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O-Capped Heteroadamantyl-Substituted Hydrazines and Their Oxidation Products

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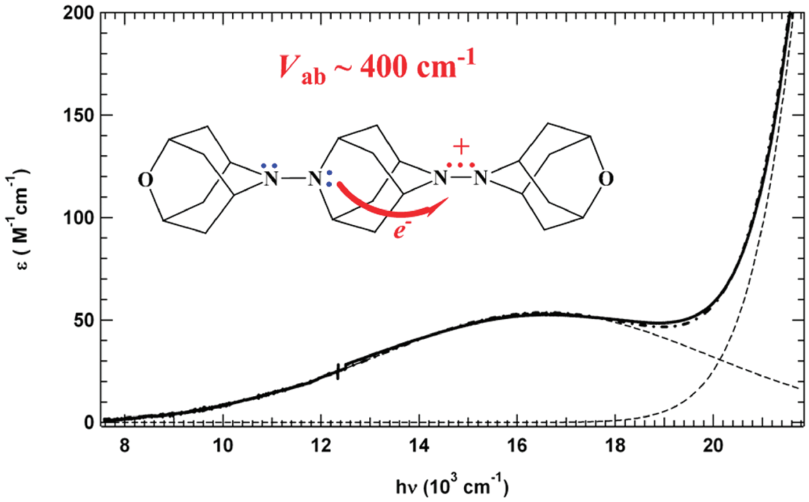

The mixed valence bishydrazine radical cation 6^+, obtained by oxidation of 2,6-bi-(2′-oxa-6′-azaadamantane-6′-yl)-2,6-diazaadamantane-2,6-diyl (**6**) with silver or nitrosonium salts, has been prepared and studied. **6** is obtained along with lesser amounts of the trishydrazine, some of the tetrahydrazine, and apparently traces of the pentahydrazine upon reaction of deprotonated 2-oxa-6-azaadamantane with 2,6-dichloro-2,6-diazaadamantane. The EPR spectrum of 6^+ shows that its charge is localized on one hydrazine unit on the EPR time scale. It shows a Hush-type Robin−Day class II mixed valence band in its optical spectrum despite the fact that the nitrogen lone pairs are held in a perpendicular geometry that would lead to no electronic interaction between the nitrogen atoms that are separated by only four σ bonds if its nitrogens were planar. The electron transfer distance that is estimated from the calculated dipole moment of 6^+ is the same as that obtained using the average distance between the electrons of the triplet state of the dication 6^{2+}, calculated from its dipolar EPR splitting, as a model for the electron transfer distance of 6^+, 3.7 Å. Using Hush's Gaussian approximation for the optical spectrum with this electron transfer distance produces an estimate of the electronic coupling V_{ab} through the saturated bridge of about 400 cm^{-1}, which is consistent with the observed EPR spectrum of 6^+. From the observed dipolar splitting, the trishydrazine diradical dication has its remote hydrazine units oxidized, although the monocation presumably forms at the central hydrazine unit, which lacks substitution by the more electron-withdrawing oxygen atoms.

Introduction

The nitrogens of Bredt's Rule protected bi- and polycyclic chloroamines such as 9-chloro-9-azabicyclo[3.3.1]nonane (**1(Cl)**) are efficiently coupled to produce hydrazines such as **2** by treatment with 1 mol of *tert*-butyllithium per mol of chloroamine.[1] We presume that metal−halogen exchange

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(1) Nelsen, S. F.; Hollinsed, W. C.; Kessel, C. R.; Calabrese, J. C. *J. Am. Chem. Soc.* **1978**, *100*, 7876–7882.

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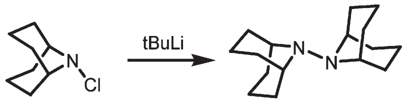
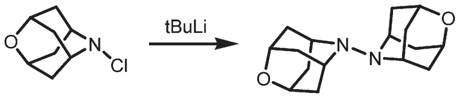
produces R_2NLi and tBuCl, and the latter is rapidly deprotonated by RLi, so the exchange and proton transfer reactions produce an equimolar mixture of bicyclic lithioamine and chloroamine, which react with each other to produce hydrazine and LiCl. This is unlikely to be an S_N2 displacement but proved to give a much higher yield than did the coupling of two $\mathbf{1}^\bullet$ radicals obtained by photolytic decomposition of the related 2-tetrazene (**1**−N=N−**1**). Although less branched hydrazines are most stable in conformations that have nearly 90° lone pair, lone pair twist angle (θ) conformations in their neutral forms, these bis-*N*,*N*′-bicyclic examples exist in $\theta = 180°$ conformations because of steric interactions between their α-branched alkyl groups. Similar reactions have been used for hydrazine formation from 8-chloro-8-azabicyclo[3.2.1]octane,[2] 2-chloro-2-aza-3,3-dimethylbicyclo[2.2.2]-octane,[3] 7-chloro-7-azabicyclo[2.2.1]heptane,[4] and 2-chloro-2-azaadamantane.[5] Although the hydrazine radical cations such as $\mathbf{2}^+$ were found by X-ray crystallography to be untwisted at their N,N bonds, calculations get them to be twisted, as will be discussed below.



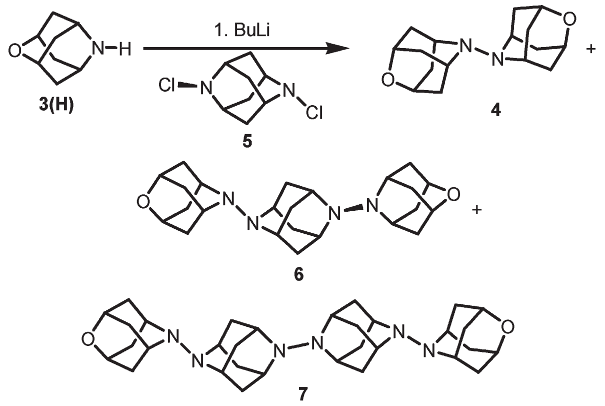
1(Cl) **2**

In this work, 2,6-heteroatom-substituted adamantanes are employed for the coupling. When 6-chloro-2-oxa-6-azaadamantane, **3(Cl)**, is employed, similar coupling to the oxygen-capped bis(*N*,*N*′)bicyclic hydrazine **4** occurs.



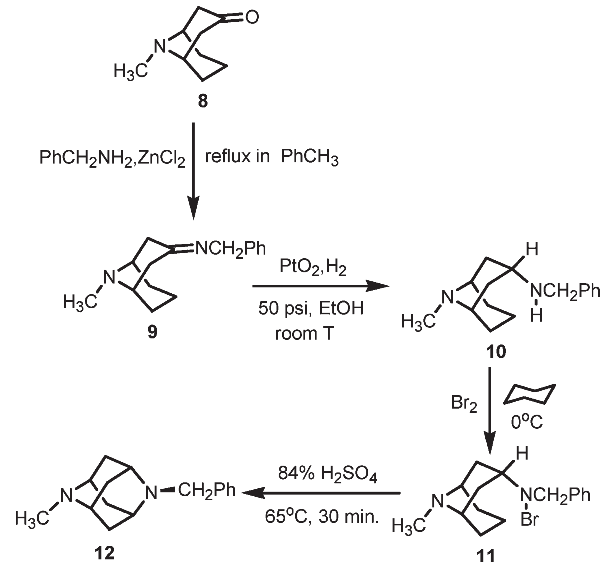
3(Cl) **4**

Furthermore, when **3(Li)** prepared by treating **3(H)** with butyllithium is reacted with 2,6-dichloro-2,6-diazaadamantane, **5**, in addition to the bis-heteroatom-substituted biadamantane monohydrazine **4**, the triadamantane bishydrazine **6** and a significant amount of the tetraadamantane trishydrazine **7** are also formed, and some of the pentaadamantane tetrakishydrazine was also detected in the mass spectrum of the sample rich in **7**.



