for **2**-R and Some Model Compounds

model compd	$\delta\Delta G_e$	R in **2**-R	$\delta\Delta G_e$
Me_2NNMe_2	37.9	Me	24.7
14	31.7	Et	25.1
21	28.2	*neo*-Pe	24.0
22	9.1	$CONMe_2$	17.1
18	1.7	COMe	14.8
		CHO	14.5
		CO-*t*-Bu	11.5
		CO_2Me	15.7
		CO_2Et	15.7
		CN	16.6
		$COCF_3$	4.4

A semiquantitative measure of the relaxation energy may be obtained by comparing vIP with $E^{\circ\prime}$. vIP represents the enthalpy for vertical ionization, while $E^{\circ\prime}$ is determined by the adiabatic free energy of ionization and includes entropy effects. $E^{\circ\prime}$ values also include solvation energies which are absent in the vIP measurement. One could have anticipated that solvation energy changes between different compounds would be so large that they would dominate an $E^{\circ\prime}$,vIP plot, but there is a good deal of evidence that this is not the case. Although solvation energies are large for radical cations, they change surprisingly little as alkyl groups are enlarged in tetraalkylhydrazines.[34] As pointed out previously,[7] *even compound types as different as fused-ring aromatic* hydrocarbons, alkylated benzenes, and bicyclic peroxides exhibit a surprisingly linear $E^{\circ\prime}$ vs vIP plot, giving the linear regression line shown in eq 10. The r value for this line is 0.987,

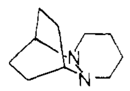
$$E(\text{reg}),\ \text{V} = 0.65_{85}\text{vIP} - 3.46_6 \qquad (10)$$

and the average vertical deviation corresponds to 1.24 kcal/mol. The data used are in three different solvents, acetonitrile for the fused aromatics, TFA/TFAA for the alkylated benzenes, and CH_2Cl_2/TFA/TFAA for the peroxides, which doubtless conceals some solvation energy changes, but these are not thought to be very large; tetraalkylhydrazines have a 1.2 kcal/mol higher $E^{\circ\prime}$ in CH_2Cl_2 than in acetonitrile. The slope of the line is substantially less than one, possibly indicating a general trend for more effective solvent stabilization for the thermodynamically less stable, higher vIP cation radicals.

We shall examine deviations from the regression line of eq 10 for the compounds studied by using $\delta\Delta G_e$ values (eq 11), as we

$$\delta\Delta G_e,\ \text{kcal/mol} = 23.06[E(\text{reg}) - E^{\circ\prime}(\text{obsd})] \qquad (11)$$

have done elsewhere[9b] for acylated hydrazines. The data for **2**-R compounds are shown graphically in Figure 5 and tabulated along with those for some analogous compounds in Table V. $\delta\Delta G_e$ is substantially larger for tetramethylhydrazine, which has perpendicular lone pairs, than it is for **14**, the hydrazine model for **2**-R. Even **21**, for which the nitrogens are flattened by the presence of the hexahydropyridazine ring[35] (flattening at N lowers relaxation energy, which is reasonable because it decreases the geometry change upon electron removal), has a larger $\delta\Delta G_e$ than any of the **2**-R derivatives. Despite the effects mentioned above, work



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[31] Henriquez, R.; Perkins, M. J.; Griller, D. *Can. J. Chem.* **1984**, *62*, 139.

[32] We do not doubt that spin density is removed from the NO system by the alkyl groups, but as Cohen and Hoffman indicate, the ρ_{NO} cross term has the opposite sign, and we expect that with alkyl instead of H at oxygen $\rho_N + \rho_O$ will be closer to 1.00 than it is for protonated nitroxides.

[33] Nelsen, S. F. *Isr. J. Chem.* **1979**, *18*, 45.

[34] Nelsen, S. F.; Rumack, D. T.; Meot-Ner (Mautner), M., manuscript in preparation.

[35] Nelsen, S. F.; Hollinsed, W. C.; Grezzo, L. A.; Parmelee, W. P. *J. Am. Chem. Soc.* **1979**, *101*, 7347.

on tetraalkylhydrazines indicates that $\delta\Delta G_e$ is not a bad measure of the relaxation energy. Using high-pressure mass spectrometry, equilibration of neutral and cation radicals for pairs of tetraalkylhydrazines in the gas phase at various temperatures allowed determination of adiabatic ionization potentials, and by subtracting aIP from vIP, experimental measurement of enthalpies of relaxation, ΔH_r, for 31 tetraalkylhydrazines.[34] The ΔH_r values are smaller than the $\delta\Delta G_e$ values, but the average difference of 6.2 kcal/mol does not depend significantly upon vIP (total range for the tetraalkylhydrazines studied, 7.02–8.32 eV), and the average deviation from 6.2 kcal/mol for the difference was 2.0 kcal/mol. For tetramethylhydrazine, ΔH_r is 32.1, 5.8 kcal/mol smaller than $\delta\Delta G_e$, and for **14**, ΔH_r is 23.3, 8.4 kcal/mol lower than $\delta\Delta G_e$. Despite differing solvent stabilizations and entropy effects, changes in $\delta\Delta G_e$ appear to reflect changes in ΔH_r rather well.

