One-Electron Oxidation of Tetrasubstituted Hydrazides and Dihydrazides

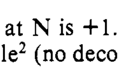
Stephen F. Nelsen,* Silas C. Blackstock, and Daniel T. Rumack

Contribution from the Samuel M. McElvain Laboratories of Organic Chemistry, Department of Chemistry, University of Wisconsin, Madison, Wisconsin 53706. *Received September 22, 1982*

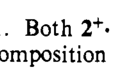
Abstract: Cyclic voltammetry curves showing no sign of radical-cation decomposition were observed for eight *N,N'*-diacyl-*N,N'*-dialkylhydrazines (**7–14**) which are Diels–Alder adducts of 1,3-cyclohexadiene and cyclic diacyldiimides or diethyl azodicarboxylate and their olefin-hydrogenated analogues. Protection of the alkyl groups from deprotonation is not required for long radical-cation lifetime under CV conditions, because 1,4-dioxo-9,10-diazadecalin (**15**) and *N,N'*-dimethylphthalhydrazide (**16**) also show no cation decomposition on the CV timescale. $E°'$ values for these compounds fall between 1.26 and 1.48 V vs. SCE. In contrast, 1,2-dicarboethoxytetrahydro- and -hexahydropyridazine (**17** and **18**), biscarbamates with unprotected alkyl groups, show totally irreversible oxidations with peak potentials above 2.3 V. Formyltrimethylhydrazine (**19**) has $E°'$ = 1.14 V, and its radical cation decomposes by deprotonation on the CV timescale, as indicated by observing shorter radical-cation lifetime at a higher concentration of **19**, and in the presence of base. Dimethylaminophthalimide (**20**) has $E°'$ = ca. 1.44 V, and fast scan rates must be used to see any radical-cation reduction wave. The alkyl protected *N,N*-diacylhydrazine **21** gives a radical cation which is stable on the CV timescale and has $E°'$ = 1.17 V. The ESR spectrum of 2,7-diaza-3,6-dioxatricyclo[6.2.2.0^{2,7}]dodecane ($\mathbf{13}^{+\cdot}$) has $a(2N)$ = 9.6 G, $a(4H)$ = 2.9 G, and g = 2.0044.

The thermodynamics for electron loss from amino nitrogen compounds R_2NX can be easily studied only when the radical cation $(R_2NX)^{+\cdot}$ persists for tens of milliseconds in the presence of about millimolar neutral R_2NX. In addition to the R_2NX oxidative wave, the $(R_2NX)^{+\cdot}$ reduction wave can then be observed by cyclic voltammetry (CV). The formal potential for oxidation, $E°'$, lies between the oxidation and reduction peak potentials. When the heterogeneous electron-transfer rate is fast enough so that the peak potential separation lies reasonably near the 57 mV for a completely electrochemically reversible one-electron redox curve, $E°'$ may be measured accurately by CV. Differences in $E°'$ for compounds studied under exactly the same conditions give differences in the free energy for electron transfer: $\Delta(\Delta G_e°)$ (kcal/mol) = 23.06 × $\Delta E°'$ (V), allowing $\Delta(\Delta G_e°)$ to be easily measured to a resolution of about 0.2 kcal/mol.

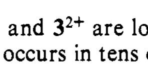
When X is the strong resonance electron-releasing group NR_2, radical-cation lifetime is long for most alkyl groups R, and $\Delta(\Delta G_e°)$ has been measured for many tetraalkylhydrazines.[1] Cation lifetimes become shorter, however, when X is not as cation-stabilizing as NR_2. The rate-limiting decomposition reaction for oxidized R_2NX is often deprotonation at carbon attached to nitrogen. A crude energy diagram showing this reaction is given in Figure 1. The base accepting the proton, B, is usually neutral R_2NX under CV conditions. The activation energy for proton transfer, $\Delta G^{\ddagger}{}_{-H^+}$ in Figure 1, depends on the energy difference between B + $(R_2NX)^{+\cdot}$ and I, the transition state for proton transfer. The energy of I should depend on the basicity of B and the amount of hyperconjugative bond weakening of the CH bond, which depends upon both the electron density in the π orbital at N (π_N) and the overlap of the CH bond with π_N. The importance of hyperconjugative CH bond weakening is demonstrated by the fact that, when special alkyl groups which hold the HC bond–π_N axis dihedral angle near 90° are employed, great increases in $(R_2NX)^{+\cdot}$ lifetime are observed. We shall call such alkyl groups "protected". When R_2N is the 9-azabicyclo[3.3.1]nonyl group **1**, rapid decomposition does not occur even when the formal charge density at N is +1. Both $\mathbf{2}^{+\cdot}$ and $\mathbf{3}^{2+}$ are long-lived on the CV timescale[2] (no decomposition occurs in tens of seconds). Modes of decomposition other than deprotonation take over when α-deprotonation is inhibited. For example, **1** produces cations with much longer lifetimes than tertiary and secondary R_2N groups which have α-deprotonation similarly inhibited.[3] When X is chosen such that electron removal is thermodynamically very difficult, short lifetimes result even for **1**(X) compounds. When X is the powerful σ-withdrawer NR_3^+ (compound **4**) so that the oxidized form is a dication radical, electron removal is thermodynamically 2 V (46 kcal/mol) more difficult than for **3**. Oxidized **4** decomposes so rapidly that the $E°'$ measurement can barely be made.[2] When carbonyl groups were attached to N of **1**, as in amide **5** and carbamate **6**, no reduction wave could be observed at any scan rate, so $E°'$ measurements could not be made. $E_p{}^{ox}$ for **5** is +2.06 V (at a 200 mV/s scan rate),[2] and that for **6** is also above 2 V. Thus even **1** fails to provide enough protection to allow thermodynamic measurements on electron loss from amide nitrogen.