Thus, in addition to formal coupling of $\mathbf{3}^\bullet$ radicals, we observe mixed coupling of $\mathbf{3}^\bullet$ radicals with $^\bullet\mathbf{4}^\bullet$ diradicals as well as coupling of $^\bullet\mathbf{4}^\bullet$ diradicals with themselves. Although these reactions are not very clean, it would be difficult to obtain these compounds by other methods. Our principal interest was in the one electron oxidation product of **6**, which produces a rather unusual mixed valence radical cation that has hydrazine charge-bearing units that are connected by a saturated bridge having four bonds between the nitrogens. This allows determining the size of the electronic coupling between the nitrogens from their optical spectra using Marcus−Hush theory. For a review of optical spectrum analysis of bishydrazine mixed valence radical cations with both σ- and π-bridges, see ref 6.

SCHEME 1. **Rassat's Route to a 2,6-Diazaadamantane Derivative**



Results and Discussion

Compound Preparation. Stetter and Heckel published two different preparations of 2,6-diazaadamantane derivatives in 1972−1973,[7,8] and Rassat and co-workers published a different synthesis of the bisnitroxide that had a 2,6-dialkyl-2,6-diazaadamantane intermediate in 1974.[9] However, we found no papers on derivatives of these compounds since. My group found out why when Michael Ramm attempted to repeat these reactions in the early 1990s. In our hands, the methods published do not produce the results stated.

Rassat used the free radical chain cyclization shown as the last reaction in Scheme 1 to construct the diazaadamantane derivative **12**.

Unfortunately, neither Ramm nor Li obtained any **12** under the published reaction conditions (they found only debromination) and did not find conditions that do work.

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[2] (a) Nelsen, S. F.; Cunkle, G. T.; Evans, D. H.; Clark, T. *J. Am. Chem. Soc.* **1983**, *105*, 5928–5929. (b) Nelsen, S. F.; Cunkle, G. T.; Evans, D. H.; Haller, K. J.; Kaftory, M.; Kirste, B.; Clark, T. *J. Am. Chem. Soc.* **1985**, *107*, 3829–3839.

[3] Nelsen, S. F.; Gannett, P. M. *J. Am. Chem. Soc.* **1982**, *104*, 5292–5297.

[4] Nelsen, S. F.; Blackstock, S. C.; Steffek, D. J.; Cunkle, G. T.; Kurtzweil, M. L. *J. Am. Chem. Soc.* **1988**, *110*, 6149–6153.

[5] Nelsen, S. F.; Tran, H. Q.; Ismagilov, R. F.; Ramm, M. T.; Chen, L.-J; Powell, D. R. *J. Org. Chem.* **1998**, *63*, 2536–2543.

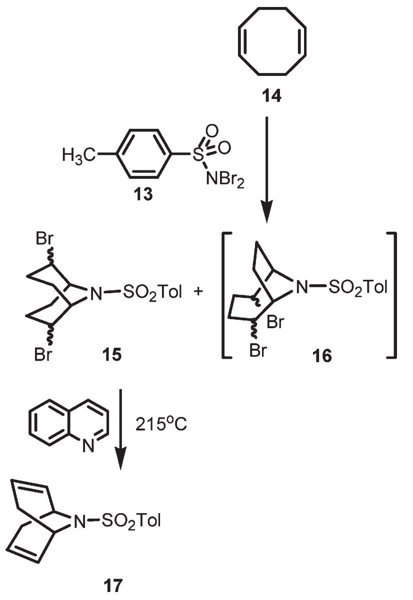
[6] Nelsen, S. F. In *Advances in Physical Organic Chemistry*; Richard, J. P., Ed.; Academic Press Ltd: London, 2006; Vol. 41, pp 183−215.

[7] (a) Stetter, H.; Heckel, K. *Tetrahedron Lett.* **1972**, 801–804. (b) Stetter, H.; Heckel, K. *Chem. Ber.* **1973**, *106*, 339–348.

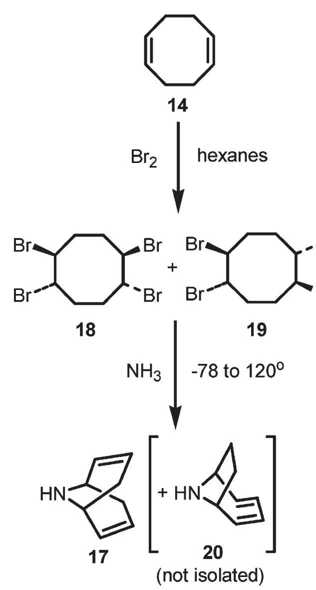
[8] Stetter, H.; Heckel, K. *Tetrahedron Lett.* **1972**, 1907–1908.

[9] Dupeyre, R.-M.; Rassat, A.; Ronzaud, J. *J. Am. Chem. Soc.* **1974**, *96*, 6559–6568.

SCHEME 2. One of Stetter's Routes to a 2,6-Diazaadamantane Precursor



SCHEME 3. Preparation of 17 by the Method of Ganter and Portman



Stetter and Heckel do not mention that addition of *N*,*N*-dibromo-*p*-toluenesulfonamide (**13**) to 1,5-cyclooctadiene (**14**) (see Scheme 2) produces a mixture of stereoisomers of the 1,5-addition product **15** that they write, and that heating with quinoline only produces a tiny yield of the desired diene **17**, apparently because only the diaxial adduct eliminates HBr under these conditions. The azabicyclo[4.2.1] diastereomeric mixture **16** is also formed, and we did not find conditions that allowed reasonable yields of **17** to be obtained from this route. Stetter also prepared the dibromide mixture **15** by reaction of ammonia with the diepoxide from **14** followed by N-tosylation, double O-tosylation, and reaction of the ditosylate with HBr, but we also failed to be able to obtain **17** from the mixture of diastereomers that this route provided either.

