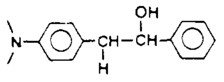
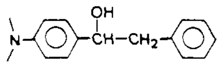
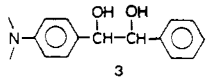
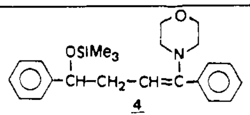
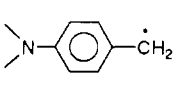
Table I

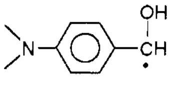
Donor	Acceptor	Solvent	Products (quantum yield)[a]				k_q ($M^{-1}s^{-1}$)[b]
			ØCHO	NØCH$_3$	N-Ø-⟍_Ø	H_2A or ·HA	
 1	Tl	benzene	4.85 X 10^{-3}	3.73 X 10^{-3}		1.4 X 10^{-4}	1.3 X 10^{10}
	Tl	CH_3CN	7.73 X 10^{-4}	9.96 X 10^{-5}	6.72 X 10^{-4}	1.1 X 10^{-4}	
	ß-Lap	benzene	0.764	0.669	0.095	0.283	
			NØC(=O)-CH$_2$Ø			H_2A or ·HA	
 2	Tl	benzene	5.88 X 10^{-4}	+ other products		5.28 X 10^{-4}	4.2 X 10^{9}
	Tl	CH_3CN	1.12 X 10^{-4}			4.59 X 10^{-4}	
	ß-Lap	benzene	0.029			0.027	
			ØCHO	NØCHO			
 3	Tl	benzene	1.2 X 10^{-3}	0.7 X 10^{-3}		1.2 X 10^{-3}	5.3 X 10^{9}
	Tl	CH_3CN	6.2 X 10^{-4}	4.8 X 10^{-4}		4.7 X 10^{-4}	
	ß-Lap	benzene	0.25	0.22		0.35	
			ØCHO				
 4	Tl	benzene	0.063			2.0 X 10^{-4}	2.7 X 10^{9}
	Tl	CH_3CN	0.021			7.7 X 10^{-5}	

[a] Samples were vacuum degassed through several freeze-pump-thaw cycles. Quantitative measurement of products formed from donors were obtained from HPLC analysis. The reduction products from the electron acceptors were determined by monitoring the absorbance change during irradiation. Incident light intensities were measured by Ferrioxatate actinometry. [b] Quenching experiments were performed in benzene solvent with Tl as electron acceptor, and samples were degassed by bubbling with argon for 30 min through a serum cap prior to each measurement.

the two radicals formed in the acceptor amine-radical mediated cleavage from **1** and **3**, **5**, and **6**, respectively. While **6** should


5

and


6

be an excellent electron or H-atom donor, readily oxidized to the corresponding aldehyde, **5** should undergo preferential reduction or dimerization. Although the dimer of **5** has not been detected, the presence of substantial amounts of reduced acceptor suggests that some non-redox routes for consumption of **5** are operative.

To further test the possibility that vinylogous diheteroatom-substituted molecules can undergo oxidative photofragmentation as a general process, amino silyl ether **4** was studied under irradiation in solution with Tl (the corresponding alcohol has not proved isolable). Although **4** is stable and unreactive in the dark, irradiation of Tl in solutions containing **4** in degassed acetonitrile or benzene leads to rapid and relatively efficient formation of benzaldehyde as the major product. Here again, quenching of the excited acceptor most likely involves single-electron transfer from the "donor" enamine center, in this case followed by fragmentation to give the neutral allylic radical $CH_2{=}C\dot{H}C(Ph)\text{-}\overline{N(CH_2)_2OCH_2CH_2}$, benzaldehyde, and silylcation.[22] The relatively low yields of reduced Tl for reaction of **4** compared to fragmentation indicate a largely "catalytic" role of the light-absorbing acceptor in this case. Recent results[2-4] demonstrating parallel reactivity for aminoalcohols, 1,2-diamines, and aminothiols suggest that many additional examples of electron-transfer-induced photofragmentation may be possible for other diheteroatom-substituted organics.

Acknowledgment. We are grateful to the U.S. Department of Energy (Grant DE-FG02-86ER13504) for support of this research.

