was not found to be enhanced by a lack of solvation of the binding cleft. In fact, interactions between chloroform and the anthracene plates of the tweezers lead to strong binding of chloroform in the cleft. For the acid tweezer, the differential favoring binding 9-Me-A over chloroform is enough to enable the displacement of the solvent. However, the differential is not enough in the case of the ester tweezer to allow 9-Me-A to replace the one to two chloroform molecules in the cleft.

On the technical side, the present results have demonstrated the value of the double-annihilation route to computing absolute free energies of binding.[23] This is an important development for facilitating direct comparisons between theory and experiment in host-guest chemistry. The benefit for precision of using double-wide sampling[26] as opposed to performing all of the perturbations in one direction has also been documented. Care must still be exercised in keeping the perturbation steps small to avoid degradation of precision. As noted previously,[20] this concern is amplified in a more cohesive and structured solvent such as water in comparison to most organic solvents including chloroform. Though the computational effort is currently large, continuing enhancements in computational resources will make calculation of free energies of binding in solution routine.

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Supplementary Material Available: Complete specifications of the geometries of 9-methyladenine, **6**, and **7** in Z-matrix format (5 pages). Ordering information is given on any current masthead page.

Electron Transfer across Polypeptides. 6. Long-Range Electron Transfer in Osmium-Ruthenium Binuclear Complexes Bridged with Oligoproline Peptides

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Abstract: A series of binuclear $[(NH_3)_5Os(Pro)_nCo(NH_3)_5](CF_3COO)_5$ (n = 0-4) complexes have been synthesized. Long range intramolecular electron transfer reactions in these polypeptides were studied by the formation of the $Os^{II}(Pro)_nisoRu^{III}$ precursor complexes by using reducing radicals (ca. CO_2^- and e_{aq}) generated by pulse radiolysis techniques. For the n = 0 complex, the intramolecular electron-transfer rate was very fast, and only a lower limit of 5×10^9 s^{-1} could be estimated at 25 °C. For the n = 1-3 complexes, the rates and activation parameters for electron transfer were determined to be 3.1×10^6 s^{-1}, $\Delta H^* = 4.2$ kcal/mol, $\Delta S^* = -15$ eu/mol; 3.7×10^4 s^{-1}, $\Delta H^* = 5.9$ kcal/mol, $\Delta S^* = -19$ eu/mol; 3.2×10^2 s^{-1}, $\Delta H^* = 7.4$ kcal/mol, and $\Delta S^* = -23$ eu/mol, respectively. For n = 4, only a rate constant of 50 s^{-1} at 25 °C was observed. By using a rearranged form of the transition-state expression, a plot of $\ln k + \Delta H^*/RT$ vs distance can be used to separate the electronic factor from the nuclear reorganization factor for these electron-transfer reactions. This analysis yielded a slope for the electronic factor $\beta = 0.65$ Å^{-1}. The results of the experiments presented here show that rapid rates of electron transfer across polypeptides can be observed for a metal-to-metal separation of >20 Å even for a low driving force for the reaction ($\Delta E° = 0.25$ eV). These results can be used to predict fast rates of electron transfer (ca. in the millisecond time scale) across metal-to-metal distances of 40 Å if the driving force and reorganization energy are appropriately controlled.

Introduction

Rates of electron-transfer (ET) reactions can vary by more than 18 orders of magnitude, ranging in time scale from subpicoseconds to many hours and days. Understanding the mechanism of these ET processes requires a detailed study of the factors that influence their rates.[1,2] These factors include distance, reorganization energy, driving force, and the electronic structure of the donor and acceptor as well as the bridging ligand that connects them. Recent studies have focused on *intra*molecular ET reactions where the electron-transfer step in a donor-acceptor complex occurs without complications from diffusion and other molecular interactions. In such molecules, systematic variations in the factors controlling the rates can be studied.

One of the important factors that control the rate of these reactions is the distance between the donor and the acceptor. In most cases studied, the rate of the intramolecular ET reactions was shown to decrease as the distance between the donor and acceptor increases; however, the magnitude of this decrease varied with the nature of the donor-acceptor molecules studied.[1-10] To investigate the effect of distance on intramolecular ET under controlled conditions, we and other groups have designed binuclear