The three **2**-alkyl examples show $\delta\Delta G_e$ 7.0 (7) kcal/mol lower than that of model hydrazine **14**, indicating that trialkylhydroxylamines have somewhat lower relaxation energies than do tetraalkylhydrazines. This result also indicates that the flattening which occurs at both nitrogens of hydrazines upon electron removal is not the only source of their high relaxation energy, because only one nitrogen is present in **2**-R, yet their $\Delta\Delta G_e$ values are about 78% as large as that of **14**. We note that the $\delta\Delta G_e$ value for **2**-R does not lie close to halfway between those of hydrazine **14** and peroxide **18**, but much closer to that of **14**. Because ΔH_r is 23.3 kcal/mol for **14**, we estimate that for **2**-Me at 16–18 kcal/mol. We are unable to accurately estimate the difference in resonance stabilization between $R_2NNR_2^{\bullet +}$ and $R_2NOR^{\bullet +}$ reasonably from these numbers because of the flattening at nitrogen which occurs. This both causes different amounts of twisting in the vertical cations ($\delta\Delta G_e$ is certainly sensitive to this), and the flattening at one nitrogen of **2**-Me costs more energy than flattening at one nitrogen of **14**, but the question is complex because both nitrogens flatten in **14** upon electron removal.

The $\delta\Delta G_e$ values for **2**-acyl compounds are substantial, despite the fact that the nitrogen has been shown to be planar for **2**-CHO. For these compounds, the rehybridization of the lone pair at nitrogen which accompanies electron loss for **2**-alkyl is not present, yet $\delta\Delta G_e$ is over half as large as it is for **2**-alkyl. The major exception to this is for **2**-$COCF_3$, where the very electron-withdrawing trifluoroacetyl group is present, and the $\delta\Delta G_e$ quoted is only 4.4 kcal/mol, but it should be noted that this compound required a different solvent for measurement of $E^{\circ\prime}$, so the number may well not be directly comparable with the others. **2**-CN shows the highest vIP in the series but has a $\delta\Delta G_e$ comparable to the acylated compounds.

Calculations of ΔH_r by AM1[19] reproduce the observed trend in $\delta\Delta G_e$ for the series **18**, **2**-CHO, **2**-Me, **14**, in which the 2,3-positions of 2,3-disubstituted bicyclo[2.2.2]octane are occupied by OO, ONCHO, ONMe, and NMeNMe, surprisingly well. ΔH_r values of 5.7, 12.0, 15.3, and 19.7 kcal/mol, respectively, were obtained. This is the same order as observed for $\delta\Delta G_e$, and a plot of $\delta\Delta G_e$ vs calculated ΔH_r is nearly linear.[36] This encourages us to try to use AM1 calculations to understand the bonding in $R_2NOR'^{\bullet +}$. As discussed in more detail elsewhere,[9b] calculations support the contention that removal of an electron from an acylated nitrogen substantially destroys the amide resonance of the neutral compound. Formamide cation radical is calculated by AM1-UHF to have an H_2N–CHO rotational barrier of only 0.6 kcal/mol.[9b] Replacing the amide hydrogen by HO and H_2N, so the principal spin-bearing system changes from a nitrogen p orbital to an ON and NN "three-electron π bonds" increases the calculated rotational barrier somewhat, to 2.9 and 2.8 kcal/mol, respectively. Figure 6 shows AM1-UHF calculations for rotation about the ON–CHO and HO–NCHO bonds of $HONHCOH^{\bullet +}$, demonstrating the point that an essentially intact three-electron π bond is calculated to be present (rotational barrier 12.8 kcal/mol) and that there is little N–CHO resonance calculated to be present. These results are consistent with the ESR splitting constants and spin densities estimated from them. Electron removal from **2**-COR′ largely eliminates N,C=O conjugation, and **2**-$COR'^{\bullet +}$, like **2**-alkyl$^{\bullet +}$, is best described as having the odd electron in the π^*(NO) orbital. Despite the nitrogen remaining planar in both oxidation states, this large change in bonding leads to substantial relaxation energies upon electron loss.

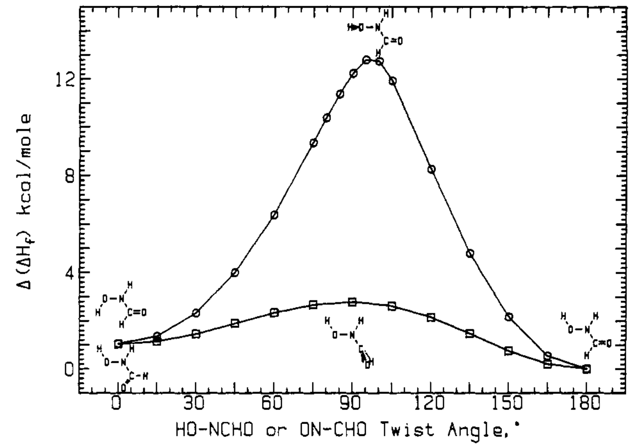

Figure 6. AM1-UHF calculated rotational barriers for $HONHCHO^{\bullet +}$ bond rotations: circles show HO–NCHO rotation, and squares HON–CHO rotation.