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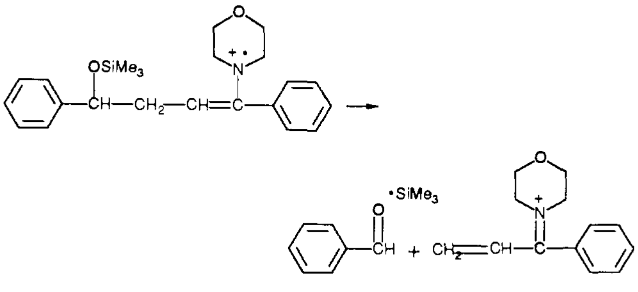
[22] An alternative possibility is that cleavage to generate a silyl radical occurs:



We thank a referee for pointing this out.

Long-Range Electron Transfer in a Cytochrome c Derivative Containing a Covalently Attached Cobalt-Cage Complex

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Received September 2, 1988

Much emphasis has been placed recently on understanding the factors that control the rates of long-range (>10 Å) electron transfer in biological systems.[2,3] We have chosen to focus specifically on the relationship between the rate of intramolecular electron transfer and the distance between redox sites. This may be accomplished through the use of covalently modified proteins in which intramolecular rates of electron transfer between two fixed metal sites, separated by a known distance, can be measured. These protein derivatives can be prepared through modification of specific sites on structurally characterized redox proteins with inorganic probes. Using horse heart cytochrome *c* as a molecular

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[1] Present address: Department of Chemistry, University of Georgia, Athens, GA 30602.

[2] McLendon, G. *Acc. Chem. Res.* **1988**, *21*, 160-167.

[3] Scott, R. A.; Mauk, A. G.; Gray, H. B. *J. Chem. Educ.* **1985**, *62*, 932-938.

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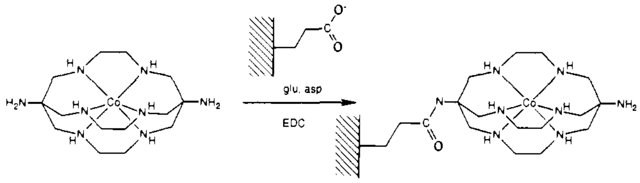
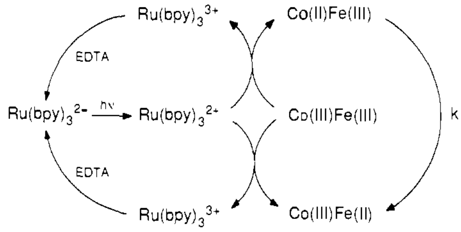
Scheme I



Scheme II



framework, we have covalently attached the macrocyclic cage complex $[Co(diAMsar)]^{3+}$ first prepared by Sargeson et al.[4] to several acidic residues of the protein.

The attachment procedure utilized was the familiar carbodiimide-assisted coupling reaction first applied to protein systems by Hoare and Koshland as a method of carboxylate quantitation.[5] The carbodiimide activates the carboxylate group toward nucleophilic attack by an amine group. Using the water-soluble 1-ethyl-3-[3-(dimethylamino)propyl]carbodiimide (EDC), we were able to promote the condensation of carboxylates provided by the protein with pendant amine groups furnished by the cobalt complex, providing a stable amide-bond linkage (Scheme I). Horse heart cytochrome *c* contains 13 carboxylate groups which reside primarily on the protein surface and hence are available for reaction. The above reaction procedure resulted in the preparation of seven unique singly modified derivatives. The purified cobalt-containing proteins were found to contain one cobalt atom per heme group based on inductively coupled plasma atomic absorption and UV–vis spectroscopy. Circular dichroism spectroscopy indicated that insignificant tertiary structural changes occur upon surface [Co(diAMsar)] attachment. The modification site for each species was determined by tryptic-peptide mapping, peptide sequencing, and mass spectrometry (FAB MS/MS). Details of the preparation and characterization of the [Co(diAMsar)]-modified cytochromes *c* are available in Supplementary Material.

Preliminary molecular modelling studies show that the resulting heme edge-to-cobalt complex distances in these seven derivatives span from 10 to 20 Å and provide a suitable system for evaluating the distance dependence of electron-transfer rates. Although a large inner-sphere reorganizational energy is expected for the [Co(diAMsar)] due to the large changes in equilibrium Co–N bond lengths between Co(III) and Co(II) complexes,[6] this effect should be partially offset by the large driving force for the reaction. The reduction potential for the attached complex [$E^{0\prime}$, Co(III)/Co(II)] is –0.56 V vs SCE, while the heme *c* potential [$E^{0\prime}$, Fe(III)/Fe(II)] is +0.02 V. Here we report experiments that demonstrate that intramolecular electron transfer from Co(II) to Fe(III) in the thermodynamically unstable mixed-valence state of one of these derivatives takes place at a measurable rate over a distance of ~15 Å.