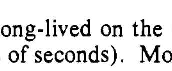
1(X)



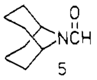
$2^{+\cdot}$



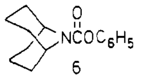
3^{2+}



4



5



6

Results

In this work we examined the electrochemistry of protected *N,N'*-diacylhydrazines. Because a basic nitrogen is not present, we expected to be able to measure $E°'$ despite the high value expected. We quickly found that many protected *N,N'*-diacylcyclohydrazines show reversible cyclic voltammograms, as summarized in Table I, entries **7–14**. These oxidations were done at platinum electrodes rather than the gold electrodes we employed in our tetraalkylhydrazine work because the gold/acetonitrile electrochemistry interferes with the potential region of interest here. Tetraalkylhydrazines have significantly slower electron-transfer rate constants at platinum than at gold. The heterogeneous electron-transfer rate constants for 1,1-dibenzyl-2,2-dimethylhydrazine have been determined to be 1.9×10^{-2} cm/s at gold and 3.9×10^{-3} cm/s at platinum, with ΔE_{pp} values of 75 and 115 mV, respectively, at 100 mV/s scan rates.[4] The reproducibility of ΔE_{pp} values is also significantly poorer at platinum. It will be seen from Table I that most of the diacylhydrazines **7–14** have smaller ΔE_{pp} values than do most tetraalkylhydrazines, and therefore exhibit faster heterogeneous electron-transfer rates. In all cases, the reduction current is as large as the oxidation current, so no cation-radical decomposition was detected on the CV

---

(1) Nelsen, S. F. *Acc. Chem. Res.* **1981**, *14*, 131.

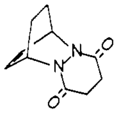
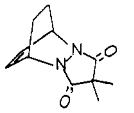
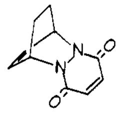
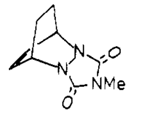
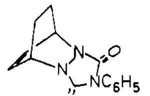
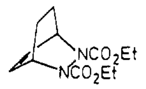
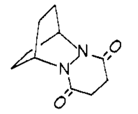
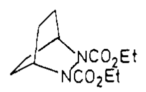
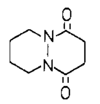
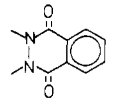
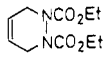
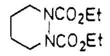
(2) Nelsen, S. F.; Kessel, C. R.; Brien, D. J. *J. Am. Chem. Soc.* **1980**, *102*, 702.

(3) Nelsen, S. F.; Gannett, P. M. *J. Am. Chem. Soc.* **1982**, *104*, 5292.

(4) Evans, D. H.; Kinlen, P. J.; Nelsen, S. F. *J. Electroanal. Chem.* **1979**, *97*, 265.

0002-7863/83/1505-3115$01.50/0

Table I. Electrochemical Data[a] for *N,N'*-Diacyl-*N,N'*-dialkylhydrazines

compound	compd no.	$E^{\circ\prime}$, V	ΔE_{pp}, V
	7	1.26	0.06_5
	8	1.30	0.09_9
	9	1.42	0.06_7
	10	1.43	0.07_8
	11	1.46	0.10_4
	12	ca. 1.48	0.14_4
	13	1.32	0.06_5
	14	1.48	0.08_7
	15	1.42	0.06_7
	16	1.44	0.06_3
	17	irrev[b]	
	18	irrev[b]	

[a] Conditions: 1-3 mM substrate in acetonitrile containing 0.1 *M* tetrabutylammonium perchlorate, at a platinum electrode, vs. SCE. [b] $E_p^{ox} = 2.3$ at 500 mV/s scan rate. [c] $E_p^{ox} > 2.3$ at a 500 mV/s scan rate.

timescale, even at 20 mV/s scan rates. An irreversible second oxidation wave is also observed above 2 V in each case.

Despite their thermodynamically difficult formation, these protected diacylhydrazine radical cations are very persistent. The ESR spectrum of a solution of $13^{+}\cdot$ prepared by $NOPF_6$ oxidation in methylene chloride lasts for more than 48 h. The ESR spectrum of $13^{+}\cdot$ consists of a large quintet ($a(2N) = 9.6$ G) of smaller quintets ($a(4H) = 2.9$ G), with unresolved smaller coupling to other protons clearly present. The *g* factor is 2.0044.