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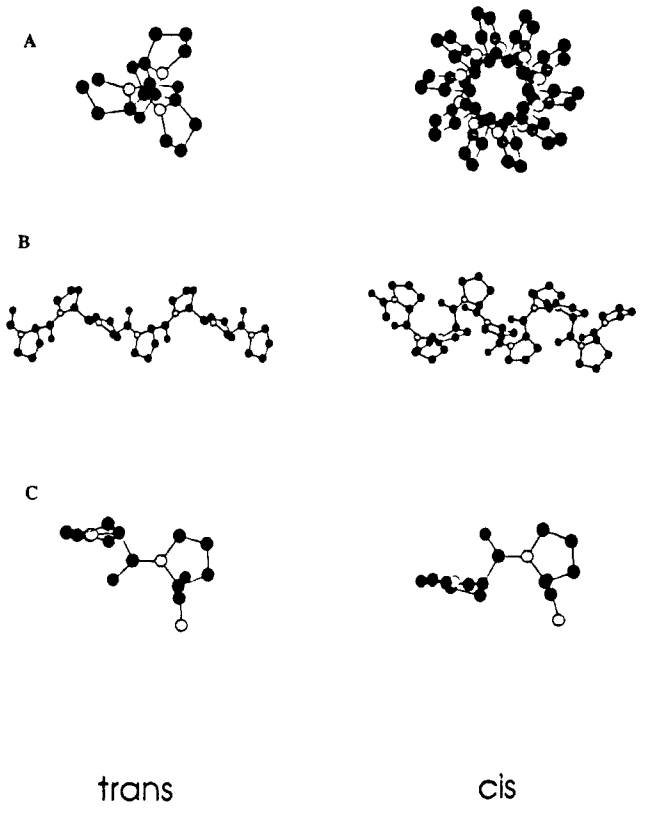

Figure 1. (A) Structures of *trans*-polyproline (II) and *cis*-polyproline (I) determined from fiber X-ray diffraction (ref 21) viewed along the helical axis. (B) Structures of *trans*- and *cis*-prolylproline shown in the extended form by rotating part A by 90°. (C) Structures of *trans*- and *cis*-prolylproline showing the 180° rotation around the peptide bond. Open circles are oxygen atoms, closed circles are carbon atoms, and small closed circles are carbonyl oxygen atoms.

ET complexes where the donor and acceptor sites are covalently attached and are held apart by rigid chemical bridges.[1-11] Earlier studies from this group[11] have centered on metal-to-metal intramolecular electron transfer across oligoproline peptides. The oligoproline peptides (Figure 1A,B) proved to be reasonably rigid molecules for studying long-range intramolecular electron transfer as a function of distance between a donor and acceptor.

The structural rigidity of proline oligomers in comparison to other naturally occurring amino acids is due mainly to the cyclic structure of the proline ring. The five-membered ring of the proline side chain restricts rotation around the peptide bond, resulting in cis–trans conformational isomerism[12-18] as shown in Figure 1C. Polyproline bridges have been used as rigid chemical spacers in early studies of energy transfer between organic donors and acceptors.[19] In polar solvents the efficiency of energy transfer was found to follow the r^{-6} distance dependence for weak dipolar energy transfer.[20] The results of these energy-transfer studies show that polyproline can be used as a spectroscopic ruler in the 10–60-Å range.[19]

Fibers of polyproline crystallized from aqueous solution possess an all-trans conformation (>95% trans). When the same polyproline is crystallized from solvents of lower polarity, especially aliphatic alcohols, fibers of the cis isomer are obtained instead. Figure 1A,B shows the fiber structures of *cis*- and *trans*-polyproline.[21] X-ray diffraction analysis of poly-*l*-proline fibers shows clear structural differences between the cis and trans forms. As can be seen in Figure 1B both proline oligomers are helical in structure with different unit cell properties. *trans*-Polyproline makes a left-handed helical cycle every three residues with a 3.12-Å translation per residue along the helical axis. In the cis isomer a right-handed helical turn consists of $3\text{-}^1/_3$ proline units with 1.85-Å translation per residue. One of the interesting features of the fiber structure of these two proline isomers (Figure 1A) is that the trans isomer possesses an extended structure where polar solvents can hydrate the peptide bonds and stabilize the open structure. In less polar media the cis conformation is more compact and is stabilized when the polymer turns the hydrocarbon part of the proline residue to the weakly polar solvents. The conversion between *trans*- and *cis*-prolylproline isomers (Figure 1A) occurs with a half-life of approximately 1–2 min at room temperature[22] ($\Delta H^{\ddagger} \sim 20$ kcal mol^{-1}, $\Delta S^{\ddagger} \sim 0$). These rates and activation parameters refer to a single peptide residue; for high molecular weight oligomers several hours are required to complete this isomerization. The interconversion between the trans and cis isomers is known to be one of the slowest processes controlling conformational changes in peptides and proteins.[23] This study was carried out in aqueous acidic media, conditions under which the all trans conformation of the proline oligomers is known to predominante (>95%).[24-26]