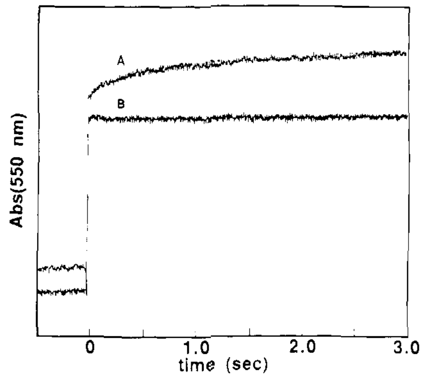


Figure 1. The time dependence of the absorbance at 550 nm (due to cytochrome *c* heme Fe(II)) of a solution of the [Co(diAMsar)]-modified cytochrome *c* (modified at either Glu-66 or Glu-69) (A) or native cytochrome *c* (B) after flash photolysis (at $t = 0$) in the presence of $[Ru(bpy)_3]^{2+}$. The solution in a 1-cm pathlength cell contained an anaerobic solution of 10 μM cytochrome *c* derivative, 65 μM $[Ru(bpy)_3]Cl_2$, and 6 mM Na_2H_2EDTA in 0.1 M sodium phosphate buffer, pH 7.0.

The long-lived excited state of $Ru(bpy)_3^{2+}$ (bpy = 2,2′-bipyridine), which has been shown to reduce $[Co(diAMsar)]Cl_3$[7] and both the heme *c* and surface $Ru(II)(NH_3)_5$His-33 moiety of a modified ferricytochrome *c*,[8] was used as a photoreductant in flash-photolysis experiments to measure the Co(II) → Fe(III) intramolecular electron-transfer rate in one of the [Co(diAMsar)]-cytochrome *c* derivatives (Scheme II). This derivative was shown to have a modified T-11 fragment (residues 61–72) in the tryptic peptide map, for which sequencing identified either Glu-66 or Glu-69 as the site of [Co(diAMsar)] attachment.[9] This places the attached [Co(diAMsar)] at 14–15 Å from the nearest heme pyrrole edge. Figure 1 compares the transient absorbance change at 550 nm of a deaerated solution of $Ru(bpy)_3^{2+}$ with either native cytochrome *c* or the [Co(diAMsar)]-modified cytochrome *c* immediately after the flash. In both solutions, there is an instantaneous increase in absorbance at 550 nm indicative of heme reduced directly by $Ru(bpy)_3^{2+*}$. Once produced, this species is stable over the time period of the experiment. With the [Co(diAMsar)]-modified protein, however, there is a subsequent slower production of reduced heme not seen with the native protein. Variation in protein concentration from 10 to 20 μM does not affect the rate of this process, within experimental error. This slower reduction phase can be attributed to intramolecular electron-transfer Co(II)/Fe(III) → Co(III)/Fe(II) (see Scheme II), and an exponential fit of the data gives a k_{et} of 2.8 ± 0.3 s^{-1} at 25 °C.

To put this result into context with other recent work in this area, we have attempted to compare our rate constant with distance-dependent electron-transfer rates measured by Axup et al. for $(NH_3)_5$Ru-modified Zn-substituted myoglobin (Mb) derivatives[10] by correcting our rate constant for differences in the reorganizational energy and driving force between the two systems. We assume that k_{et} can be expressed as a function of separation distance (r) by[11]

$$k_{et}(r) = \nu \exp[-\beta(r - r_0)] \exp[-(\lambda + \Delta G^0)^2/4\lambda RT]\ \mathrm{s}^{-1} \qquad (1)$$

In this expression, ν is the frequency factor (assumed as $10^{10}\ s^{-1}$ [12]), r_0 is the edge–edge site separation at van der Waals contact (assumed as 3 Å[11]), λ is the vertical reorganizational energy,[11] and ΔG^0 ($= -nF\Delta E^0$) is the driving force for the electron transfer. For the (Ru,Zn)Mb system, $\Delta E^0 \approx +0.8$ V,[10] and the distance dependence (eq 3 of ref 10) allows calculation of $\lambda \approx 1.4$ eV. In our [Co(diAMsar)]-cyt *c* derivatives, $\Delta E^0 \approx 0.58$ V, and λ is

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(4) Geue, R. J.; Hambley, T. W.; Harrowfield, J. M.; Sargeson, A. M.; Snow, M. R. *J. Am. Chem. Soc.* **1984**, *106*, 5478–5488.

(5) Hoare, D. G.; Koshland, D. E. *J. Am. Chem. Soc.* **1966**, *88*, 2057–5058.