We were surprised to discover that alkyl group protection is not required for long radical-cation lifetime in these species. Neither **15** nor **16** showed any radical-cation decomposition on the CV timescale. Chloro amines, which have only slightly higher $E^{\circ\prime}$ values ($E^{\circ\prime}$ for **1**(Cl) is 1.49 V[2]), absolutely require alkyl group protection for observation of a radical-cation reduction wave at any scan rate, as do the second oxidation waves for tetraalkylhydrazines, all of which are lower in $E^{\circ\prime}$ than the first wave of any diacylated hydrazine studied. Cutting the formal nitrogen charge density by at least a factor of 2 could be principally responsible for this qualitative difference in electrochemical behavior.

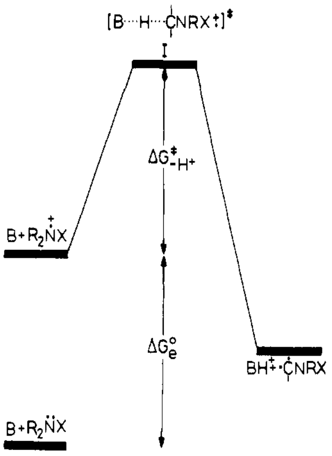
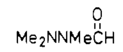
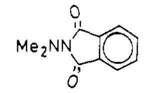
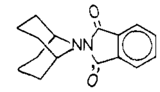


Figure 1. Qualitative free-energy diagram for α-deprotonation of $(R_2NX)^{+}\cdot$, illustrating the relationship of the free energy for electron loss (ΔG_e°) with the activation energy for proton loss, ($\Delta G^{\ddagger}_{-H^+}$).

Table II. Electrochemical Data[a] for Monoacyl-Trialkyl and *N,N*-Diacylhydrazines

compound	compd no.	$E^{\circ\prime}$, V	ΔE_{pp}, V
 $Me_2NNMeCH{=}O$	19	ca. 1.14	0.12
	20	ca. 1.44[b]	0.20[b]
	21	1.17	0.06_5

[a] Conditions as for Table I, except where noted. [b] At 20 V/s scan rate, where most of the cation still decomposes before the reduction scan is obtained.

In contrast to *N,N'*-diacylhydrazides, the unprotected biscarbamates **17** and **18** not only show totally irreversible oxidation waves, but their peak potentials are substantially higher than their reversible protected biscarbamate analogues **12** and **14**. These results suggest a large conformational effect on both oxidation potential and cation lifetime, but we are as yet unable to comment cogently on what factors are involved.

Encouraged by far higher kinetic stabilities for *N,N'*-bishydrazide radical cations than we have expected, we also examined a few mono- and *N,N*-diacylated compounds. These data appear in Table II. Formyltrimethylhydrazine **19** shows extensive radical-cation decomposition in a 200 mV/s CV run at 3.8 mM concentration, but i_{red}/i_{ox} is near 1 in a scan run at 0.67 mM concentration. This is consistent with the expected decomposition of $19^{+}\cdot$ through deprotonation by neutral **19**, as is the observed decrease in i_{red}/i_{ox} for **19** when **20** is added to the CV solution. We employed **20** as a base of comparable strength which is harder to oxidize, so that its oxidation wave does not interfere much with that of **19**. Electron transfer is noticably slower for **19** than for most of the diacylated compounds of Table I, as reflected in a large ΔE_{pp} value, which we could not get below 120 mV. Once again, conformational effects might be causing this, but we as yet lack data to consider this point properly.

Even with two acyl groups on one nitrogen and unprotected alkyl groups, dimethylaminophthalimide **20** shows a small cation reduction wave at fast scan rates. $E^{\circ\prime}$ is not measured very accurately because a 200 mV ΔE_{pp} was observed at the 20 V/s

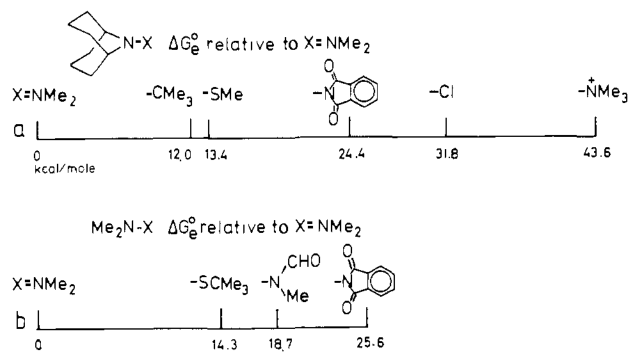


Figure 2. Comparison of ease of oxidation for R_2NX derivatives, in the form of $\Delta(\Delta G_e{}^\circ)$ in kcal/mol relative to R_2NNMe_2: (a) R_2N = 9-azabicyclo[3.3.1]nonyl, (b) R_2N = dimethylamino.