In previous reports in this series, two different series of molecules, $[(NH_3)_5OsLCo(NH_3)_5]^{5+}$ (Os–L–Co)[11c] and $[(OH_2)(NH_3)_4RuLCo(NH_3)_5]^{5+}$ (Ru–L–Co),[11b] L = iso(Pro)$_n$, n = 0–4, were synthesized with the same cobalt(III) acceptor. In the first series the strongly reducing $[(NH_3)_5Os^{II}iso]$ group was the donor, and in the second series the more moderately reducing $[(OH_2)(NH_3)_4Ru^{II}iso]$ group was the donor. Comparison of intramolecular electron-transfer rate constants for these two similar series of complexes (Os–L–Co and Ru–L–Co) showed that the difference between their electron-transfer properties is reflected in the difference in driving force as well as in the conformational changes of the polyproline bridging ligand occurring on the time scale of the intramolecular electron-transfer reaction.[11] The electron-transfer reaction in the Os–L–Co series was faster than the corresponding Ru–L–Co molecules, permitting observation over a broader range of intramolecular electron-transfer rates before conformational changes affect the observed rates. This is especially true for n = 0–2 in Os–L–Co, L = iso(Pro)$_n$, where the rates decreased from the microseconds to the seconds time scale. Beyond n = 2, the Os–L–Co series and the Ru–L–Co series did not exhibit the expected decrease in rate with increasing number of proline residues. To explain this anomaly, we argued that when the time scale for electron transfer approaches that of proline isomerization, intramolecular electron transfer occurs across an ensemble of shorter internuclear distances rather than across the extended distance of the rigid all-trans isomer. Consistent with this, in the n = 3,4 proline complexes of the Os–L–Co and the Ru–L–Co series, a range of electron-transfer rates is observed representing different proline conformers with varying distances between the metal centers.

An important question not yet fully explored for these proline oligomers is how the rates of intramolecular electron transfer vary

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at still longer distances ($n \geq 3$) in the absence of conformational changes. In order to address this question, one can increase the driving force and/or decrease the reorganizational energy. The decrease in the reorganizational energy is achieved in this study by synthesizing a series of complexes where the $[(NH_3)_5Co^{III}-]$ group was replaced with the $[(NH_3)_5Ru^{III}-]$ group, a similar acceptor group with significantly lower inner-sphere reorganization energy and therefore lower barrier to electron transfer.[1] The attractive feature of this new series of molecules, $[(NH_3)_5OsLRu(NH_3)_5]^{5+}$, (Os-L-Ru), L = iso(Pro)$_n$, is that electron transfer is expected to proceed at significantly faster rates than the two series investigated previously. This should allow one to study intramolecular rates at long distances (e.g., for n = 3 and 4 prolines), prior to the time scale of proline isomerization. The use of a ruthenium(III) acceptor, for which the redox potential can be determined directly, also results in a more accurately defined driving force for the electron-transfer reaction than in the Os-L-Co and the Ru-L-Co series since the cobalt(II/III) potential has only been indirectly estimated.[11b,28] This Os-L-Ru series is homologous to the series studied earlier and can be directly compared to the earlier studies.

In this paper we report the synthesis and electron-transfer properties of a series of $[(NH_3)_5OsLRu(NH_3)_5](TFA)_5$ complexes where L = iso(Pro)$_n$, n = 0–4. Evidence for the solution structure of *trans*-polyproline from ^{13}C and ^1H NMR will be presented. The distance dependence and the temperature dependence of the intramolecular electron-transfer rates at different distances will be analyzed.

Experimental Section

I. Synthesis of $[(NH_3)_5OsLCo(NH_3)_5](BF_4)_5 \cdot xH_2O$, L = iso(Pro)$_n$, n = 0–4, Iso = Isonicotinyl Group. These complexes were prepared by the method described in ref 11c.

II. Synthesis of $[(NH_3)_5OsL](TFA)_3$, iso(Pro)$_n$, n = 0–4. The osmium complexes were prepared by reduction of the $[(NH_3)_5OsLCo(NH_3)_5](BF_4)_5$, L = iso(Pro)$_n$, complexes in 0.1 M trifluoroacetic acid (HTFA) with Eu(II) ion according to eq 1:

$$[(NH_3)_5OsLCo(NH_3)_5]^{5+} \xrightarrow{Eu^{2+}/H^+} [(NH_3)_5OsLOH]^{3+} + Co^{2+} + 5NH_4^+ \quad (1)$$

A quantity (0.05 mmol) of the binuclear Os-L-Co complex was dissolved in 0.5 mL of water and degassed with argon for 30 min. To this solution was added dropwise from a gas-tight syringe 3 mL of a freshly prepared 0.02 M Eu^{2+} solution (prepared by reducing Eu^{3+} over zinc amalgam) until the reddish-pink color characteristic of the Os(II) isonicotinamide group[33] persisted. After 2 min air was bubbled through the solution to oxidize the Os(II) complex to Os(III), and the solution turned yellow. The reaction was then monitored by HPLC for the appearance of the mononuclear osmium(III) complex and/or the disappearance of the binuclear Os-L-Co complex. The solution was diluted with water (~10 mL) and applied to a small Chelex column (Bio Rad) (5 cm × 1.5 cm). The column was washed with ~100 mL of water. The yellow band was eluted with 0.3 M HTFA and concentrated to dryness by rotary evaporation. The resulting solid was redissolved in 5 mL of water and concentrated to dryness again to remove any residual HTFA. The compound was then dissolved in 0.5 mL of water and applied to a Biogel P-2 column (50 cm × 1 cm). The yellow band was collected and concentrated to dryness by rotary evaporation.