(6) For example, the difference in Co–N bond lengths for Co(sepulchrate)$^{2+/3+}$ is 0.174 Å: Creaser, I. I.; Harrowfield, J. MacB.; Herlt, A. J.; Sargeson, A. M.; Springborg, J.; Geue, R. J.; Snow, M. R. *J. Am. Chem. Soc.* **1977**, *99*, 3181–3182. Creaser, I. I.; Geue, R. J.; Harrowfield, J. MacB.; Herlt, A. J.; Sargeson, A. M.; Snow, M. R.; Springborg, J. *J. Am. Chem. Soc.* **1982**, *104*, 6016–6025.

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(8) Winkler, J. R.; Nocera, D. G.; Yocom, K. M.; Bordignon, E.; Gray, H. B. *J. Am. Chem. Soc.* **1982**, *104*, 5798–5800.

(9) Conrad, D. W.; Scott, R. A., manuscript in preparation.

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(11) Marcus, R. A.; Sutin, N. *Biochim. Biophys. Acta* **1985**, *811*, 265–322.

estimated as ~2.1 eV.[13] Given these values, $k_{et}^{corr} = 8.3 \times 10^3$ s^{-1} is the rate that would have been observed for the [Co(diAMsar)]-cyt *c* derivative if the driving force and reorganizational energy for the (Ru,Zn)Mb system were applicable. This may be compared to a rate predicted by the observed distance dependence[10] of 2.2×10^4 s^{-1} at $r = 14.5$ Å. The agreement between observed and predicted rates suggests that the simple treatment of driving force and reorganizational energy effects[11] on the rate has validity for a range of modified protein systems.

Acknowledgment. We thank Larry Faulkner for the use of instrumentation, for helpful discussions concerning the electrochemical and photochemical experiments, and for partial financial support from National Science Foundation Grant CHE86-07984. The flash photolysis experiments were carried out in the laboratory of Professor T. L. Brown. D.W.C. acknowledges a graduate fellowship from The Electrochemical Society. This research was supported by a National Science Foundation Presidential Young Investigator Award (CHE87-14889) to R.A.S.

Supplementary Material Available: Experimental details of the preparation and characterization of the [Co(diAMsar)]-cytochrome *c* derivatives (5 pages). Ordering information is given on any current masthead page.

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(12) McLendon, G., personal communication.

(13) On the basis of a calculation for $[Co(NH_3)_6]^{2+/3+}$[14] and a Co–N bond length change of 0.174 Å,[8] we estimate $\lambda_{in} = 184$ kJ-mol^{-1} for $[Co(diAMsar)]^{2+/3+}$ self-exchange. Assuming $\lambda_{out} = 117$ kJ-mol^{-1} as for $[Co(NH_3)_6]^{2+/3+}$[14] and $\lambda \approx 100$ kJ-mol^{-1} for cytochrome $c^{2+/3+}$ self-exchange[11] gives $\lambda \approx 200$ kJ-mol^{-1} (2.1 eV) for the [Co(diAMsar)]-cytochrome *c* electron transfer. An alternative calculation using the measured self-exchange rate of $[Co(diAMsar)]^{2+/3+}$ (0.50 $M^{-1}s^{-1}$) yields $\lambda = 304$ kJ-mol^{-1} (3.1 eV) for $[Co(diAMsar)]^{2+/3+}$ self-exchange and also yields $\lambda = 200$ kJ-mol^{-1} (2.1 eV) for the [Co(diAMsar)]-cytochrome *c* reaction. (As with the (Ru,Zn)Mb analysis, we have not included the distance-dependent λ_{out} contribution pointed out by Isied et al.[15])

(14) Siders, P.; Marcus, R. A. *J. Am. Chem. Soc.* **1981**, *103*, 741–747.

(15) Isied, S. S.; Vassilian, A.; Wishart, J. F.; Creutz, C.; Schwarz, H. A.; Sutin, N. *J. Am. Chem. Soc.* **1988**, *110*, 635–637.

X-ray Crystal Structure and Hydrocarbon Solution Dynamics of Dimeric 1,1-Bis((dimethylamino)methyl)-2-propyllithium

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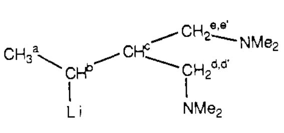
Received September 20, 1988

All dimeric alkyllithiums studied so far were found to be more reactive than their tetrameric counterparts.[1-3] While various reasons have been invoked for this,[2a,3] any sound understanding of the properties of alkyllithium dimers requires detailed knowledge of structure and bonding of these species.[4]

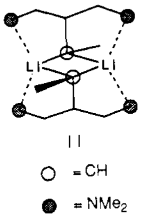
We now report that crystals obtained from pentane solutions of 1,1-bis((dimethylamino)methyl)-2-propyllithium (I) yielded the first X-ray data for a dimeric alkyllithium. Also reported are the dynamics of $(I)_2$ in hydrocarbon solutions.