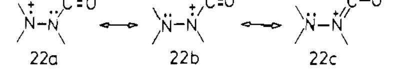
scan rate we had to use to see the reduction wave. The protected alkyl example **21** showed no cation decomposition at any scan rate, allowing an accurate $E^{\circ\prime}$ measurement for this compound.

Discussion

Thermodynamic Ease of Electron Removal. The effect of acylamino groups on the ease of electron removal from amino nitrogen compounds is compared with that for other substituents in Figure 2, where $\Delta(\Delta G_e{}^\circ)$ values relative to R_2NNMe_2 compounds are displayed. Two series are shown: R_2N = 9-azabicyclo[3.3.1]nonyl (**1**) in Figure 2a, and R_2N = dimethylamino in Figure 2b. Replacing NMe_2 by the diacylamino group phthalimido increases $\Delta G_e{}^\circ$ by about 25 kcal/mol in each series. The phthalimido group lies between thiomethyl and chloro in its $\Delta(\Delta G_e{}^\circ)$ value for **1**. *N,N′*-Diacylhydrazines are also quite hard to oxidize relative to hydrazines. For the two cases for which data are available for hydrazines with C=O replaced by CH_2,[5] **7** and **13**, $E^{\circ\prime}$ is 1.30 and 1.33 V ($\Delta(\Delta G_e{}^\circ)$ is 30.0 and 30.7 kcal/mol) higher for the diacyldialkylhydrazine than for the tetraalkylhydrazine. Compounds **7**–**12** show that the effect of changing the identity of the *N,N′*-diacyl groups is relatively small, the total range being 0.22 V in $E^{\circ\prime}$. Because *N,N′*-phthalimidodimethylhydrazine **16** and its *N,N*-phthalimido analogue **20** have the same $E^{\circ\prime}$, it is clear that there is little difference between substituting two acyl groups *N,N′* and *N,N* on the ease of electron loss from a hydrazine.

Most of the increase in $\Delta(\Delta G_e{}^\circ)$ upon CO substitution comes with the first acyl group substituted, since $\Delta(\Delta G_e{}^\circ)$ for **19** is 73% as large as that for **20**, comparing $E^{\circ\prime}$ for both with the 0.33 V observed for Me_2NNMe_2 under these conditions (see Figure 2b). The effect of replacing CH_3 by COR on the free energy for electron loss is very nonadditive, the first substitution raising $E^{\circ\prime}$ about three times as much as the second. Other substituent changes, such as successively replacing the hydrogens of CH_3 by methyl groups, make successively smaller changes on cation stability.[6] The "saturation effect" seen here is significantly larger than when saturated groups are attached to centers undergoing oxidation. This is presumably principally a result of the change in the size of the π system as the strongly conjugated acyl groups are added.

Spin Distribution. We had initially expected that substitution of COR at nitrogen of a hydrazine would tend to localize the π positive charge and spin on the unsubstituted nitrogen, i.e., that **22a** would be a much more important resonance structure than



22a 22b 22c

22b. In MO terms, the five-electron, four-center π system of **22** is isoelectronic with butadiene radical anion, which also would lead one to predict the spin to pile up at the outer atoms and **22a** and **22c** to be the best resonance structures. These considerations have little merit, as shown experimentally by the relatively long lifetimes for unsymmetrically acylated hydrazine radical cations under CV conditions.

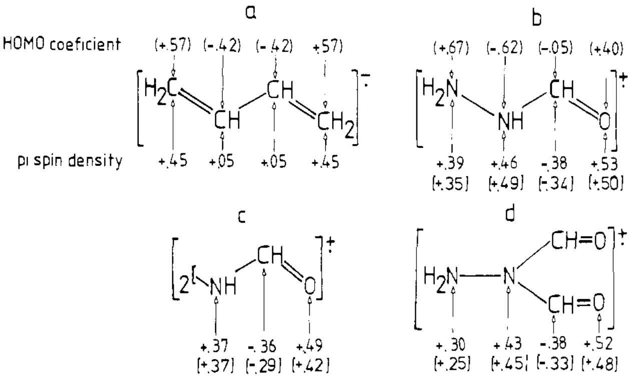


Figure 3. Calculated spin densities for the radical cations of idealized butadiene radical anion (a), formylhydrazine radical cation (b), *N,N′*-diformylhydrazine radical cation (c), and *N,N*-diformylhydrazine radical cation (d). INDO π spin densities are shown below each structure. The numbers in brackets are CNDO π spin densities for the same structures used in the INDO calculations.