Conclusion

The bicyclooctyl system of **2**-R kinetically protects the bridgehead positions next to both O and N, causing their cation radicals to be unusually long-lived, and allowing CV study of the thermodynamics of electron transfer even when R is an acyl group. ESR studies suggest that about 75% of the spin is centered at the nitrogen p orbital for **2**-alkyl$^{\bullet +}$, and **2**-acyl$^{\bullet +}$ has about three-fourths of the spin in the NO three-electron π bond, with about two-thirds of this spin at N. Deviations of $E^{\circ\prime}$ from the regression line of an $E^{\circ\prime}$,vIP plot of hydrocarbons and bicyclic peroxides, $\delta\Delta G_e$, were used to estimate relaxation energies. **2**-Me has 78% as large a $\delta\Delta G_e$ value as does hydrazine **14**, leading to an estimate for its enthalpy of relaxation at about 16–18 kcal/mol, which is considerably closer to that for the hydrazine **14** than to the peroxide **18**. $\delta\Delta G_e$ for **2**-CHO is also substantial, 59% as large as for **2**-Me. Electron loss from **2**-COR is argued to mostly eliminate N,C=O resonance.

Experimental Section

Acylations were accomplished with an acid chloride (method A) or an anhydride (method B). **Method A.** A mixture of 1 mmol of **3**-H·HCl (0.147 g) and 1.1 mmol of triethylamine in 3 mL of methylene chloride was deaerated with N_2 for 1 h, and 1.1 mmol of an acid chloride was added dropwise. After stirring 12 h, the mixture was washed with 4 mL of brine, and the aqueous phase was extracted with two 5-mL portions of ether. The combined organic layers were dried with magnesium sulfate and concentrated. **Method B.** A suspension of 10 mmol of **3**-H·HCl (1.47 g) in 20 mL of chloroform was treated with 10 mmol of sodium bicarbonate (0.85 g) in 15 mL of water, followed by 2 g of NaCl and 10 mmol of an anhydride, added dropwise. After 2 h of reflux, the aqueous phase was separated and washed with three 10-mL portions of ether. The combined organic layers were washed with three 5-mL portions of saturated sodium bicarbonate, dried with magnesium sulfate, and concentrated. **Catalytic hydrogenation** employed a Parr shaker at room temperature with 10% Pd/C catalyst in ethyl acetate, unless otherwise noted.

2-Oxa-3-azabicyclo[2.2.2]oct-5-ene Hydrochloride (3-H·HCl). A mixture of 43.3 g (0.29 mmol) of 1-chloro-1-nitrosocyclohexane,[37] 300 mL of ether, and 100 mL of ethanol was cooled in an ice bath while 38 g (0.48 mol) of 1,3-cyclohexadiene in 50 mL of 3:1 ether–ethanol was added over a 2-h period. The dark blue solution was stored without

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[36] The slope of the plot is 2.2, and vertical deviations from a linear regression are only 0.0, −1.1, +1.9, and −0.8 kcal/mol, respectively. It is certainly an accident that the calculated ΔH_r values agree as well as they do with $\delta\Delta G_e$ for these compounds, but AM1 calculations of relaxation energies of amino nitrogen compounds do appear to be close enough in many cases to be useful in interpreting experimental data and making predictions.

[37] Barnes, M. W.; Patterson, J. M. *J. Org. Chem.* **1976**, *41*, 733.

stirring at 5 °C for 48 h, while the product crystallized out as white flakes. Filtration, washing with three 100-mL portions of ether, and vacuum-drying gave 42.6 g (98%) of **3**-H·HCl, mp 162 °C (lit. mp 164–168 °C,[38] 162–163 °C[39]).

2-Oxa-3-azabicyclo[2.2.2]octane hydrochloride (2-H·HCl) was obtained by catalytic hydrogenation in 95% EtOH, using 10% Pd/C catalyst **2**-H·HCl (1.53 g) gave 0.63 g (40% yield) after recrystallizing twice from EtOH–Et_2O: mp 190 °C (dec); ^{1}H NMR (DMSO-d_6) δ 4.28 (br s, 1 H), 3.67 (br s, 1 H), 3.36 (br OH, 1 H), 2.29–1.60 (m, 8 H); ^{13}C NMR (DMSO-d_6) δ 70.7 (CH), 46.5 (CH), 23.5 (CH_2), 19.6 (CH_2).

***N*-(Dimethylcarbamoyl)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CONMe$_2$)** was prepared by method A. After Kugelrohr distillation and recrystallization white crystals were afforded in 64% yield, mp 50–51.5 °C (Et_2O). The empirical formula $C_9H_{14}N_2O_2$ was established by high-resolution mass spectroscopy (hrms). ^{1}H NMR δ 6.66 (dd, 1 H), 6.46 (dd, 1 H), 4.53 (m, 2 H), 2.89 (s, 6 H), 2.21–1.98 (m, 2 H), 1.52–1.19 (m, 2 H); ^{13}C NMR δ 163.6 (Cq), 134.0 (CH), 130.2 (CH), 69.9 (CH), 49.2 (CH), 37.5 (CH_3), 24.1 (CH_2), 20.0 (CH_2).