SCHEME 4. Preparation of 3(Cl) and 5

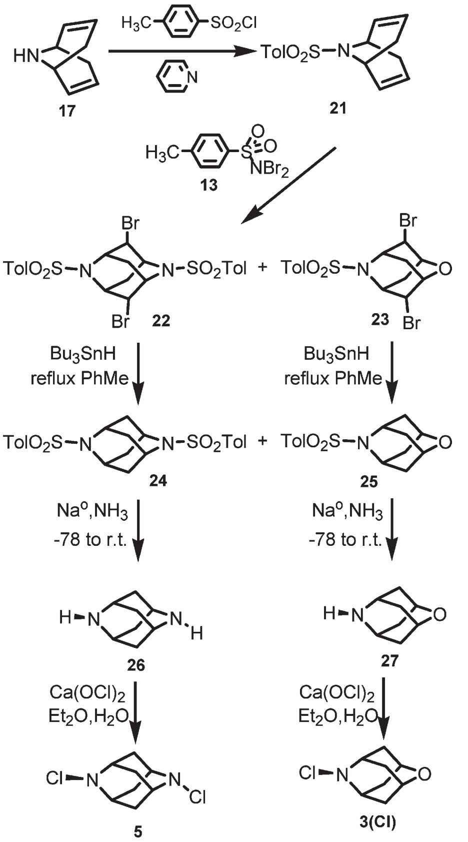


TABLE 1. Cyclic Voltammetry Data for 4 and 6 in CH_3CN and CH_2Cl_2

cmpd	$E°_1$ (CH_3CN)[a]	$E°_2$ (CH_3CN)[a]	$E°_1$ (CH_2Cl_2)[a]	$E°_2$ (CH_2Cl_2)[a]
4	0.21 (0.07)		0.30 (0.14)	
6	0.13 (0.06)	0.41 (0.07)	0.22 (0.19)	irrev.

[a] Potentials in V vs SCE, using Fc/Fc^+ as an internal standard. The number in parentheses is $E_p^{ox} - E_p^{red}$.

We finally successfully prepared **17** from the route shown in Scheme 3, by the method of Ganter and Portman,[10] producing 34 g of material in two steps. The workup was changed significantly.

Introduction of the second nitrogen and oxygen to prepare both the 2-oxa-6-azaadamantane and 2,6-diazaadamantane derivatives occurred after protection of the nitrogen by a tosyl group, addition of dibromotosylamide **13**,[7,8] free radical debromination, and detosylation (see Scheme 4).

It is not clear why **23** was formed in higher yield than was **22** in this reaction, but it clearly was, as demonstrated by an X-ray structure (see Supporting Information). We presume that that our sample of **13** must have still been wet, despite our attempts to dry it.

Oxidation Products of 4, 6, and 7. Cyclic voltammetry results are shown in Table 1. Potentials were measured using decamethylferrocene ($E°$ in acetonitrile −0.11 V vs SCE) as an internal standard. Second electron removal from dihydrazine **6** was reversible in acetonitrile but irreversible in methylene chloride, in which a sharp, irreversible absorption wave was found positive of the **6**,**6**$^+$ wave. The solvents used

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[10] Ganter, C.; Portman, R. E. *Helv. Chim. Acta* **1971**, *54*, 2069–2077.

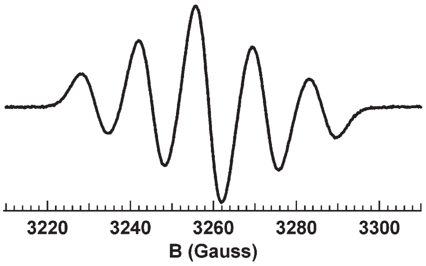

FIGURE 1. Room temperature EPR spectrum of $\mathbf{6}^+$ obtained by oxidation of a 2-fold excess of neutral **6** in CH_2Cl_2 with $Ag^+NO_3^-$.

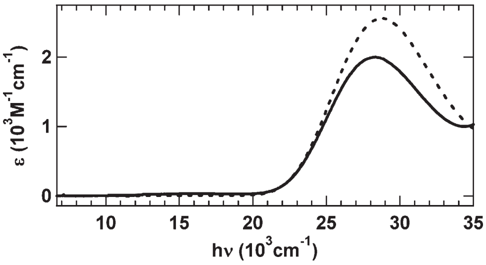

FIGURE 2. Optical absorption spectra showing the π,π^* transitions of monohydrazine $\mathbf{4}^+NO_3^-$ (dashed line) and dihydrazine $\mathbf{6}^+NO_3^-$ (solid line), from $Ag^+NO_3^-$ oxidation of the neutral compounds in CH_2Cl_2.

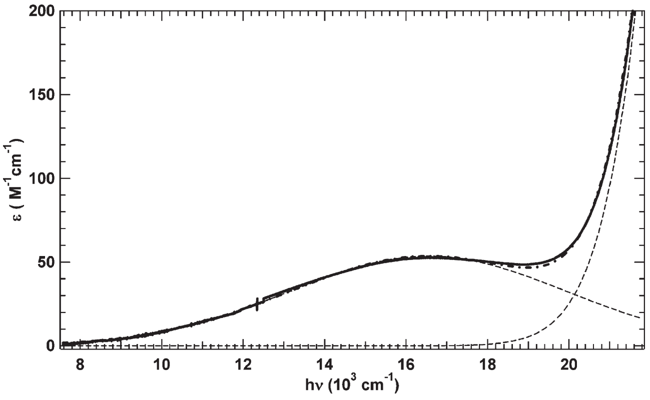

FIGURE 3. Optical spectrum of the mixed valence band region of the optical spectrum of $\mathbf{6}^+NO_3^-$ in CH_2Cl_2 that has been fit with two Gaussians.

contained 0.1 M tetrabutylammonium perchlorate as supporting electrolyte. Trihydrazine **7** proved too insoluble in acetonitrile for obtaining reliable data and showed irreversible cyclic voltammetry waves in CH_2Cl_2, so no data appear in Table 1.

The EPR spectra of $\mathbf{4}^+$, $\mathbf{6}^+$, and $\mathbf{7}^+$ (see Figure 1 for that of $\mathbf{6}^+$) at room temperature were indistinguishable 1:2:3:2:1 five line patterns with a(N) = 13.5 Gauss, as expected for charge and spin localized on a single hydrazine unit, showing that electron transfer between the hydrazine units of both $\mathbf{6}^+$ and $\mathbf{7}^+$ is slow on the EPR time scale at room temperature. The central hydrazine of $\mathbf{7}^+$ is presumably the one that is oxidized because the outer hydrazines have more electron-withdrawing oxaadamantane substitution on one side, while the central one has diazaadamantanes on both sides. We note that it is 0.08 V (1.8 kcal/mol) harder to remove the first electron from **4**, which has an oxaadamantane unit on both hydrazine nitrogens, than from **6**, which only has an oxaadamantane on one of its hydrazine nitrogens.

As for other hydrazine radical cations,[11,12] the optical spectra of $\mathbf{4}^+$ and $\mathbf{6}^+$ each show a $\pi_{NN}\rightarrow\pi^*_{NN}$ excitation, at 28 800 cm^{-1} (ε_{max} = 2560 M^{-1} cm^{-1}) for $\mathbf{4}^+$, and 28 300 cm^{-1} (ε_{max} = 2000 M^{-1} cm^{-1}) for $\mathbf{6}^+$ (see Figure 2). In addition, only the mixed valence bis(hydrazine) shows weak absorption near 16 000 cm^{-1} that we attribute to a Hush-type class II mixed valence band.[6] Figure 3 shows the spectrum of a more concentrated solution of $\mathbf{6}^+NO_3^-$ in CH_2Cl_2 that has been fit with two Gaussian bands, one to represent the class II charge transfer absorption, and the one that is off scale for the π,π^* absorption. It will be noted that, when the spectrometer that was used changes light sources at 800 nm, a noticeable change occurs in the spectrum for this weak band, which introduces some error in the analysis. The mixed valence band was fit with a Gaussian having E_{max} 16 540 cm^{-1}, ε_{max} = 53.5 M^{-1} cm^{-1}, and full width at half-height = 8000 cm^{-1}. The bandwidth is compatible with our assignment as a Hush-type band, for which the minimum full width at half-height according to Hush theory (which is $16\ln(2)k_BTE_{max})^{1/2}$) is 6164 cm^{-1} at the observed E_{max}, and larger bandwidths are observed experimentally than with this minimum value.[6]