Previous work on trialkylsulfenamides, R_2NSR', is pertinent to consider here.[7] ESR spectra demonstrate that there is little increase in spin at N over a hydrazine in the radical cation, because the nitrogen splittings for two sulfenamide cation radicals are only 8% larger than for the hydrazine analogue with SR′ replaced by NMeR′, suggesting that if the formal $\rho_N{}^\pi$ in a tetraalkylhydrazine radical cation is taken as 0.50, that of a trialkylsulfenamide is only about 0.54. Nevertheless, unprotected sulfenamide radical cations are short-lived under CV conditions, Me_2NS^tBu requiring a 50-V scan rate for observation of a significant radical-cation reduction wave. Sulfenamides are significantly harder to oxidize than hydrazines, $\Delta E^{\circ\prime}$ corresponding to 10–13 kcal/mol for sulfenamides and hydrazines of comparable substitution. This strongly confirms the reasonable supposition that, when $\Delta G_e{}^\circ$ is larger, the radical-cation energy lies closer to that of the transition state for deprotonation (I; see Figure 1), resulting in a smaller $\Delta G^\ddagger{}_{-H^+}$ and thus in a shorter lifetime. Both the monoacyl and diacyl dimethylamino compounds **19** and **20** have longer radical-cation lifetimes under CV conditions than does Me_2NS^tBu, despite much higher $E^{\circ\prime}$ values. These facts seem inconsistent with **22a** being the most important resonance structure for unsymmetrically acylated hydrazines and, instead, suggest a rather low $\rho_N{}^\pi$ at the dimethylamino nitrogen of $\mathbf{19}^{+\cdot}$ and $\mathbf{20}^{+\cdot}$.

To see if this result might have been predictable by simple MO theory, we have carried out CNDO and INDO calculations[8] on the parent cations formylhydrazine, *N,N*-diformylhydrazine, and *N,N′*-diformylhydrazine. Idealized structures were used, partially because the approximate nature of the calculations did not seem to justify complete minimization, but also because the energy optimization failed to work for these compounds.[8c] All three species were calculated in planar geometries (which we are convinced are the INDO minima) with 120° bond angles, and all NH distances were set at 1.068 Å (a calculation on H_2NNHCN, which could be energy minimized, gave all three NH bond lengths close to this figure). Calculations on formylhydrazine stepping each bond length in 0.01-Å increments gave minimum INDO energies

---

(5) Nelsen, S. F.; Hollinsed, W. C.; Grezzo, L. A.; Parmelee, W. P. *J. Am. Chem. Soc.* **1979**, *101*, 7347.

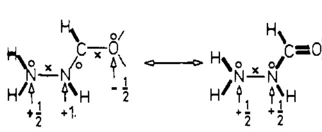
(6) For a recent application of the saturation effect, see: Nugent, W. A.; Kochi, J. K. *J. Am. Chem. Soc.* **1976**, *98*, 5979.

(7) Nelsen, S. F.; Steffek, D. J.; Cunkle, G. T.; Gannett, P. M. *J. Am. Chem. Soc.* **1982**, *104*, 6641.

(8) (a) Pople, V. A.; Beveridge, D. H. "Approximate Molecular Orbital Theory"; McGraw-Hill: New York, 1970. (b) We employed Professor F. Weinhold's program BONDO for these calculations. This program is described in detail in University of Wisconsin, Theoretical Chemistry Institute Technical Note 628G, Dec 1979. (c) Although the SCF portion of the program only takes a minute for a given $H_2NNHCHO$ structure, attempted energy minimization on only two bonds was incomplete in 2 h, presumably caused by slow convergence in the SCF calculation. BONDO employs Powell optimization (Powell, M.J.D. *Comput. J.* **1967**, *7*, 155).

with bond lengths HC = 1.12, CO = 1.28, NC = 1.38, and NN = 1.295 Å, and these parameters were used for all three molecules. A total spin density of exactly 1 was obtained in the heavy-atom π system in all three cases, and the spin density distribution did not seem tremendously sensitive to small bond-length changes during our partial minimization calculations. The INDO and HOMO coefficients and total π spin density thus obtained for formylhydrazines are compared with those for idealized butadiene radical anion at the top of Figure 3. Although the HOMO coefficients show nodes between the outer heavy atoms in both cases, the total spin density distribution is very different for these two four-atom, five-electron π systems. The highest spin density for all three formylated hydrazine radical cations is calculated to be at O, but a large negative spin density is calculated at C, and a carbonyl group effectively removes only 13–15% of the α spin density from the two nitrogen "three-electron π" system in the three formylated hydrazines shown in Figure 3. Interestingly, the difference in spin distribution for *N,N*- and *N,N′*-diformyl substitution is calculated to be very small, in that the sum of the nitrogen spin densities is 0.73 and 0.74, respectively. This certainly agrees with the experimental result that *N,N*- and *N,N′*-phthalimidodimethylhydrazine have the same $E^{\circ\prime}$. The CNDO spin densities calculated for the same structures are also shown in Figure 3. The spin distribution by CNDO resembles that by INDO calculations.