***N*-(Dimethylcarbamoyl)-2-oxa-3-azabicyclo[2.2.2]octane (2-CONMe$_2$)** was prepared by catalytic hydrogenation of **3**-CONMe$_2$. Starting with 0.18 g of precursor, 0.16 g (89% yield) of pure oil was obtained after a bulb-to-bulb distillation. The empirical formula was established by hrms. ^{1}H NMR δ 4.0 (br s, 1 H), 3.86 (br s, 1 H), 2.89 (s, 6 H), 2.31–1.98 (m, 5 H), 1.78–1.50 (m, 3 H); ^{13}C NMR δ 163.3 (Cq), 71.1 (CH), 47.7 (CH), 38.0 (CH_3), 21.5 (CH_2), 23.3 (CH_2).

***N*-Acetyl-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-COMe)** was prepared by method B. Starting with 0.74 g of hydroxylamine afforded 0.69 g (90% yield) of a paste after Kugelrohr distillation. The empirical formula was established by hrms. ^{1}H NMR δ 6.69–6.42 (m, 2 H), 5.21 (br s, 1 H), 4.75 (br s, 1 H), 2.2–2.0 (m, 2 H), 1.96 (s, 3 H), 1.67–1.36 (m, 2 H); ^{13}C NMR δ (C=O unobserved), 133.3 (CH), 131.8 (CH), 72.2 (CH), 46.8 (CH), 23.9 (CH_2), 21.4 (CH_2), 21.1 (CH_3).

***N*-Acetyl-2-oxa-3-azabicyclo[2.2.2]octane (2-COMe)** was prepared by catalytic reduction of **3**-COMe. Starting with 0.77 g of precursor, 0.69 g (88% yield) of a clear oil was obtained after Kugelrohr distillation. The empirical formula was established by hrms. ^{1}H NMR δ 4.58 (br s, 1 H), 4.23 (br s, 1 H), 2.20–1.97 (m, 7 H), 1.90–1.60 (m, 4 H); ^{13}C NMR δ 167.1 (Cq), 71.7 (CH), 43.8 (CH), 23.6 (CH_2), 22.5 (CH_2), 18.1 (CH_3).

***N*-(Acetyl-d_3)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-COCD$_3$)** was prepared by method B. Starting with 0.3 g of **3**-H·HCl afforded 0.27 g of a clear oil, 86% yield. The empirical formula was established by hrms. ^{1}H NMR, same as that of **3**-COCH$_3$ except no methyl signal.

***N*-(Acetyl-d_3)-2-oxa-3-azabicyclo[2.2.2]octane (2-COCD$_3$)** was prepared by catalytic hydrogenation of 0.27 g of **3**-COCD$_3$. A clear oil (0.25 g) was obtained, which was purified by passing through neutral alumina (1:30 by weight) with 7:3 EtOAc–hexane. The empirical formula was established by hrms.

***N*-(Carboethoxy)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CO$_2$Et)** was prepared by the method of Riddell et al.,[39] starting with 37.7 g of very impure **3**-COCl and 26.5 g (0.24 mol) of ethyl chloroformate. Distillation afforded a crude product, bp 105 °C/2.55 mmHg (lit. bp 129–124 °C/2 mmHg). Purification was done by silica gel medium-pressure LC (10% EtOAc in hexane; flow rate 0.25 L/min; t_R 10.0 min), affording 5.53 g of pure product. ^{1}H NMR δ 6.45 (m, 2 H), 4.77 (m, 2.1 H), 4.81 (dt, 2.0 H), 2.26–2.04 (br m, 1.5 H), 1.82–1.29 (br m, 1.5 H), 1.25 (t, 3.2 H).

***N*-Pivaloyl-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CO-*t*-Bu)** was prepared by method A. Starting with 0.5 g of unsaturated bicyclohydroxylamine hydrochloride, 0.24 g (38% yield) of a clear oil was obtained after preparative LC (silica gel, 35% EtOAc in hexane, flow rate 0.20 L/min) and Kugelrohr distillation. The empirical formula was established by hrms. ^{1}H NMR δ 6.63 (t, 1 H), 6.50 (t, 1 H), 5.28 (br s, 1 H), 4.73 (br s, 1 H), 2.20–1.96 (m, 2 H), 1.43 (br d, 2 H), 1.16 (s, 9 H); ^{13}C NMR δ 177.0 (Cq), 132.9 (CH), 130.5 (CH), 71.2 (CH), 47.0 (CH), 26.2 (CH_3), 23.5 (CH_2), 20.5 (CH_2).

***N*-Pivaloyl-2-oxa-3-azabicyclo[2.2.2]octane (2-CO-*t*-Bu)** was prepared by catalytic hydrogenation of 0.24 g of **3**-CO-*t*-Bu; 0.20 g (83% yield) of product was obtained after Kugelrohr distillation, mp 76–77 °C (EtOAc/hexane). The empirical formula was established by hrms. ^{1}H NMR δ 4.52 (br s, 1 H), 4.20 (br s, 1 H), 2.07 (br d, 4 H), 1.66 (br d, 4 H), 1.21 (s, 9 H); ^{13}C NMR δ 175.2 (Cq), 72.5 (CH), 45.5 (CH), 39.0 (Cq), 26.9 (CH_3), 25.0 (CH_2), 23.8 (CH_2).