We studied the optical spectra of $\mathbf{6}^+$ generated by oxidation with five reagents in both CH_2Cl_2 and CH_3CN, but especially the reactions with $NO^+PF_6^-$ and $NO^+SbF_6^-$ in CH_2Cl_2 did not complete even after stirring for 12 h, and gave lower ε_{max} values if calculated as 100% yield oxidation reactions than $Ag^+NO_3^-$, apparently because of solubility and surface fouling problems. The reaction with $NO^+BF_4^-$, which is also very insoluble, did appear to finish and gave a smaller ε_{max} about the same size as that found in CH_3CN. A different problem was encountered using $Ag^+SbF_6^-$. Our sample anomalously produced absorption in the 16 000 cm^{-1} region for $\mathbf{4}^+$, which $AgNO_3$ did not, and an anomalously high ε_{max} of 172 M^{-1} cm^{-1}, which we do not trust either. We suggest that the best data in CH_2Cl_2 are given by the $AgNO_3$ oxidation. We had less severe reproducibility problems for the oxidations in acetonitrile, in which the NO^+ salts are much more soluble (see Table 2).

According to Hush's Gaussian band approximation, the electronic coupling V_{ab} is given by eq 1

$$V_{ab} = 0.0206([\bar{\nu}_{max}\varepsilon_{max}\Delta\bar{\nu}_{1/2})^{1/2}/d_{ab} \qquad (1)$$

but we found for aromatic-bridged bishydrazines for which rate constants were determined using EPR that including a refractive index correction for ε_{max} dependence on solvent[6] that was introduced in this context by the Kodak group[13] improves agreement between optical and EPR rate constant and includes the corrections in the V_{ab} estimates of this work, as well. The correction used multiplies the eq 1 answer by a factor of 0.89 for CH_2Cl_2 and a factor of 0.914 for CH_3CN, and we use these values here.

It is necessary to know the electron transfer distance on the diabatic surfaces, d_{ab}, to extract the V_{ab} from the charge

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(11) Nelsen, S. F.; Blackstock, S. C.; Yumibe, N. P.; Frigo, T. B.; Carpenter, J. E.; Weinhold, F. *J. Am. Chem. Soc.* **1985**, *107*, 143–149.

(12) Nelsen, S. F.; Tran, H. Q.; Ismagilov, R. F.; Chen, L.-J; Powell, D. R. *J. Org. Chem.* **1998**, *63*, 2536–2543.

(13) Gould, I. R.; Young, I. H.; Mueller, J. L.; Farid, S. *J. Am. Chem. Soc.* **1994**, *116*, 8176–8187.

TABLE 2. Optical Data for the Hush Band of 6^+

solvent	oxidant	ε_{max} (M^{-1} cm^{-1})	E_{max} (cm^{-1})	$\Delta\bar{\nu}_{1/2}'$[a] (cm^{-1})
CH_2Cl_2	$Ag^+NO_3^-$	53	16540	8000
	$Ag^+SbF_6^-$	(172)[b]	(15800)[b]	(11100)[b]
	$NO^+BF_4^-$	28	16630	8800
	$NO^+PF_6^-$	[c]	16500	10100
	$NO^+SbF_6^-$	[c]	16050	9100
CH_3CN	$Ag^+NO_3^-$	37	17240	8600
	$Ag^+SbF_6^-$	36	17400	8100
	$NO^+BF_4^-$	18	17530	7500
	$NO^+PF_6^-$	54	17900	9500
	$NO^+SbF_6^-$	36	17300	8100

[a] Full width at half-height. [b] All three of these parameters are anomalous, and we conclude that something went wrong with this solution. [c] Solid remained after 12 h, so oxidation was incomplete. The measured ε_{max} is certainly too low for these oxidants and is not reported.

transfer band of a localized mixed valence compound using Hush theory. Because of extensive charge delocalization into the bridge, which is made up of the same material as the charge-bearing units in an organic example, d_{ab} does not correspond to the distance between any of the atoms. Because calculations can only be carried out with the electronic couplings intact, one can only calculate the distance on the adiabatic surface, d_{12}, but Cave and Newton have shown how to convert d_{12} to d_{ab} using the mixed valence band absorption spectrum (eq 2)[14] where

$$d_{ab} = [{d_{12}}^2 + 4(2.06 \times 10^{-2})^2 \varepsilon_{max} \Delta\bar{\nu}_{1/2}/\bar{\nu}_{max}]^{1/2} \qquad (2)$$

ε_{max} is the molar absorption coefficient (M^{-1} cm^{-1}), $\Delta\bar{\nu}_{1/2}$ is the full bandwidth at half-height (cm^{-1}), and $\bar{\nu}_{max}$ is the transition energy at the band maxium (cm^{-1}). The correction is certainly smaller than experimental error for these compounds, so we simply used the calculated d_{12} values for them to estimate d_{ab}. Equation 3 has been recommended as a way of calculating d_{12} for mixed valence

$$d_{12}(\mu) = 2\mu_1/4.8032 \qquad (3)$$

compounds, from their ground state dipole moment, μ_1, calculated using the center of mass as the origin.[15] Although only the component of μ_1 in the electron transfer direction should be used, this direction is difficult to define, especially for these molecules, and we used all of μ_1 in calculating $d_{12}(\mu)$. We expect d_{ab} to be near d_{12} for these molecules and significantly shorter than the distance between the midpoints of the NN bonds of the hydrazine units, d_{HyHy}, but longer than the distance between the closest nitrogens, $d_{N,N}$. Table 3 shows these distances as well as μ_1 and $d_{12}(\mu)$ calculated for 6^+ using semiempirical (AM1), B3LYP/6-31G* (labeled DFT), and UHF/6-31G* calculations.[16] It may be noted that the B3LYP calculation does not incorrectly delocalize the charge for 6^+, which it does for most aromatic-bridged systems,[17] and that the unsophisticated semiempirical AM1 calculation gives a $d_{12}(\mu)$ value only 4% larger than the average of all three values.

TABLE 3. Calculated Distances, Dipole Moment, and Electron Transfer Distance, d_{12} Using Equation 3 for 6^+

species	calc	d_{NN} (Å)[a]	d_{HyHy} (Å)[b]	μ_1 (Debye)	$d_{12}(\mu)$ (Å)
6^+	AM1	3.55	4.72	9.57	3.98
	DFT	3.48	4.66	8.84	3.69
	UHF	3.45	4.64	9.07	3.78

[a] Distance between the nitrogens of the 1,5-diazaadamantane ring. [b] Distance between the midpoints of the hydrazine bonds.

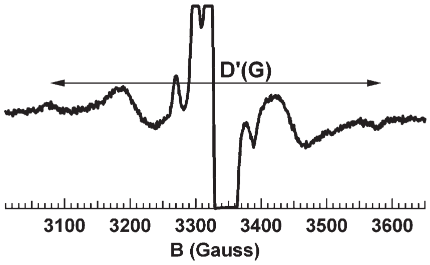

FIGURE 4. ESR spectrum at 118 K of 6^{2+} obtained by oxidation with $NO^+PF_6^-$ in the mixed solvent.