III. Synthesis of $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5](TFA)_5$, L = iso(Pro)$_n$, n = 0–4. The osmium–ruthenium binuclear complexes were prepared as shown by reaction 2:

$$[(NH_3)_5Ru^{III}(OH_2)]^{3+} + [(NH_3)_5Os^{III}LOH]^{3+} \xrightarrow{Ru(II)\ catalyst} [(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+} \quad (2)$$

where L = iso(Pro)$_n$.

Aquopentaammineruthenium(III) trifluoromethanesulfonate, $[(NH_3)_5Ru^{III}(OH_2)](TFMS)_3$, (0.02 mmol) and $[(NH_3)_5Os^{III}LOH](TFA)_3$, L = iso(Pro)$_n$, (0.04–0.06 mmol) were dissolved in 200 μL of water and degassed for 30 min. To this solution, 10 μL of a solution of $[(NH_3)_5Ru(OH_2)]^{2+}$ was added (20 mg of $[(NH_3)_5Ru(TFMS)](TFMS)_2$[41] in 150 μL of water, freshly reduced over Zn/Hg). The formation of the binuclear complex was monitored by HPLC. After 3–4 h, another 10 μL of $[(NH_3)_5Ru(OH_2)]^{2+}$ was added, and the reaction was continued overnight. The reaction was quenched by the addition of a few drops of acetonitrile to convert $[(NH_3)_5Ru(OH_2)]^{2+}$ to $[(NH_3)_5Ru(NCCH_3)]^{2+}$, followed by 0.5 mL of ethanol and 0.1 mL of 1 M trifluoroacetic acid. Addition of about 100 mL of diethyl ether to this solution resulted in the formation of a yellow precipitate, which was filtered and washed with ether. The crude binuclear product was purified from the mononuclear complex by using a reverse-phase C-18 silica gel column (30 cm × 1 cm). The binuclear complex was eluted with 0.1 M CH_3CN in 5×10^{-4} M HTFA containing 1.5% MeOH. The yellow band corresponding to the binuclear complex (as identified by HPLC) was collected and concentrated to dryness by rotary evaporation. To confirm the identity of the binuclear complex a small quantity of the solid was reduced over Zn(Hg) and reanalyzed on HPLC to show the disappearance of the binuclear complex and the reappearance of the mononuclear starting materials.

IV. Kinetics Experiments. The kinetics of intramolecular electron transfer in the complexes $[(NH_3)_5OsLRu(NH_3)_5]^{5+}$, where [L = iso(Pro)$_n$], n = 1–4, were determined by using 2 MeV electron pulse radiolysis techniques as described in ref 11c. The reactions were carried out in an acidic formate buffer (0.2 M sodium formate, 0.1 M HTFA) containing 0.1 M CH_3CN and monitored at λ = 525 and 505 nm. Solutions of the Os^{III}-L-Ru^{III} complexes ranging from 1×10^{-3}–2×10^{-6} M were used. Treatment of the kinetic data is described in ref 11c. For the $[(NH_3)_5Os\text{-iso}]^{3+}$ and the $[(NH_3)_5Os\text{-iso-}Ru(NH_3)_5]^{5+}$ species, the kinetics experiments were carried out in 2×10^{-3} M HTFA solutions containing 1 M CH_3CN and 1.0 M *tert*-butyl alcohol with 0.097 and 0.088 M of the complexes, respectively. For these complexes, the pulse radiolysis experiments were conducted at the 30 ps pulsewidth, 20 MeV linear accelerator facility at Argonne National Laboratory.[8] The reactions were monitored at λ = 530 and 650 nm.

The enthalpy and entropy of activation for the rates of intramolecular electron transfer were determined by using the following equation

$$k = k_B T/h \exp(-\Delta H^*/RT) \exp(\Delta S^*/R) \quad (3)$$

V. Electrochemical Experiments. The reduction potentials for the Os-L-Ru complexes were determined by differential pulse polarography on the $[(NH_3)_5Os\text{-L-}Ru(NH_3)_5]^{5+}$ complexes by using a glassy carbon electrode in 0.1 M HTFA with 0.1 M CH_3CN added to prevent catalytic decomposition of the binuclear complexes.[30]

VI. Proton and ^{13}C NMR Experiments. The proton and ^{13}C NMR experiments were recorded on a Varian XL-400 MHz NMR spectrometer. The concentration of $[(NH_3)_5Co(Pro)_n]$, n = 1–4, complexes was usually 2–3 mM in 0.01 M DCl. The ^{13}C spectra were obtained by using the standard ^{13}C pulse sequence (see Varian XL-400 instrument manual version 1986) on the instrument operating at 100.751 MHz for the ^{13}C nucleus. The ^{13}C NMR experiments were performed at 6 °C, with a sweep width of 20 000 Hz, an average of 40 000–50 000 transients requiring 8–11 h of acquisition, and a pulse width of 8 μs. The ^{13}C spectra were run by using dioxane as a reference (δ = 67.4 ppm from TMS, all peaks have been converted to the TMS scale).