***N*-Neopentyl-2-oxa-3-azabicyclo[2.2.2]octane (2-*neo*-Pe)** was prepared by LAH reduction of **2**-CO-*t*-Bu in 80% yield after Kugelrohr distillation at reduced pressure. The empirical formula was established by hrms. ^{1}H NMR δ 3.82 (br s, 1 H), 2.69 (br s, 2 H), 2.17 (br m, 4 H), 1.63 (br m, 4 H), 0.95 (s, 9 H); ^{13}C NMR (acetone-d_6) δ 72.2 (CH_2), 69.8 (CH), 56.7 (CH), 33.9 (Cq), 30.3 (CH_3), 27.8 (CH_2), 24.7 (CH_2).

***N*-(Carbomethoxy)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CO$_2$Me)** was prepared by method A. Starting with 0.37 g of the hydrochloride salt, a pure oil was obtained after workup; 0.23 g (55% yield). The empirical formula was established by hrms. ^{1}H NMR ($CDCl_3$) δ 6.58 (dq, 2 H), 4.80 (m, 2 H), 3.77 (s, 3 H), 2.30–2.07 (m, 2 H), 1.68–1.33 (m, 2 H).

***N*-Methyl-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-Me)** was prepared by reduction of 3.00 g (16.4 mmol) of **3**-CO$_2$Me with 1.45 g (38.3 mmol) of LAH, affording 0.80 g (39%) as a clear liquid after bulb-to-bulb distillation, bp 70 °C/0.4 mmHg. ^{1}H NMR δ 6.72 (br t, 1.1 H), 6.32 (br t, 1.0 H), 4.40 (br m, 1.1 H), 3.88–3.40 (br m, 2.0 H), 3.28–2.92 (br m, 0.7 H), 2.44 (s, 3.0 H), 2.16–1.92 (br m, 2.2 H), 1.53–1.04 (br m); ^{13}C NMR δ 132.4, 128.9, 68.0, 55.9, 44.7, 23.4, 22.7.

***N*-(Carbomethoxy)-2-oxa-3-azabicyclo[2.2.2]octane (2-CO$_2$Me)** was prepared by catalytic hydrogenation of **3**-CO$_2$Me; 0.22 g (96% yield) of product was obtained as a clear oil (pure after workup). The empirical formula was established by hrms. ^{1}H NMR δ 4.20, 4.15 (two overlapping br s, 2 H), 3.80 (s, 3 H), 2.21–2.02 (m, 4 H), 1.85–1.50 (m, 4 H); ^{13}C NMR δ 156.5 (Cq), 71.4 (CH), 52.5 (CH_3), 47.9 (CH), 24.4 (CH_2), 23.5 (CH_2).

***N*-(Carbomethoxy-d_3)-2-oxa-3-azabicyclo[2.2.2]octane (2-CO$_2$CD$_3$)** was prepared by combining 50 mg of **2**-COCl, 1 mL of CD_3OD, and 10 mg of DMAP in a sealed vial for 10 h, concentrating, dissolving, in CH_2Cl_2, and washing with 1 mL of 1.5 M HCl. The organic layer was dried ($MgSO_4$), filtered, and concentrated. Kugelrohr distillation afforded 30 mg of an oil (60% yield). The empirical formula was established by hrms. ^{1}H NMR, same as that of **2**-CO$_2$Me except that the methyl signal was missing.

***N*-Methyl-2-oxa-3-azabicyclo[2.2.2]octane (2-Me)** was prepared as described by Riddell et al.;[16a] 0.414 g (22%) of product was obtained. ^{1}H NMR δ 3.84 (br s, 0.9 H), 2.79 (s, 3.6 H), 2.18 (br m, 4.2 H), 1.67 (br t, 4.3 H).

***N*-(Carboethoxy)-2-oxa-3-azabicyclo[2.2.2]octane (2-CO$_2$Et)** was prepared by the method of Riddell et al.,[39] starting with 3.5 g (19.1 mmol) of **3**-CO$_2$Et and 100 mg of 10% Pd–C, affording 2.20 g (62%) of pure product, bp 110 °C/0.6 mmHg (lit. bp 120–124 °C/2 mmHg. ^{1}H NMR δ 4.24 (q, 3.5 H), 2.44–2.04 (br d, 3.3 H), 2.04–1.48 (br d, 4.5 H), 1.32 (s, 3.2 H).

2(Carbo-*tert*-butoxy)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CO$_2$-*t*-Bu) was prepared by method B. Starting with 1.47 g of hydrochloride salt and 2.18 g of *t*-Boc anhydride affforded 1.96 g (93% yield) of white solid after Kugelrohr distillation, mp 37–42 °C. The empirical formula was established by hrms. ^{1}H NMR δ 6.55 (m, 2 H), 4.74 (br s, 2 H), 2.28–2.03 (m, 2 H), 1.64–1.10 (including s at δ 1.46 (15 H)); ^{13}C NMR δ 157.0 (Cq), 131.2 (CH), 80.9 (Cq), 70.3 (CH), 50.0 (Ceh), 28.1 (CH_3), 23.6 (CH_2), 20.5 (CH_2).