TABLE 4. Dipolar Splittings and d_{EPR} Values for 6^{2+} in Mixed Solvent with Three Oxidants and for the Neutral Diradicals Studied by Rassat and Co-workers

species	oxidant	D' (Gauss)	d_{EPR} (Å)
6^{2+}	$NO^+BF_4^-$	570	3.65
	$NO^+PF_6^-$	500	3.80
	$NO^+SbF_6^-$	580	3.63
28		250	4.81
29		230	4.95

We found in previous work that using the thermally excited triplet of the diradical dication oxidation level of hydrazine-centered mixed valence compounds as an experimental model for the electron transfer distance of the monocation mixed valence electron transfer distance, using the dipolar splitting in Gauss (D') with the point dipole approximation formula of eq 4 for the average distance between the electrons gave better fit of optically derived rate constant predictions to the

$$d_{EPR} = 30.3(D')^{-1/3} \qquad (4)$$

observed rate constants than using calculated $d_{12}(\mu)$ values.[6] We studied the dications in the 1:1:1 $CH_2Cl_2/CH_3CN/CH_3(CH_2)_2CN$ mixed solvent mixture developed previously for minimizing problems with polycrystalline material, which show narrower signals than those of the triplet, centered at $g = 2$.[18] The large $g = 2$ features shown for the spectrum of 6^{2+} in Figure 4 show that we have serious polycrystallinity problems even in the mixed solvent. The dipolar splittings and the d_{EPR} values derived from them for 6^{2+} appear in Table 4, along with data for two neutral diazaadamantane derivative diradicals studied by Rassat and co-workers (see below).

We doubt that the differences in d_{EPR} obtained in different solvents represent real counterion effects upon electron transfer distance and suggest that they instead correspond to the experimental error in obtaining dipolar splittings from

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(14) (a) Cave, R. J.; Newton, M. D. *Chem. Phys. Lett.* **1996**, *249*, 15–19. (b) Cave, R. J.; Newton, M. D. *J. Chem. Phys.* **1997**, *106*, 9213–9226.

(15) Nelsen, S. F.; Newton, M. D. *J. Phys. Chem. A* **2000**, *104*, 10023–10031.

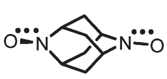
(16) The geometries were optimized using Spartan'02: *Spartan'02*; Wavefunction, Inc.: Irvine, CA.

(17) Blomgren, F.; Larsson, S.; Nelsen, S. F. *J. Comput. Chem.* **2001**, *22*, 655–664.

(18) Nelsen, S. F.; Ismagilov, R. F.; Powell, D. R. *J. Am. Chem. Soc.* **1997**, *119*, 10213–10222.

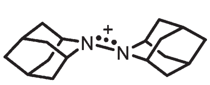
these broad and rather weak spectra. We will therefore use averaged value of 3.7 Å, which is within any reasonable expected error the same as the value calculated by DFT for 6^+ (Table 3), for the electron transfer distance in analysis of our optical data.

Rassat's group studied the triplet EPR spectra of frozen solutions of the neutral bisnitroxides 2,6-dioxy-2,6-diazaadamantane,[9] **28**, and its bridgehead tetramethyl analogue, **29**.[19] As shown in Table 4, they have dipolar splittings approximately half of that for $\mathbf{6}^{2+}$, producing d_{EPR} distances over 1 Å (over 30%) larger. Larger electronic coupling leading to smaller d_{EPR} would be expected for $\mathbf{6}^+$ if its nitrogens were more pyramidal than those of Rassat's nitroxides, but it is not obvious that this is the case. The X-ray structure of 2,2′-bis-2-azaadamantane radical cation, **30**, the closest available model for the nitrogens of $\mathbf{6}^+$, has a nitrogen pyramidality α′ (the deviation of the average of the bond angles at nitrogen from the 120° of a planar nitrogen system, which we use as the criterion for pyramidality because it is nearly linear with s character in the lone pair) of 3.4°, and that calculated using B3LYP/6-31G* α′ at the 180° lone pair lone pair twist is 2.4° (1.8° at the calculated energy minimum).[5] An X-ray structure is not available for **28**, but its α′ value calculated at the energy minimum is 3.5°. Bisnitroxides ought to have lower spin density at N than bishydrazine radical cations because of the greater electronegativity of oxygen than of nitrogen, which will increase the electronic coupling at a given amount of pyramidalization for bishydrazine radical cations. For example, Rassat estimated the relative charges at O and N of **28** were 0.365 and 0.135, from a rough calculation on $H_2N{-}O^{\bullet}$.[9] The energy gap between the 3e$-\pi$ bond MOs and those of the σ bonds of the bridges will also affect the electronic coupling through the bridge of $\mathbf{6}^+$ relative to Rassat's nitroxides,[20] which will affect D' and d_{EPR} in the dication models for the radical cations, but we do not have a good way of estimating the size of this effect. Our EPR experiment indicates that electronic communication through the bridge is significantly larger for $\mathbf{6}^{2+}$ than for Rassat's nitroxides, which also agrees with dipole moment calculations on $\mathbf{6}^+$.



28

29



30

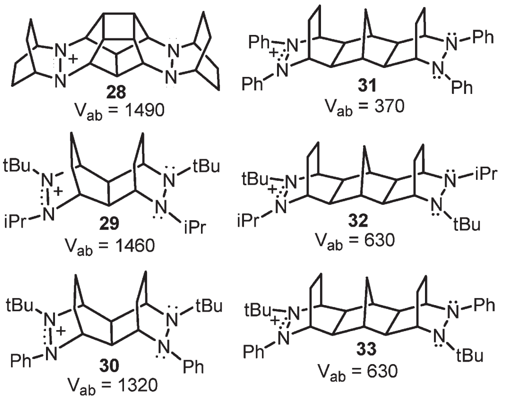
Although the EPR spectra of $\mathbf{7}^{2+}$ at low temperatures are quite broad and have more overlap with the signals that we attribute to polycrystallinity, the D' values of 87.2 Gauss obtained using $Ag^+NO_3^-$ oxidation and 83.7 Gauss using $Ag^+SbF_6^-$ oxidation in the mixed solvent correspond to d_{EPR} values of 6.83 and 6.93 Å, respectively, which fits our expectation that the remote hydrazines would be oxidized instead of adjacent ones because of Couloumb repulsion between adjacent oxidized hydrazines, despite their oxaadamantane substitution. Oxidation of the outer hydrazine units is also calculated to give the more stable diradical dication.

H_{ab} values calculated from the optical spectra of $\mathbf{6}^+$ (Table 2) using eq 1 with d_{ESR} replacing d_{ab} appear in Table 5.