Table I. Interatomic Distances [Å]

	α-C–Li	α-C–Li′	Li–Li′	Li–N	Li–N′
$(I)_2$	2.19	2.21	2.40	2.09	2.15
III	2.20	2.24	2.39	2.16	2.16
$(IV)_4$ (≡V)	2.27	2.28	2.48, 2.54	2.07	
VI	2.29	2.25, 2.31	2.49, 2.56	2.01	



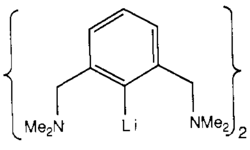
I



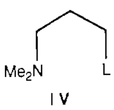
II

I was obtained by treatment of *tert*-butyl[1,1-bis((dimethylamino)methyl)-2-propyl]mercury with 1 equiv of *t*-BuLi in *n*-pentane at −15 °C. After removing volatile materials (pentane, $(t\text{-}Bu)_2Hg$) by bulb-to-bulb distillation (room temperature, 10^{-5} Torr), I was extracted from the residue with pentane and purified by repeated crystallization from pentane to yield colorless crystals subliming (10^{-5} Torr) around 80 °C.[5]

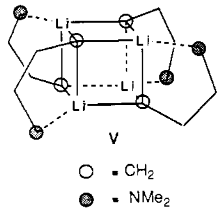
X-ray analysis indicated the crystals to consist of dimeric units II as shown in detail in Figure 1 and located at C_i symmetry sites in the unit cell.[6] In this structure, the two lithium atoms are bridged by the two α-carbons, and their coordination spheres are completed by the intramolecularly coordinated dimethylamino groups. The interatomic distances between Li and α-C and N, respectively, of $(I)_2$ (≡II) and those of III[7] and the related tetramers $(IV)_4$ (≡V)[8] and VI[9] containing only one intramolecularly coordinated dimethylamino group per lithium are given in Table I. The interatomic distances are almost identical in $(I)_2$ and III. It is interesting to notice the larger α-C–Li and Li–Li interatomic distances in the tetramers $(IV)_4$ (≡V) and VI. Although dimers so far were found to be more reactive than tetramers, they may have tighter carbon–lithium bonds, as suggested by the present



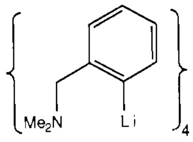
III



IV



V



VI

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(1) Glaze, W. H.; Freeman, C. H. *J. Am. Chem. Soc.* **1969**, *91*, 7198.

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(3) Vos, M.; de Kanter, F. J. J.; Schakel, M.; van Eikema Hommes, N. J. R.; Klumpp, G. W. *J. Am. Chem. Soc.* **1987**, *109*, 2187.

(4) Crystal structures of dimers of other types of organolithiums: Schleyer, P. v. R.; Setzer, W. N. *Adv. Organomet. Chem.* **1985**, *24*, 353.

(5) A considerable amount of decomposition was observed.

(6) Crystal data are as follows: $(C_9H_{21}N_2Li)_2$, monoclinic, dimensions: 0.25 × 0.25 × 1.75 mm, space group $P2_1/n$, $a = 7.778$ (1) Å, $b = 15.647$ (1) Å, $c = 9.367$ (3) Å, $\beta = 94.43$ (2)°, $Z = 2$, $F_{000} = 368$, $D_{calcd} = 0.959$ g·cm^{-3}, μ(Cu Kα) = 3.9 cm^{-1}. Data collected on an Enraf-Nonius CAD4 [Nickel filtered Cu Kα radiation, $\lambda = 1.5418$ Å, $\sin \theta_{max}/\lambda = 0.609$; $\pm h,\pm k,-l$; 4612 reflections; $\omega/2\theta$ scan]. The structure was solved by direct methods (SHELXS 86) and refined on F (SHELX 76) to a final $R(R_w) = 0.048$ (0.041) for 1560 reflections with $I > 2.5\sigma(I)$; $w = {}^1/\sigma^2(F)$. All positional parameters, anisotropic thermal parameters for the non-H atoms, and isotropic thermal parameters for the H-atoms were refined. A final difference map showed no residual density outside 0.21 and −0.11 e·Å^{-3}.

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