***N*-(Carbomethoxy)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CO$_2$Me)** was prepared by method A. Starting with 0.37 g of the hydrochloride salt, an oil was obtained after workup (0.23 g (55% yield)). The empirical formula was established by hrms. ^{1}H NMR ($CDCl_3$) δ 6.58 (dq, 2 H), 4.80 (m, 2 H), 3.77 (s, 3 H), 2.30–2.07 (m, 2 H), 1.68–1.33 (m, 2 H).

***N*-Formyl-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-CHO)** was prepared by method B. Starting with 1.47 g of hydrochloride salt and an excess of acetic formic anhydride afforded 0.27 g (49%) of product after preparative LC (bp 36–40 °C) (silica gel, 16% EtOAc in hexane, flow rate 0.11/min; t_R 9.2 min). The empirical formula was established by hrms. ^{1}H NMR δ 8.18 (br s), 7.81 (br s), 5.14, 4.90, 4.78, 4.49 (four br s), 2.45–2.00 (m), 1.78–1.43 (m); ^{13}C NMR δ 152.2 (Cq, br), 131.0 (two CH, unresolved), 71.1 (CH), 48.4 (CH, br), 22.7 (CH_2), 21.7 (CH_2, br).

***N*-Formyl-3-oxa-2-azabicyclo[2.2.2]octane (2-CHO)** was prepared by hydrogenation of 0.67 of **3**-CHO in 70% yield, mp 105–106.5 °C ($CHCl_3$/Et_2O/EtOAc). The empirical formula was established by hrms. ^{1}H NMR δ 8.28 (br s), 7.80 (br s), 4.43, 4.35, 4.19, 3.87 (four br s), 2.38–1.59 (m, mixture of conformations, broadened); ^{13}C NMR δ 151.6 (Cq), 72.3 (CH), 47.9 (CH), 25.0 (CH_2), 24.7 (CH_2) major; 129.7 (CH), 126.5 (CH), 68.0 (CH), 56.6 (CH), 45.9 (CH_3), 25.4 (CH_2), 24.7 (CH_2) minor.

Oxalyl-3,3′-bis(2-oxa-3-azabicyclo[2.2.2]octane) ((2-CO)$_2$) was prepared by combining 1.5 g of **2**-H·HCl and 15 mL of pyridine in a flame-dried 50-mL round-bottom flask and adding dropwise by means of a syringe 0.44 mL of oxalyl chloride. The solution was left stirring overnight. Acid workup gave 1.20 g of a crude yellow product, which was purified by Al_2O_3 chromatography (activity I, basic); mp 128–130 °C. The empirical formula was established by hrms. ^{1}H NMR δ 4.50, 4.42, 4.27, 3.98 (four br d, 4 H), 2.37–2.13 (br m, 8 H), 1.89–1.63 (br m, 8 H); ^{13}C NMR (more than one conformation detected) δ 161.4 (Cq), 73.4 (CH), 73.2 (CH), 72.9 (CH), 50.2 (CH), 49.8 (CH), 46.1 (CH),

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(38) Kesler, E. *J. Heterocycl. Chem.* **1980**, *17*, 1113.

(39) Riddell, F. G.; Turner, E. S.; Boyd, A. D. *Tetrahedron Lett.* **1976**, *35*, 259.

45.7 (CH), 25.1 (CH_2), 24.8 (CH_2), 24.7 (CH_2), 24.7 (CH_2), 23.6 (CH_2).

***N*-(Chlorocarbamoyl)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-COCl)** was prepared by method A. Starting with 0.44 g of **3**-G·HCl afforded the desired product as an oil (100% yield). The empirical formula was established by hrms. ^{1}H NMR δ 6.75–6.51 (m, 2 H), 5.25–5.01 (br hump, 1 H), 4.97–4.82 (br s, 2 H), 2.38–2.10 (br m, 2 H), 1.56–1.48 (br m, 2 H); ^{13}C NMR δ 131.6 (CH), 130.8 (CH), 72.4 (CH), 51.4 (CH), 22.6 (CH_2), 20.8 (CH_2).

***N*-(Chlorocarbamoyl)-2-oxa-3-azabicyclo[2.2.2]octane (2-COCl)** was prepared by hydrogenation of 0.58 g of **3**-COCl, giving 0.69 g of product as an oil after Kugelrohr distillation. The empirical formula was established by hrms. ^{1}H NMR (amide rotation frozen at probe temperature) δ 4.57 (br s, 1 H), 4.43 (br s, 2 H), 4.37 (br s, 1 H), 2.23 (br m, 4 H), 1.82 (br m, 4 H); ^{13}C NMR (amide rotation frozen at probe temperature) δ 141.1 (Cq), 142.6 (Cq), 73.6 (CH), 51.8 (CH), 49.7 (CH), 24.7 (CH_2), 23.7 (CH_2).