For the $[(NH_3)Co(Pro)_n]^{3+}$ complexes, the amount of cis isomer in these predominantly trans structures was determined by measuring the relative peak heights of the C^β and C^γ proline ring resonances, which are

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Table I. Reduction Potentials of the $[(NH_3)_5Os^{III}iso(Pro)_nRu^{III}(NH_3)_5]^{5+}$, n = 1–4, Series

n	$Os^{II/III}$, V vs NHE	$Ru^{II/III}$,[a] V vs NHE
0	−0.24	−0.04
1	−0.30	−0.05
2	−0.30	−0.04
3	−0.30	−0.04
4	−0.30	−0.05

[a] Interference from the $RuOH_2$ form generated during the reduction process introduced a ~20 mV error in the RuII/III potential.

well separated in the cis and trans isomers by ~2–3 ppm. To calculate the percent trans conformer from the ^{13}C NMR spectra, the areas of the amino terminal C^{β} and C^{γ} were subtracted from the area of the trans C^{β} and C^{γ} peak, because the β carbon (or δ carbon) of the amino terminal proline has no conformational isomers and is located in the same region.[18]

Results

Synthesis and Characterization of the Complexes. The binuclear complexes $[(NH_3)_5OsLRu(NH_3)_5](TFA)_5$, where L = iso(Pro)$_n$, n = 0–4, were synthesized by the reaction of $[(NH_3)_5RuOH_2]^{3+}$ with $[(NH_3)_5OsLOH]^{3+}$ in the presence of a catalytic amount of $[(NH_3)_5RuOH_2]^{2+}$ in aqueous acidic solution. After precipitation and chromatographic purification, the complexes were characterized by a number of physicochemical techniques. The HPLC elution behavior of the osmium peptide complexes and the osmium peptide ruthenium complexes was used to monitor the progress of the reaction and also as a criterion of purity. Figure 2 shows the elution profile of the Os–L–Ru complexes, $[(NH_3)_5RuOH_2]^{3+}$, and the Os–peptide complexes obtained at various stages of the formation of the binuclear complexes. Figure 2B shows the elution profile of the mononuclear starting materials. Figure 2C shows the pure Os–L–Ru binuclear complex after chromatographic purification. Chemical reduction of the Os–L–Ru complexes with Eu^{2+} resulted in the recovery of the mononuclear starting materials as in Figure 2A.

The spectra of $[(NH_3)_5OsLRu(NH_3)_5]^{5+}$, L = iso(Pro)$_n$, n = 0–4, in 0.1 M HTFA are dominated by the charge-transfer bands of the Os^{III}–iso chromophore with two shoulders around 400 and 330 nm and two bands around 292 and 242 nm. The spectra of the corresponding $[(NH_3)_5OsL]^{3+}$ complexes in 0.1 M HTFA show two shoulders at 400 and 330 nm and two shoulders at 289 and 245 nm.

The reduction potentials of the $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+}$, L = iso(Pro)$_n$, n = 0–4, complexes (Table I) were determined by differential pulse polarography at a glassy carbon electrode in 0.1 M HTFA solution containing one drop of CH_3CN. The osmium and ruthenium reduction potentials are approximately constant throughout the series with two reduction waves separated by approximately 0.25 V. Figure 3 shows a differential pulse polarogram for $[(NH_3)_5Osiso(Pro)_3Ru(NH_3)_5]^{5+}$.

Electron-Transfer Reactions of the Os^{II}L–Ru^{III} Complexes. The intramolecular electron-transfer reaction studied in which an electron is transferred from an Os(II) to Ru(III) is shown in eq 4.

$$[(NH_3)_5Os^{II}LRu^{III}(NH_3)_5]^{4+} \xrightarrow{k_{et}} [(NH_3)_5Os^{III}LRu^{II}(NH_3)_5]^{4+} \quad (4)$$

Aquation of the Ru(II)–carboxylate bond in the Os^{III}–L–Ru^{II} product complex occurs on a time scale of 50–100 ms.[31] The reverse reaction can be neglected because it is thermodynamically unfavorable by 0.25 eV. The $[(NH_3)_5RuOH_2]^{2+}$ generated by this aquation reaction can reductively catalyze further aquation of ruthenium from Os^{III}–L–Ru^{III}, resulting in decomposition to the mononuclear constituents $[(NH_3)_5OsL]^{3+}$ and $[(NH_3)_5RuOH_2]^{3+}$. This process was inhibited by adding 0.1 M CH_3CN to the reaction medium.