The formyl groups may well be releasing π electrons toward the partially positive nitrogen atom to which they are bonded. There has been considerable experimental activity and discussion about the π-donating ability of acyl,[9] cyano,[10] and other[11] electron-withdrawing groups toward positively charged centers in the last few years, and the situation here is quite analogous. We believe it worth emphasizing that the calculations place the largest nitrogen spin density at the formylated nitrogen, making the formal positive charge greatest here despite its bearing the electron-withdrawing formyl group. For formylhydrazine cation radical, the NH_2 nitrogen INDO spin density is calculated as 84% of that of the NHCHO nitrogen. Putting a second formyl group on the same nitrogen decreases the total spin density at the two nitrogens, but increases the polarization toward the substituted nitrogen, and the NH_2 nitrogen spin density is calculated to be 71% of the $N(CHO)_2$ spin density. We point out the analogy between this result and the substantial neutral free-radical center stabilization which occurs when electron-releasing and -donating groups are attached to a radical center. Balaban has called this the "push-pull" effect,[12] Katritzky calls it "merostabilization",[13] and Viehe refers to a "capto-dative" effect.[14] These calculations appear to agree with this powerful stabilizing effect also being present for radical cations. Linnett's double quartet theory[15] allows convenient representation of many radicals, and Linnett structures for formylhydrazine radical cation are presented below as **23a** and **23b**.



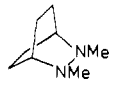
23a 23b

Both have the same number of bonding electrons, and **23b**, which treats the formyl substituent as not interacting with the three-electron hydrazine π bond, has a more uniform charge distribution, but requires close pairing of the electrons in the formyl group, and is presumably therefore a less important contributor. A Linnett structure which donates an electron from the formyl group to the dinitrogen group has one less bonding electron.

We also briefly examined the INDO calculated effect of twisting at the NC and NN bonds of formylhydrazine radical cation. Twisting about the CN bond increases the energy and spin density at the nitrogens. Twisting all the way to 90° costs 12 kcal/mol, and >99% of the spin density is at the two nitrogens. The nitrogen spin densities become nearly equal, but a little more appears at the formyl-substituted nitrogen (52%). Twisting at the NN bond is more costly in energy, a 70° NN twist destabilizing by 24.7 kcal/mol, comapred to 11.3 kcal/mol for a 70° NC twist. The SCF portion of the calculation goes into oscillation at twist angles of 80° and greater, so we did not calculate the 90° NN twisted structure.

The INDO calculations give the result that CHO groups directly substituted at nitrogen have a roughly additive effect on the spin distribution, removing about 13–15% of the spin from the three-electron π-bond dinitrogen system. The π spin density is calculated to be higher at the substituted position. This result is in qualitative agreement with the relatively long lifetime observed for the unprotected unsymmetrically acylated hydrazine cations, those from **19** and **20**.

The ESR of $\mathbf{13}^{+\cdot}$ allows estimation of the π spin density at N, but we point out that this information is difficult to interpret very quantitatively. The nitrogen splitting of $\mathbf{13}^{+\cdot}$ is 69% as large as that of $\mathbf{24}^{+\cdot}$,[16] but this does not necessarily mean that their $\rho_{\mathrm{N}}{}^{\pi}$ values are in this proportion. Even if spin polarization effects are ignored (and the high carbonyl carbon negative spin densities given by INDO suggests this is not wise), the fact that the observed a(N) is a time average over thermal bending motions at nitrogen clearly affects the value observed. The nitrogen ESR splitting of hydrazine radical cations increases noticably with methyl substitution [a(N) (G): $(H_2NNH_2)^{+\cdot}$, 11.5;[17] $(CH_3NHNHCH_3)^{+\cdot}$, 13.0;[18] $((CH_3)_2NN(CH_3)_2)^{+\cdot}$, 13.4[19]] despite the fact that $\rho_{\mathrm{N}}{}^{\pi}$ must decrease in this series because of hyperconjugative spin removal to the methyl groups. It seems reasonable that acylation would increase the difficulty of bending a hydrazine radical cation at N relative to alkyl substitution. If this is the case, the real $\rho_{\mathrm{N}}{}^{\pi}$ for $\mathbf{13}^{+\cdot}$ would be greater than the 0.69 observed ratio of a(N) for $\mathbf{13}^{+\cdot}/\mathbf{24}^{+\cdot}$ would indicate. The ESR spectrum of $\mathbf{24}^{+\cdot}$ shows a four-hydrogen splitting of 2.5 G, assigned to the anti methylene hydrogens of the bicyclic system. Despite a lower a(N) value, the four hydrogen splitting of $\mathbf{13}^{+\cdot}$ is observed to be 2.9 G, and we assign it to the analogous hydrogens. We expect a higher $a(H_\gamma)$ for a given $\rho_{\mathrm{N}}{}^{\pi}$ if the nitrogen were harder to bend, and suggest that observing a larger $a(4H_\gamma)$ for $\mathbf{13}^{+\cdot}$ than for $\mathbf{24}^{+\cdot}$ is most consistent with the former requiring more energy to bend at nitrogen than the latter.



24

Conclusions

Several *N,N′*-diacylhydrazines give radical cations which are long-lived on the CV timescale, and even dimethylamino mono- and *N,N*-diacylhydrazine radical cations are long-lived enough to enable measurement of $E^{\circ\prime}$ values by CV. The first substitution of COR for alkyl raises $E^{\circ\prime}$ about three times as much as does the second such substitution, so the effect of carbonyl substitution on the ease of electron removal from hydrazine "saturates" unusually rapidly. The relatively long radical-cation lifetime and

---

(9) (a) Creary, X.; Geiger, C. C. *J. Am. Chem. Soc.* **1982**, *104*, 4151. (b) Chau, H.S.-I.; Berchtold, G. A. *Ibid.* **1981**, *103*, 898.