***N*-(Trifluoroacetyl)-2-oxa-3-azabicyclo[2.2.2]oct-5-ene (3-$COCF_3$)** was prepared by method A. Starting with 0.44 g of **3**-H·HCl gave 0.59 g of crude oil (95% crude yield), which was carried on without further purification. ^{1}H NMR δ 6.64 (m, 2 H), 5.28 (br s, 1 H), 4.90 (br s, 1 H), 2.40–2.04 (br m, 2 H), 1.56 (br t, 2 H).

***N*-(Trifluoroacetyl)-2-oxa-3-azabicyclo[2.2.2]octane (2-$COCF_3$)** was prepared by catalytic reduction of **3**-$COCF_3$. Kugelrohr distillation at reduced pressure afforded 0.40 g of oil (75% yield). The molecular formula was established by hrms. ^{1}H NMR, two sets of overlapping bridgehead peaks observed, assigned to two amide bond conformers: δ 4.54, 4.35 and 4.48, 4.30 in a 3.7:1 ratio (2 H total), 2.91 (br d, 4 H), 1.82 (m, 4 H); ^{13}C NMR δ 73.8 (CH), 46.7 (CH), 24.8 (CH_2), 23.2 (CH_2).

***N*-Cyano-2-oxa-3-azabicyclo[2.2.2]octane (2-CN)** was prepared by treating the free base with cyanogen bromide. The hydrochloride salt, **2**-H·HCl (0.23 g, 1.5 mmol) was dissolved in 5 mL of saturated $NaHCO_3$ and extracted with four 5-mL portions of Et_2O. The combined extracts were dried (Na_2SO_4) and filtered. The free amine solution was added to the cyanogen bromide in 3 mL of Et_2O dropwise at 0 °C. The solution became cloudy immediately and a white solid precipitated out. To the solution was added 5 mL of 10% NaOH. The layers were separated, extracting the aqueous layer with three 5-mL portions of Et_2O. The combined ether extracts were dried, filtered, and concentrated. A yield of 90 mg (43%) was obtained after Kugelrohr distillation, mp 35–36 °C. The empirical formula was established by hrms. ^{1}H NMR δ 4.13 (br s, 1 H), 3.51 (br s, 1 H), 2.41–2.00 (m, 4 H), 1.98–1.53 (m, 4 H); ^{13}C NMR δ 115.2 (Cq), 71.3 (CH), 53.6 (CH), 24.3 (CH_2), 22.8 (CH_2).

ESR. All the ESR spectra reported at one temperature were obtained by electrochemical oxidation in the cavity of the spectrometer, using as a cell a modification of the cell reported by Ohya-Nishiguchi[42a] and constructed by Kapp.[42b] Samples were passed through activated neutral alumina with 20% EtOAc in hexane as eluant. It was found that minute amounts of N–H hydroxylamines as impurities were easily oxidized to their corresponding nitroxides, ruining the ESR spectra. Solutions consisted of 0.5 (preferred) to 2.0 M substrate in CH_2Cl_2 0.1 M in *n*-Bu_4NClO_4 as supporting electrolyte. The solutions were deoxygenated by bubbling N_2 through a solution cooled to −78 °C for ca. 15 min. The cell was connected to a variable dc voltage power supply and the potential increased until a signal appeared on a spectrometer. Usually the current was around 20 μA but could be as high as 80 μA. The temperature in the probe was initially set at ca. −65 °C and later varied until the best combination of resolution and signal intensity was achieved. Temperatures were measured before and after the experiment. The *g* factor was measured by calibrating after each spectrum with strong pitch ($g = 2.0028$). *g* factors measured are as follows: **2**-Me$^{\bullet+}$, 2.0047; **2**-COMe$^{\bullet+}$, 2.0051; **6**-COMe$^{\bullet+}$, 2.0054; **6**-CHO$^{\bullet+}$, 2.0058; **2**-CO-*t*-Bu, 2.0053; **2**-CO_2-*t*-Bu$^{\bullet+}$, 2.0056; **2**-$CONMe_2$$^{\bullet+}$, 2.0050; **2**-COCl$^{\bullet+}$, 2.0056; **2**-$COCF_3$, 2.0055 (all at the temperatures listed in Table IV.

The variable-temperature studies were done on radical cations generated with tris(*p*-bromophenylaminium) hexachloroantimonate.[43] A 0.5–2 M solution of substrate was mixed with 1 equiv of oxidant at −78 °C and transferred by N_2 pressure though a cannula into a 3-mm-o.d. Pyrex tube that had been flushed with N_2 and cooled to −78 °C. The temperature was measured before and after each spectrum at each VT setting.