The products of the electron-transfer kinetics were verified quantitatively by HPLC to be $[(NH_3)_5RuOH_2]^{2+}$ and the corresponding mononuclear Os–peptide complex (i.e., the starting materials). Figure 2F shows the HPLC for the Eu^{2+} reduction of the n = 4 complex.

Table II. Temperature Dependence of Intramolecular Electron-Transfer Rate Constants for the Series, $[(NH_3)_5Os^{II}iso(Pro)_nRu^{III}(NH_3)_5]^{4+}$, n = 1–4

L = iso(Pro)$_1$		L = iso(Pro)$_2$		L = iso(Pro)$_3$		L = iso(Pro)$_4$	
T, K	$10^{-6}k$, s^{-1}	T, K	$10^{-4}k$, s^{-1}	T, K	$10^{-2}k$, s^{-1}	T, K	k, s^{-1}
308	4.23	306	4.68	308	4.78	308	
298	3.07	298	3.69	298	3.19	298	50
287	2.45	298	3.39	285	1.85	285	
278	1.77	289	2.39	277	1.11	277	
		278	1.65				
		277	1.51				

The Os^{II}–L–Ru^{III} complexes were generated in the kinetic studies from the parent Os^{III}–L–Ru^{III} solutions by rapid reaction with the $CO_2^{\bullet-}$ or $(CH_3)_2COH^{\bullet}$ radicals formed by pulse radiolysis techniques from sodium formate or isopropyl alcohol, respectively, and monitored at λ = 525 nm. (The rate constants for the reduction of Os^{III}–L–Ru^{III} by $CO_2^{\bullet-}$ and $(CH_3)_2COH^{\bullet}$ were 4×10^9 M^{-1} s^{-1} and 6×10^8 M^{-1} s^{-1}, respectively.)[11c] About half of the $CO_2^{\bullet-}$ radical produces the precursor complex; the rest directly produces the product, Os^{III}–L–Ru^{II}. This ratio is estimated from the initial apparent extinction coefficient of the Os^{II}–L–Ru^{III} based on all radicals produced (about 6000 to 7000 M^{-1} cm^{-1} at 525 nm for all the complexes, while that for $[(NH_3)_5Os^{II}isoPro]$ was 1.3×10^4 M^{-1} cm^{-1}). Inasmuch as reaction 4 is not reversible and was followed by Os^{II} disappearance, the exact initial distribution is immaterial. Table II shows the observed intramolecular electron-transfer rate constants for the Os^{II}–L–Ru^{III} complexes (eq 4) as a function of temperature for n = 1–3 prolines. The rate constants and distances between the donor and acceptor are listed in Table III.

The bimolecular reaction

$$[(NH_3)_5Os^{II}LRu^{III}(NH_3)_5] + [(NH_3)_5Os^{III}LRu^{III}(NH_3)_5] \rightarrow [(NH_3)_5Os^{III}LRu^{III}(NH_3)_5] + [(NH_3)_5Os^{III}LRu^{II}(NH_3)_5] \quad (5)$$

is also expected to have a contribution to the electron-transfer rate. The rate constant for this reaction was measured to be 9×10^6 M^{-1} s^{-1} at 25 °C for L = iso(Pro)$_4$ and is nearly the same for all the molecules in the series. Thus the growth rate of Os^{II} from $CO_2^{\bullet-}$ reduction was always 500 times larger than the second-order electron-transfer rate, and a concentration region could usually be found where the intramolecular electron transfer dominated the reaction and the second-order term was negligible or easily corrected for.

The only exception was the (Pro)$_4$ complex, since the practical lower limit for Os^{III}–L–Ru^{III} concentration is about 2×10^{-6} M. In this case the observed rate constants were 150, 87, and 78 s^{-1} at 1×10^{-5}, 4×10^{-6}, and 2×10^{-6} M, respectively. Linear extrapolation of the rate constant to zero concentration gave k_{et} = 50 s^{-1}. Since the error limit on the intramolecular rate is quite large, approximately ±20 s^{-1}, no attempt was made to measure the temperature dependence for the (Pro)$_4$ complex.

Another bimolecular electron-transfer reaction

$$[(NH_3)_5Os^{II}L]^{2+} + [(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+} \rightarrow [(NH_3)_5Os^{III}L]^{3+} + [(NH_3)_5Os^{II}LRu^{III}(NH_3)_5]^{4+} \quad (6)$$

which can contribute to the observed rate, especially in multiply pulsed solutions, was also considered. Multiple pulsing was usually done for each measurement, since trace impurity often caused the first pulse to exhibit a large rate constant. The rate constant for this reaction is expected to be the same as the corresponding reaction with Os^{III}–L–Co^{III}, 5×10^5 M^{-1} s^{-1}, but in the Os^{III}–L–Ru^{III} case this rate constant is a factor of 20 smaller than the rate constant expected for

$$[(NH_3)_5Os^{II}L]^{2+} + [(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+} \rightarrow [(NH_3)_5Os^{III}L]^{3+} + [(NH_3)_5Os^{III}LRu^{II}(NH_3)_5]^{4+} \quad (7)$$

(which should be comparable to reaction 5). This reaction (eq 7) introduces a second but much slower exponential decay into all multiply pulsed solutions, as expected.