(10) (a) Talley, J. J.; Gassman, P. G. *Tetrahedron Lett.* **1981**, *22*, 5253. (b) Gassman, P. G.; Saito, K. *Ibid.* **1981**, *22*, 1311. (c) Gassman, P. G.; Saito, K.; Talley, J. J. *J. Am. Chem. Soc.* **1980**, *102*, 7613, and earlier work cited here. (d) Olah, G. A.; Prackash, G. K. S.; Arranagh, M. *Ibid.* **1980**, *102*, 6640.

(11) (a) Paddon-Row, M. N.; Santiago, C.; Houk, K. N. *J. Am. Chem. Soc.* **1980**, *102*, 6562. (b) Reynolds, W. F.; Davis, P.; Taft, R. W.; Topsom, R. D. *Tetrahedron Lett.* **1981**, *22*, 1795.

(12) For a review, see Balaban, A. T. *Rev. Roum. Chim.* **1971**, *6*, 725.

(13) Beldock, R. W.; Hudson, P.; Katritzky, A. R.; Soli, F. *J. Chem. Soc., Perkin Trans. 1* **1974**, 1422.

(14) For a review, see Viehe, H. G.; Merênyi, R.; Stella, L.; Janousek, Z. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 917.

(15) Linnett, J. W. "The Electronic Structure of Molecules"; Menthuen: London, 1964.

(16) Nelsen, S. F.; Weisman, G. R.; Hintz, P. J.; Olp, D.; Fahey, M. R. *J. Am. Chem. Soc.* **1974**, *96*, 2917.

(17) Adams, J. Q.; Thomas, J. R. *J. Chem. Phys.* **1963**, *39*, 1904.

(18) Smith, P.; Stevens, R. D.; Kaba, R. A. *J. Phys. Chem.* **1971**, *75*, 2046.

(19) Nelsen, S. F. *J. Am. Chem. Soc.* **1966**, *88*, 5666.

INDO calculations suggest that spin density is higher on the acylated nitrogen than on the alkylated nitrogen of unsymmetrically acylated hydrazine radical cations.

These results greatly increase both the available potential range and structural diversity of amino nitrogen compounds which give long-lived radical cations. The only such compounds previously reported to have $E^{\circ\prime}$ above 1 V vs. SCE were protected chloro amines. The study of conformational effects on both $E^{\circ\prime}$ and cation-radical lifetime for acylated hydrazines should prove important in considering how conformation affects reactivity.

Experimental Section

The methods used to prepare **7**–**9** and **13**,[5] **10** and **11**,[20] **12**, **14**, **17**, and **18**,[21] **15**,[22a] **16** and **20**,[22b] and **19**[23] have been previously published.

9-Phthalimido-9-azabicyclo[3.3.1]nonane (21) was prepared by refluxing equimolar amounts of 9-amino-9-azabicyclo[3.3.1]nonane, **1**-(NH_2),[24] and phthalic anhydride in benzene with a water separator for 10 h, removal of solvent, and sublimation to give **21** as a colorless solid, mp 118 °C, in 88% yield: ^1H NMR (acetone-d_6) δ 1.4–2.4 (complex, 12 H), 3.1 (br s, 2 H), 7.5 and 7.9 (2 m, 4 H). The empirical formula was established by high resolution mass spectroscopy.

Cyclic voltammetry[25] and ESR[26] experiments were conducted as previously described. INDO and CNDO calculations were performed on a Harris/7 computer, using program BONDO.[8]

Acknowledgment. We thank the National Science Foundation for partial financial support of this work under Grant CHE 8026111. We thank Professor F. A. Weinhold of this department for patient instruction in the use of BONDO and helpful discussion.

Registry No. **1** (NH_2), 4390-44-7; **7**, 72282-78-1; **8**, 23292-39-9; **9**, 72282-77-0; **10**, 78790-57-5; **11**, 10316-53-7; **12**, 3310-58-5; **13**, 72282-81-6; **13**$^{+\cdot}$, 84960-96-3; **14**, 3310-59-6; **15**, 3661-10-7; **16**, 22527-64-6; **17**, 35691-30-6; **18**, 52944-50-0; **19**, 3645-44-1; **20**, 4770-30-3; **21**, 84960-95-2; phthalic anhydride, 85-44-9; formylhydrazine radical cation, 84960-97-4; *N,N*-diformylhydrazine radical cation, 84960-99-6.

---

(20) Snyder, J. P.; Bandurco, V. T.; Darack, F.; Olsen, H. *J. Am. Chem. Soc.* **1974**, *96*, 5159.

(21) Anderson, J. E.; Lehn, J. M. *J. Am. Chem. Soc.* **1967**, *89*, 81.