ENDOR. The ENDOR spectrum of **2**-*neo*-Pe$^{\bullet+}$ was determined in Berlin on equipment previously described;[44] generation of the cation using tris(*p*-bromophenylaminium) hexachloroantimonate in CH_2Cl_2 gave a better signal-to-noise ratio than electrolytic generation. The ESR signal was not saturated even with a microwave power level of 200 mW (ENDOR cavity), but ^{1}H and ^{14}N ENDOR experiments succeeded, although the line widths were rather large (350–400 kHz for ^{1}H), and the signal-to-noise ratio of proton couplings <5 MHz was poor. Switching the field setting between the high- and low-field portions of the ESR spectrum produced intensity changes of the ^{14}N ENDOR signals characteristic of cross-relaxation processes W_{x2} at 220 K, showing that the ^{14}N nucleus exhibits an appreciable hyperfine anisotropy, as expected from its high π spin population. These cross-relaxation effects also affect the ^{1}H ENDOR amplitudes, making it possible to deduce the relative splitting signs. Only one hydrogen splitting had a sign different from a(N), which certainly has a positive sign. We assign it to $a(H_1)$, which might be expected to have a negative splitting. The ca. 1 G $a(H_{5n,8n})$ splitting was not resolved from it in the ENDOR experiment, but the ESR was fit better, including this splitting. The rather unfavorable relaxation behavior of **2**-*neo*-Pe$^{\bullet\bullet}$ is not completely understood, but relaxation rates are obviously higher here than for nitroxides. At 220 K, $g = 2.00479$, and ENDOR coupling constants (error ±0.05 MHz) observed were 52.28 (N), 32.18, 12.55, 4.68, −2.60, 0.80 MHz; at 200 K, 52.1 (N), 31.84, 12.50, 4.70, −2.74, 0.89 MHz.

Electrochemistry. Unless noted otherwise, CV was run at ambient temperature at approximately 2×10^{-3} M in CH_3CN (Burdick and Jackson "Distilled in Glass") or CH_2Cl_2. Tetra-*n*-butyl perchlorate (TBAP) (0.1 M) was used as supporting electrolyte and was obtained from Eastman and recrystallized from 1:1 H_2O–EtOH. The apparatus used has been described previously.[45]

Cation radical decomposition rates were estimated from the chemically quasi-reversible CV waves as described by Nicholson and Shain.[14] The current ratio was calculated from the CV wave using Nicholson's method,[46] and the rate constants thus estimated are quoted in the text.

Photoelectron spectra were obtained on a Varian IEE-15 electron spectrometer controlled by a SuperMeGa microcomputer (CP/M operating system). The command interpreter/executer for the computer was PESOS11, written by Geoff Sobering (UW, Madison). Gaussian fitting was done with PEASYST[47] after transfer to an IBM PC. All spectra were calibrated internally with the argon 15.759-eV line. The ionization peaks were corrected for base-line drift and simulated with a Gaussian curve. The reported vIP are the maximum of the Gaussian curve.

Crystal Structure of 2-CHO. Intensity data were measured with a Philips PW 1100 four-circle computer-controlled diffractometer, using graphite-monochromated Mo Kα radiation ($\lambda = 0.71069$ Å). The crystal structure was solved by SHELX 76[48] and refined by SHELX 76 with anisotropic vibrational parameters for O, N, and C atoms and isotropic parameters for H atoms. The scattering factors for O, N, and C atoms are from Cromer and Mann[49] and those for H from Stewart et al.[50] The following crystal data were obtained: orthorhombic space group $P2_12_12_1$; $a = 13.299$ (7) Å, $b = 7.835$ (4) Å, $c = 6.709$ (4) Å, $Z = 4$, for 731 reflections, $R = 0.0436$, $R_w = 0.0832$.

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Supplementary Material Available: Stereoviews of **2**-CHO structure and crystal packing, atomic coordinates for **2**-CHO, atomic displacement factors for **2**-CHO, discussion of estimation of ρ_N and ρ_O from ESR splittings, and experimental procedures for the preparation of **6**-CO_2Me, **6**-CHO, **9**-CO_2Et, **2**-Et, **10**-CO_2Et, **10**-Me, and **20** (11 pages). Ordering information is given on any current masthead page.

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(40) Gregson, R. P.; Mirrington, R. N. *Aust. J. Chem.* **1976**, *35*, 2037.

(41) Fieser, L. F.; Fieser, M. *Reagents for Organic Synthesis*; Wiley: New York, 1967; Vol. I, p 4.

(42) (a) Ohya-Nishiguchi, H. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 2064. (b) Kapp, D. L. Ph.D. Thesis, University of Wisconsin, 1985.

(43) Schmidt, W.; Steckhan, E. *Chem. Ber.* **1980**, *13*, 577.

(44) Kirste, B.; Alder, R. W.; Sessions, R. B.; Bock, M.; Kurreck, H.; Nelsen, S. F. *J. Am. Chem. Soc.* **1985**, *107*, 2635.

(45) Nelsen, S. F.; Willi, M. R.; Mellor, J. M.; Smith, N. M. *J. Org. Chem.* **1986**, *51*, 2091.

(46) Nicholson, R. S. *Anal. Chem.* **1966**, *38*, 1406.

(47) Written by J. A. Thompson-Colon.

(48) Sheldrick, G. M. SHELX, program for crystal structure determination, University of Cambridge, 1976.

(49) Cromer, D. T.; Mann, J. B. *Acta Crystallogr., Sect. A: Cryst. Phys. Diffr., Theor. Gen. Crystallogr.* **1968**, *A24*, 321.

(50) Stewart, R. F.; Davidson, E. R.; Simpson, W. T. *J. Chem. Phys.* **1965**, *42*, 3175.