TABLE 5. V_{ab} **Values (cm^{-1}) for** $\mathbf{6}^+$ **Using** d_{ESR} **as the Electron Transfer Distance**

solvent	oxidant	V_{ab}
CH_2Cl_2	$Ag^+NO_3^-$	410
CH_3CN	$Ag^+NO_3^-$	380
	$Ag^+SbF_6^-$	350
	$NO^+BF_4^-$	480
	$NO^+PF_6^-$	370
	$NO^+SbF_6^-$	320

SCHEME 5. V_{ab} **(cm^{-1}) Values Obtained from the Optical Spectra of Doubly 4-σ- (28−30) and 6-σ-Bond-Bridged (31−33) Mixed Valence Hydrazine-Centered Dications**



We show only a single value for CH_2Cl_2 because we had great difficulty in reproducing data from different oxidizing agents in this solvent, we believe because of oxidant solubility problems. We show data with several oxidants for CH_3CN, which reflects the reproducibility of these experiments. Because of the scatter in the values obtained in CH_3CN, the average V_{ab} of 380 cm^{-1} obtained in CH_3CN is not significantly different from that obtained in CH_2Cl_2, which was also the case for other hydrazine-centered mixed valence cations, for which a significant effect of solvent on electronic coupling was not observed.[6] Scheme 5 shows the V_{ab} values for 4- and 6-σ-bond-bridged mixed valence bishydrazine radical cations (**28**−**33**), which illustrate the effects of changing number of σ bonds and of hydrazine substituents on V_{ab}.[21] For **29**, **30** and for **32**, **33**, the compounds with both *syn*- and *anti*-*tert*-butyl groups were studied, but only the *syn* (**29**,**30**) or *anti* (**32**,**33**) ones are illustrated in Scheme 5. Because no significant differences in V_{ab} values between *syn* and *anti* compounds were found, the V_{ab} values shown are averages for the two, for which approximately a ±30 cm^{-1} scatter in the V_{ab} calculated for the hydrazines as solvent was changed, which we believe illustrates the reproducibility in extracting V_{ab} from the optical data. We do not know why the tetraphenyl-substituted compound **31** gave a V_{ab} only 59% as large as diphenyl-substituted **33**, but the diphenyl-substituted compound **30** was 90% as large as tetraalkyl-substituted **29**, and no significant difference was observed between the diphenyl-substituted **33** and the tetraalkyl-substituted **32**. The tetraphenyl-substituted compound **31** has about the same V_{ab} as that observed for $\mathbf{6}^+$. The tetraphenyl-substituted 4-σ-bond-bridged compound

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(19) Chiarelli, R.; Rassat, A.; Cromzee, Y.; Jeannin, Y.; Novak, M. A.; Tholence, J. L. *Phys. Scr.* **1993**, *T49*, 706–710.

(20) Newton, M. D. *Chem. Rev.* **1991**, *91*, 767–792.

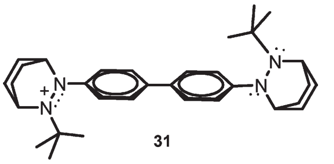
(21) Nelsen, S. F.; Trieber, D. A., II. Ismagilov, R. F.; Teki, Y. *J. Am. Chem. Soc.* **2001**, *119*, 5684–5694.

remains unknown. Because delocalization of charge onto the phenyl group will lower V_{ab} by decreasing charge at the hydrazine unit but also flatten the nitrogen, which increases steric effects with the substituent on the other nitrogen leading to increased twisting, there is a subtle interplay of effects on V_{ab} for changing alkyl to phenyl, and rationalization of the values in the absence of reliable geometrical information seems unwise. For the diphenyldialkyl and tetraalkyl 6-bond-bridged cases of Scheme 5, increasing from 4 to 6 all *anti*-aligned σ bonds causes V_{ab} to drop to 43% of the size it was at 4 bonds. Even though the expected V_{ab} would be zero if **6**$^+$ had planar nitrogens, the observed value, averaging 380 cm^{-1} for the data in CH_2Cl_2 and 410 cm^{-1} for the Table 5 entry in CH_3CN, is 60−65% as large as the diphenyldialkyl and tetraalkyl 6-bond-bridged cases, which we suggest is unexpectedly large for this compound.

The rate constants for thermal intramolecular electron transfer within **6**$^+$ that are predicted from the optical spectra in both CH_2Cl_2 and CH_3CN are completely consistent with the five-line EPR spectra that are observed because the rate constants predicted are below 1.5×10^5 s^{-1}, and rate constants below $\sim 10^7$ s^{-1} are immeasurably slow on the EPR time scale for these hydrazine-centered mixed valence compounds.

Conclusion

Although perhaps unexpectedly large, the electronic coupling through the saturated 4-σ-bond bridge in these compounds, for which their geometry should enforce $V_{ab} = 0$ if the nitrogens were planar, is not large enough to allow electron transfer to be rapid enough to measure by EPR even in the lower reorganization energy solvent, CH_2Cl_2, although it is about 35% as large as that through the 9-bond unsaturated bridge of the biphenyl-bridged bishydrazine radical cation **31**.[6]



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Experimental Section

Compound Preparation. 1,2,5,6-Tetrabromocyclooctane (18 and 19). The mixture of 1,2-*trans*-5,6-*trans*-tetrabromocyclooctane isomers was synthesized similarly to the method of Ganter and Portman.[10] Br_2 (126 mL, 2.44 mol) was added dropwise to cycloocta-1,5-diene (150 mL, 1.22 mol) in hexanes (700 mL) in a 2 L flask with mechanical stirring at 0 °C under a nitrogen atmosphere. The solid product was filtered, washed with hexanes (100 mL × 3), and dried to provide the desired product (312.00 g, 60%): ^{1}H NMR ($CDCl_3$) δ 4.81−4.51 (m, 4 H), 2.89−2.73 (m, 3 H), 2.62−2.34 (m, 2 H), 2.21−2.02 (m, 3 H); ^{13}C NMR ($CDCl_3$) δ 58.5, 57.5, 31.8, 26.9; MS, EI+ 265.9.

9-Azabicyclo[3.3.1]nona-2,6-diene (17). Reactions similar to those of Ganter and Portman were used. Excess NH_3 (liquid) (200 mL) was condensed using a dry ice bath with 1,2,5,6-tetrabromocyclooctane (in three batches of 150 g and one of 100 g, a total of 1.29 mol) in a steel hydrogenation bomb with magnetic stirring, heated at 120 °C overnight, and the reactor was cooled again with dry ice and opened in a fume hood. NH_3 was evaporated as the temperature increased from −78 °C to room temperature under air. CH_2Cl_2 (2 L) was added to extract the product. The CH_2Cl_2 extracts were combined and concentrated together with silica gel powder (100 g) and loaded on the top of a silica gel column packed with hexanes. The column was flashed with 20% ethyl acetate in hexanes (2 L) and followed by using 2% methanol and 2% ammonia−water in ethyl acetate (3 L) to elute the desired product (34.45 g, 22%, $R_f = 0.23$ on TLC plates when eluted with 2% methanol and 2% ammonia−water in ethyl acetate). $KMnO_4$ was used as visualizing reagent: ^{1}H NMR ($CDCl_3$) δ 5.87−5.73 (m, 4 H), 3.71−3.63 (m, 2 H), 2.47−2.34 (m, 2 H), 1.91−1.81 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 131.0, 123.7, 46.6, 29.7; HRMS, EI+ monoisotopic $[M - H]^+$ calcd 120.0813, found 120.0813 (< 1 ppm).