(22) (a) Nelsen, S. F.; Clennan, E. L. *J. Am. Chem. Soc.* **1978**, *100*, 4004. (b) Drew, H. D. K.; Hatt, H. H. *J. Chem. Soc.* **1937**, 16.

(23) Beltrami, R. T.; Bissel, E. R. *J. Am. Chem. Soc.* **1956**, *78*, 2467.

(24) Nelsen, S. F.; Hollinsed, W. C.; Kessel, C. R.; Calabrese, J. C. *J. Am. Chem. Soc.* **1978**, *100*, 7876.

(25) Nelsen, S. F.; Peacock, V. E.; Weisman, G. R. *J. Am. Chem. Soc.* **1976**, *98*, 5269.

(26) Nelsen, S. F.; Weisman, G. R.; Hintz, P. J.; Olp, D.; Fahey, M. R. *J. Am. Chem. Soc.* **1974**, *96*, 2916.

Comparison of Free Energy Changes for Nitrogen Inversion and Electron Loss for Some Amino Nitrogen Compounds

Stephen F. Nelsen,* Glen T. Cunkle, Peter M. Gannett, Joseph T. Ippoliti, and Richard J. Qualy

Contribution from the Samuel M. McElvain Laboratories of Organic Chemistry, Department of Chemistry, University of Wisconsin, Madison, Wisconsin 53706. *Received September 1, 1982*

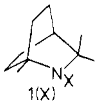
Abstract: 2-Chloro-1,3,3-trimethyl-2-azabicyclo[2.2.2]octane [**1**(Cl)] was found by ^{13}C NMR to have a $\Delta G^{\ddagger}_{N}$ (−95 °C) of 7.57 (3) kcal/mol and 9-chloro-9-azabicyclo[3.3.1]nonane [**4**(Cl)] a $\Delta G^{\ddagger}_{N}$ (+35 °C) of 14.24 (5) kcal/mol. The $E^{\circ\prime}$ for **1**(Cl) in acetonitrile is +1.25 V vs. SCE and its vertical first ionization potential 8.10 eV. $E^{\circ\prime}$ for 3,3-dimethyl-2-azabicyclo[2.2.2]octanyl-2-oxy [**2**(O·)] is +0.56 V. Comparison of $E^{\circ\prime}$ values for **1**(X), **2**(X), and 2-azabicyclo[2.2.2]octane derivatives **3**(X) and **4**(X) with X = O·, N=]$_2$, and Cl are made. Larger changes in $E^{\circ\prime}$ with bicyclic alkyl group changes are seen when $\Delta G^{\ddagger}_{N}$ for the neutral compound is larger, and the implications of this fact are discussed. The irreversible E_p^{ox} values for the corresponding methylamines reflect the same trends as the alkyl groups are changed.

Large changes in geometry at nitrogen frequently accompany electron loss from amino nitrogen compounds R_2NX. Nitrogen prefers to be pyramidal in the neutral form but planar in the radical cation. Strain energy differences resulting from these geometrical preferences must show up in the free energy of electron loss, ΔG°_{e}. Changes in ΔG°_{e} in a series of R_2NX compounds are usually measurable only if $(R_2NX)^{+\cdot}$ is long-lived under the conditions of a cyclic voltammetry (CV) experiment. Cation radical lifetimes of tens of milliseconds are required, and the factor limiting lifetime appears to usually be deprotonation of the radical cation by the neutral form. Tetraalkylhydrazines (X = NR_2) and tetraalkyltetrazines (X = (—N=N—NR_2)) give long-lived radical cations for most R groups, but when X is less cation stabilizing, the radical cations usually decompose rapidly on the CV time scale. "Bredt's rule kinetically protected" bicyclic dialkyl amino groups, in which the hydrogens on carbons attached to nitrogen are held close to the nodal plane of the half-filled nitrogen p orbital of the cation radical, turn out not to deprotonate on the CV time scale for many X groups.[1] This allows $\Delta(\Delta G^{\circ}_{e})$ measurements to be made for a wider variety of compounds than when R groups which have α-hydrogens which can be lost rapidly are present.

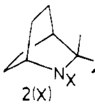
In this work changes in the free energy for electron loss, $\Delta(\Delta G^{\circ}_{e})$ values, for four bicyclic R_2N groups having three relatively small X groups are compared. Because flattening at nitrogen occurs in both electron loss and nitrogen inversion, it is suggested that comparing $\Delta(\Delta G^{\circ}_{e})$ with changes in the activation energy for nitrogen inversion, $\Delta(\Delta G^{\ddagger}_{N})$, for different R_2N groups is useful.

Results

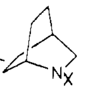
The compounds considered in this paper are derivatives of bicyclic amines **1**(H)–**4**(H). The derivatives considered are



1(X)



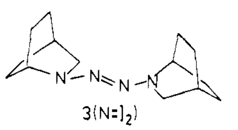
2(X)



3(X)

4(X)

chloramines (X = Cl), symmetric 2-tetrazenes (designated as X = N=]$_2$; see the example below), nitroxides (X = O·), and me-



3(N=]$_2$)

---

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