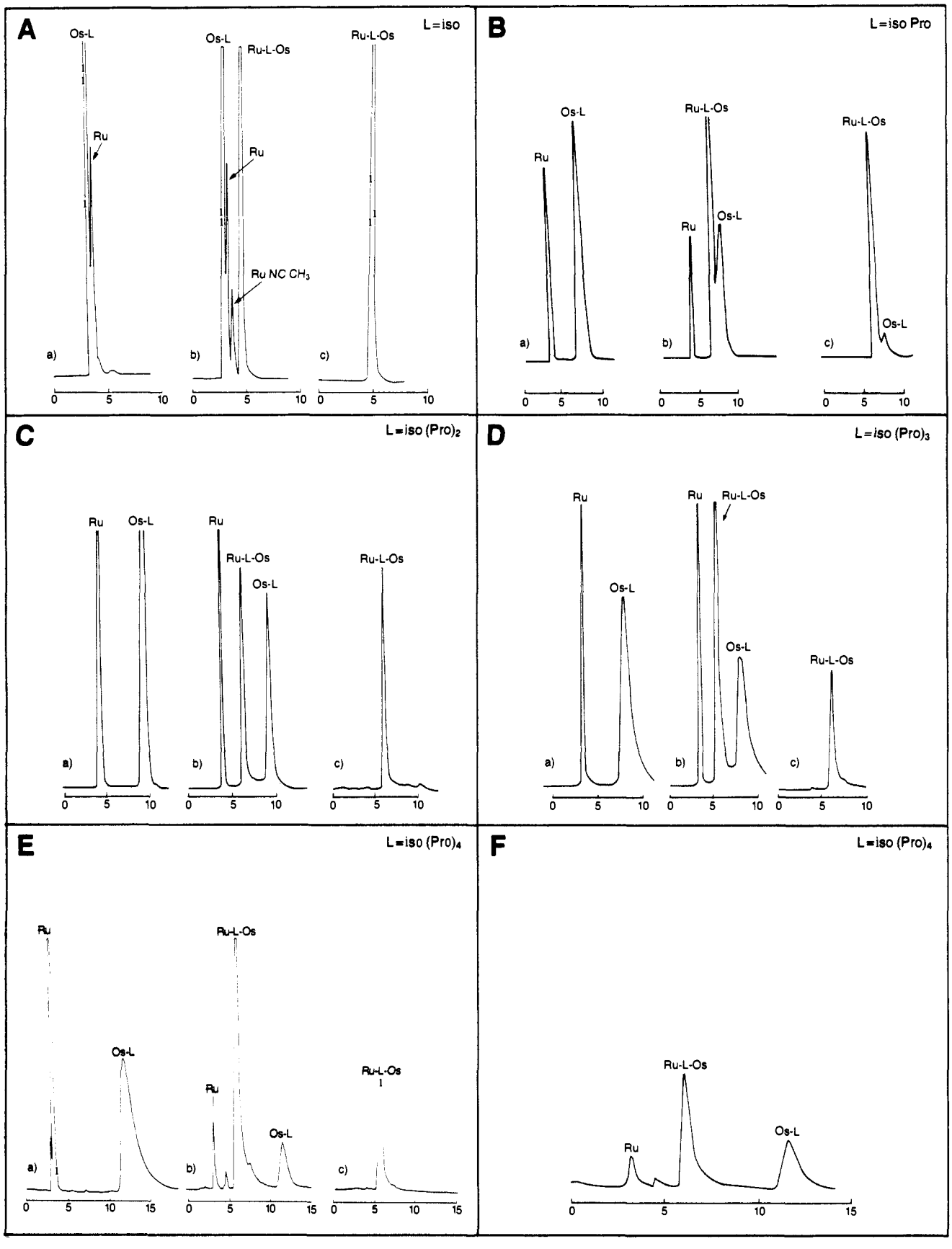


Figure 2. HPLC elution profiles showing the formation of $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+}$. For each of the proline species, L = iso(Pro)$_n$, n = 0–4 (A–E respectively) the HPLC profile shows: (A) the mononuclear $[(NH_3)_5Ru(OH_2)]^{2+}$ and $[(NH_3)_5Os^{III}L]^{3+}$ species, (B) binuclear $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+}$ in the presence of the starting materials, and (C) the purified $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+}$. For the L = iso(Pro)$_4$ species, the HPLC of Os–L–Ru after treatment with Eu^{2+}(F) shows how the reduction of the binuclear complex with Eu^{2+} leads to its mononuclear components. Conditions: Waters Assoc. Radial Compression C-18 column, 5 μm (10 cm × 0.8 cm): 10% CH_3OH (for A and B) and 20% CH_3OH (for C–F) in 0.1 M CF_3COOH, pH 2.67 (adjusted with NaOH), flow 1 mL/min; λ = 254 nm.