9-Tosyl-9-azabicyclo[3.3.1]nona-2,6-diene (21). *para*-Toluenesulfonyl chloride (1.48 g, 7.76 mmol) was added to **17** (0.47 g, 3.88 mmol) stirring in pyridine (20 mL) at 0 °C. The reaction mixture was stirred under nitrogen at 0 °C and allowed to warm to room temperature overnight. The solvent was removed under vacuum. The residue was dissolved in CH_2Cl_2, filtered, and the solution was dried together with silica gel powder (10 g) and then loaded on a silica gel column packed with hexanes. The column was flashed with 5% ethyl acetate in hexanes (1 L) and developed with 20% ethyl acetate in hexanes (1 L) to provide the desired product **21** (0.65 g, 61%): ^{1}H NMR ($CDCl_3$) δ 7.75−7.65 (m, 2H), 7.28−7.16 (m, 2H), 5.72−5.51 (m, 4H), 4.57−4.47 (m, 2H), 2.43−2.28 (m, 5H), 1.88−1.76 (m, 2H); HRMS, TOF MS EI+ $[M + H]^+$ calcd 276.1058, found 276.1057 (< 1 ppm).

2,6-Ditosyl-4,8-dibromo-2,6-diazaadamantane (22). We used Stetter's method,[7,8] with a changed workup. To CH_2Cl_2 (100 mL) in a dried 250 mL three-neck flask with magnetic stirring at −78 °C under N_2 were added dropwise **21** (1.11 g, 4.02 mmol) in CH_2Cl_2 (50 mL) from one funnel and *N*,*N*-dibromo-*p*-toluenesulfonamide (**13**)[22] (1.32 g, 4.02 mmol) in CH_2Cl_2 (50 mL) from the other funnel at the same rate. After the addition, the temperature was maintained at −78 °C for about 5 h and then allowed to increase from −78 °C to room temperature overnight. The reaction solution was concentrated and dried together with silica gel powder (20 g). The resulting mixture was loaded to a silica gel column packed with hexanes. The silica gel column was flashed with 10% ethyl acetate in hexanes (1 L) and 20% ethyl acetate in hexanes (3 L). It was observed that the top segment of the silica gel column contains some white precipitate. This white precipitate can be taken out together with the silica gel powder and extracted by CH_2Cl_2. The CH_2Cl_2 solution was filtered and dried to provide the desired product (0.49 g, 6%, R_f=0.05 when 20% ethyl acetate in hexanes was used as developing reagents): ^{1}H NMR ($CDCl_3$) δ 7.74−7.64 (m, 4H), 7.37−7.20 (m, 4H), 4.34−4.22 (m, 4H), 4.16−4.10 (m, 2H), 2.80−2.70 (m, 2H), 2.45 (s, 3H), 2.39 (s, 3H), 1.89−1.78 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 130.5, 129.5, 128.0, 127.1, 53.1, 51.4, 47.4, 29.7; HRMS, TOF MS ES+ $[M + Na]$ calcd 624.9442, found 624.9472 (4.8 ppm).

2,6-Ditosyl-2,6-diazaadamantane (24). Debromination was carried out by the method of Stetter and co-workers.[7] A mixture of **22** (8.47 g, 14.01 mmol), tri-*n*-butyl tin hydride (14.86 mL, 56.06 mmol), and AIBN (50 mg) in toluene (300 mL) was heated to reflux overnight under N_2. The solvent was removed using a vacuum pump. MeOH (50 mL) was added. The white precipitate was collected, washed with MeOH (10 mL × 3), and dried in a vacuum oven to provide the desired product (5.12 g, 82%): ^{1}H NMR ($CDCl_3$) δ 7.73−7.65 (m, 4H), 7.31−7.23 (m, 4H), 4.23−4.16 (m, 4H), 2.41 (s, 6H), 1.76−1.70 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 147.1, 143.4, 129.8, 127.0, 47.1, 33.1, 21.5; HRMS, TOF MS ES+ $[M + Na]^+$ calcd 469.1232 monoisotopic, found 469.1227 (1 ppm).

2,6-Diazaadamantane (26). The method of Stetter and co-workers[7] was used to detosylate **24** (0.80 g, 1.79 mmol) and in dry ammonia (10 mL) was treated with Na (1.0 g, 43.48 mmol) at −78 °C, followed by stirring for 4 h. Then the temperature was allowed to increase from −78 °C to room temperature under N_2 overnight. After the evaporation of the ammonia, the reaction mixture was dissolved in methanol. The solution was dried with

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(22) Chattaway, F. D. *J. Chem. Soc.* **1905**, *87*, 145–171.

silica gel powder (10 g) and loaded onto a column packed with ethyl acetate. The column was flashed by 12% methanol and 6% ammonia−water in ethyl acetate to provide the desired product (0.24 g, 94%, not very pure). This product was visualized with 10% phosphomolybdic acid in ethanol as developing reagent, and $R_f = 0.07$ using 12% methanol and 6% ammonia−water in ethyl acetate: ^{1}H NMR ($CDCl_3$) δ 3.57−3.50 (m, 4H), 2.16−2.09 (m, 8H); HRMS, EI+ M^+ calcd 138.1157 monoisotopic, found 138.1162 (3.6 ppm).

2,6-Dichloro-2,6-diazaadamantane (5). To a mixture of **26** (0.19 g, 1.73 mmol) and $Ca(ClO)_2$ (1.97 g, 13.75 mmol) at 0 °C were added water (40 mL) and ethyl ether (20 mL). The reaction mixture was stirred vigorously from 0 °C to room temperature for 4 h, diluted with water (50 mL), and extracted with ether (50 mL × 3). The ether solution was concentrated and dried in vacuo to provide the desired product (0.22 g, 77%): ^{1}H NMR ($CDCl_3$) δ 3.47−3.42 (m, 4H), 2.80−1.72 (m, 8H); HRMS, EI+ M^+ calcd 206.0378 monoisotopic, found 206.0368 (4.9 ppm).

6-Tosyl-2-oxa-4,8-dibromo-6-azaadamantane (23). To our surprise, **23** proved to be the major product of the reaction (shown above) intended to make **22**; 4.12 g, 63% ($R_f = 0.13$ when 20% ethyl acetate in hexanes was used as developing reagents) isolated from the reaction product: ^{1}H NMR ($CDCl_3$, 299.733 MHz) δ 7.78−7.70 (m, 2H), 7.30−7.23 (m, 2H), 4.45−4.31 (m, 4H), 4.17−4.10 (m, 2H), 2.88−2.77 (m, 2H), 2.41 (s, 3H), 2.13−2.03 (m, 2H); ^{13}C NMR ($CDCl_3$, 299.733 MHz) δ 148.4, 143.3, 129.3, 127.7, 69.6, 52.8, 47.8, 30.4, 21.6; HRMS, EI+ M^+ calcd 448.9296 monoisotopic, found 448.9304 (1.8 ppm). X-ray crystallography confirmed that the two bromo groups are *anti* to the oxygen atom in the adamantane cage (both bromines axial).

6-Tosyl-2-oxa-6-azaadamantane (25). A mixture of **23** (14.05 g, 31.20 mmol), tri-*n*-butyl tin hydride (33.08 mL, 124.80 mmol), and AIBN (0.512 g, 3.12 mmol) in toluene (300 mL) was heated to reflux overnight under N_2. The reaction mixture was dried together with silica gel powder (20 g) and loaded on the top of a silica gel column packed with hexanes. The column was flashed with 20% ethyl acetate in hexanes (1 L) and 40% ethyl acetate in hexanes (1 L) to provide the desired product (9.19 g, 100%): ^{1}H NMR (CD_2Cl_2) δ 7.78−7.65 (m, 2H), 7.37−7.25 (m, 2H), 4.30−4.22 (m, 2H), 4.10−4.00 (m, 2H), 2.43 (s, 3H), 2.03−1.87 (m, 4H), 1.78−1.63 (m, 4H); ^{13}C NMR (CD_2Cl_2) δ 143.9, 139.1, 130.3, 127.5, 66.8, 48.0, 34.5, 21.8; HR-MS, TOF MS ES+ $[M + H]^+$ calcd 293.1164 monoisotopic, found 293.1160 (1.4 ppm).

6-Aza-2-oxaadamantane (27). Detosylation was carried out by the method of Goanvic and Tius.[23] A solution of Na (2.78 g, 120.87 mmol) and naphthalene (18.59 g, 145.04 mmol) in DME (50 mL) was stirred at room temperature for 1 h. The solution became dark green. The fresh solution of sodium naphthalenide was added to a solution of *N*-tosyl-6-aza-2-oxaadamantane (2.10 g, 7.16 mmol) in DME (50 mL) at −50 °C until the solution was green. The mixture was quenched with aqueous NH_4Cl solution (50 mL), and a 2 M HCl solution (100 mL) was added. The aqueous phase was extracted with ether (100 mL × 3) and was then adjusted to pH 12 with NaOH and extracted with ethyl acetate. The organic phase was dried with Na_2SO_4, filtered, and evaporated to dryness. The crude product was dissolved in hot hexanes, filtered, and evaporated to afford the product as a white solid (0.39 g, 39%): ^{1}H NMR ($CDCl_3$) δ 4.21−4.13 (m, 2H), 3.40−3.31 (m, 2H), 2.15−2.03 (m, 4H), 1.91−1.79 (m, 4H); HR-MS, EI+ M^+ calcd 139.0997 monoisotopic, found 139.1001 (2.9 ppm).

***N*-Chloro-6-aza-2-oxaadamantane (3(Cl)).** To a mixture of **27** (1.17 g, 8.41 mmol) and $Ca(ClO)_2$ (2.40 g, 16.81 mmol) at 0 °C were added water (100 mL) and ethyl ether (50 mL). The reaction mixture was stirred vigorously as the solution warmed from 0 °C to room temperature over 4 h, diluted with water (150 mL), and extracted with ether (200 mL × 3). The ether solution was dried with Na_2SO_4, concentrated with silica gel powder (10 g), and loaded to the top of a silica gel column packed with hexanes. The column was flashed with 20% ethyl in hexanes (2 L) to provide the desired product (0.55 g, 38%): ^{1}H NMR ($CDCl_3$) δ 4.13−3.97 (m, 2H), 3.58−3.46 (m, 2H), 2.58−1.73 (m, 8H); HR-MS, EI+ M^+ calcd 173.0607 monoisotopic, found 173.0602 (2.9 ppm).

6,6′-Bi-(2-oxa-6-azaadamantane-6-yl) (4). To a 200 mL flame-dried flask under N_2 was added a solution of **3(Cl)** (0.51 g, 2.94 mmol) in THF (50 mL). The solution was cooled to −78 °C with a dry ice bath; 1.7 M *tert*-butyllithium (1.74 mL, 2.97 mmol) was added using a gastight Hamilton syringe. After 1 h at −78 °C and 1 h at room temperature, the mixture was poured into NH_4Cl solution, extracted with ether, dried with $MgSO_4$, filtered, concentrated with silica gel powder (10 g), and loaded to a silica gel column packed with dichloromethane. The column was flashed with 5% triethylamine in dichloromethane (1 L) to provide the desired product (0.33 g, 81%): mp 223−226 °C (dec); ^{1}H NMR ($CDCl_3$) δ 4.10−3.98 (m, 4H), 3.43−3.33 (m, 4H), 2.10−1.97 (m, 8H), 1.93−1.82 (m, 8H); ^{13}C NMR ($CDCl_3$, 299.731 MHz) δ 67.0, 47.3, 33.0; HR-MS, EI+ M^+ calcd 276.1838 monoisotopic, found 276.1840 (0.7 ppm).

2,6-Bi-(2′-oxa-6′-azaadamantane-6′-yl)-2,6-diazaadamantane-2,6-diyl (6). To a flame-dried 100 mL flask under N_2 was added a solution of **27** (2.25 g, 16.17 mmol) in THF (100 mL). The flask was cooled with a dry ice bath; 2 M *n*-BuLi in pentanes (9.51 mL, 16.17 mmol) was added dropwise. After 15 min, a solution of **5** (1.14 g, 5.50 mmol) in THF (50 mL) was added dropwise. The reaction was let stand at −78 °C for 1 h and at room temperature for 0.5 h. Saturated Na_2CO_3 solution (200 mL) was added to quench the reaction. The mixture was extracted with ether (200 mL × 3). The ether solution was washed with saturated NaCl solution, dried with $MgSO_4$, concentrated with silica gel powder (20 g), and loaded to a silica gel column packed with hexanes. The column was flashed with dichloromethane containing 1.5% 7 N NH_3 in MeOH (3 L) to provide the desired white solid product (0.210 g, 9%, TLC plates visualized with I_2 in silica gel powder): mp 294−296 °C (dec); ^{1}H NMR ($CDCl_3$) δ 4.07−4.00 (m, 4H), 3.42−3.33 (m, 4H), 3.25−3.17 (m, 4H), 2.08−1.96 (m, 8H), 1.93−1.81 (m, 16H); ^{13}C NMR ($CDCl_3$) δ 67.2, 47.5, 47.1, 33.0, 30.6; HR-MS, EI+ M^+ calcd 412.2838 monoisotopic, found 412.2831 (1.7 ppm).

6,6′-Bi-(2″-oxa-6″-azaadamantane-6″-yl)-2,2′-bi-(2,6-diazaadamantane-6,6′-diyl) (7). Compound 7 was also isolated from the column run for the above reaction: ^{1}H NMR ($CDCl_3$) δ 4.08−4.02 (m, 4H), 3.42−3.33 (m, 4H), 3.25−3.17 (m, 8H), 2.08−1.98 (m, 8H), 1.96−1.80 (m, 24H). However, the integration was not perfect: MS MALDI TOF CHCA (α-cyano-4-hydroxycinamic acid) 411.3, 412.3, 413.3, 547.3, 548.3, 549.3, 684.4, and 685.3. This compound was not very pure. It contained some bishydrazine **6** and some tetrakishydrazine according to the mass spectrum.

Solvents. The CH_2Cl_2 and CH_3CN used in this work were purified by the methods in Perrin and Armarego.[24]

Acknowledgment. We thank the National Science Foundation for partial support of this work under Grants CHE-0204197 and CHE-0647719.

Supporting Information Available: ^{1}H and ^{13}C NMR spectra of the compounds shown in Schemes 3 and 4, and of compounds **4**, **6**, and a sample rich in **7**, *xyz* coordinates for calculated structures. X-ray data for **23**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(23) Goanvic, D. L.; Tius, M. A. *J. Org. Chem.* **2006**, *71*, 7800–7804.

(24) Perrin, D. D.; Armarego, W. L. F. *Purification of Laboratory Chemicals*, 2nd ed.; Pergamon Press: New York, 1981.