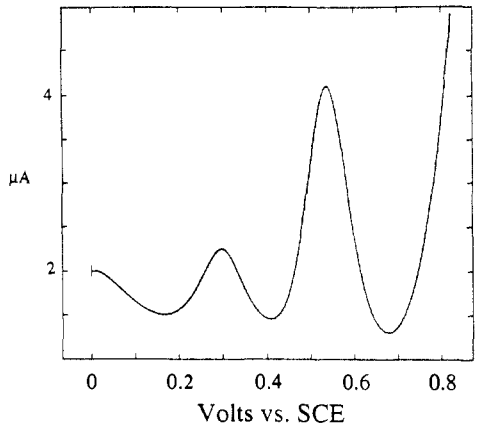


Figure 3. Differential pulse polarogram of $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{5+}$, L = iso(Pro)$_6$.

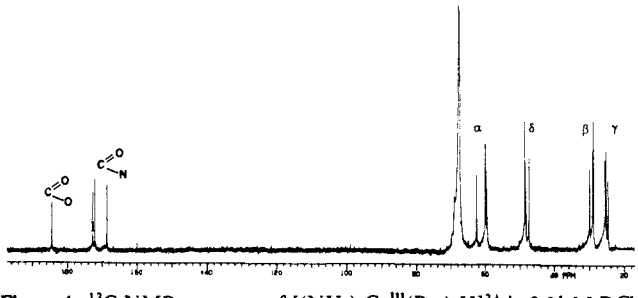


Figure 4. ^{13}C NMR spectrum of $[(NH_3)_5Co^{III}(Pro)_4H]^{3+}$ in 0.01 M DCl. (See Experimental Section for conditions.)

For the $[(NH_3)_5Osiso]^{3+}$ complex, the reduction of Os^{III} by e^-_{aq} (as seen by a decrease in aqueous electron absorbance at 650 nm) occurred with a rate constant of approximately 3×10^{10} M^{-1} s^{-1}. When the Os^{III}–iso–Ru^{III} reaction was monitored at 650 nm, the expected changes for the formation and decay of e^-_{aq} were observed, indicating that the reaction between e^-_{aq} and the Os^{III}–iso–Ru^{III} complex proceeded as expected ($k \sim 6 \times 10^{10}$ M^{-1} s^{-1}). For the Os^{III}–iso–Ru^{III} complex, the reaction with the e^-_{aq} did not produce the expected rise and fall in Os^{II} absorbance that was observed for the other binuclear complexes. At 530 nm, a wavelength where the decay of Os^{II} could be monitored, the absorbance/time profile revealed that Os^{II} was removed at least as fast as it was formed in 0.09 M Os^{III}–iso–Ru^{III}. Therefore, the rate of electron transfer between Os and Ru in the Os^{III}–iso–Ru^{III} complex is taken to be equal to or greater than the observed rate of the reaction of e^-_{aq} with the fully oxidized complex. From these experiments, the rate of intramolecular electron transfer in the Os^{II}–iso–Ru^{III} complex must be faster than 5×10^9 s^{-1}.

Determination of the Conformation of Oligoprolines by ^{13}C and Proton NMR. The NMR experiments were carried out by using the $[(NH_3)_5Co(Pro)_n]^{3+}$, n = 1–4, complexes. These complexes were used for the NMR studies because of their stability over long periods of time (ca. 3 days). Replacement of the cobalt with the corresponding ruthenium or osmium complex is not expected to introduce any changes in the conformation of the oligoproline peptide.

The ^{13}C NMR spectrum of $[(NH_3)_5Co(Pro)_4]^{3+}$, including the C-terminal and carbonyl peptide regions, is shown in Figure 4. Figure 5 shows the region of the proline ring in $[(NH_3)_5Co(Pro)_n]$, n = 1–4, with the α, β, γ, δ carbons of the proline rings. The carbon resonances summarized in Table V from the ^{13}C NMR spectra of $[(NH_3)Co(Pro)_n]^{3+}$, n = 1–4, were assigned by comparison of $[(NH_3)_5Co(Pro)_n]$ with $[(NH_3)_5Co(Pro)_{n+1}]$. The resonance lines for C^β and C^γ, identified on the basis of their chemical shifts, are similar to those obtained for oligoprolines in the literature.[24-27,32]

From the ^{13}C NMR data for the $[(NH_3)_5Co(Pro)_n]^{3+}$ complexes with n = 2–4 prolines the percentage of trans conformer in 0.01 M DCl was calculated as 84%, 91%, and 96% (±2%) trans, respectively.

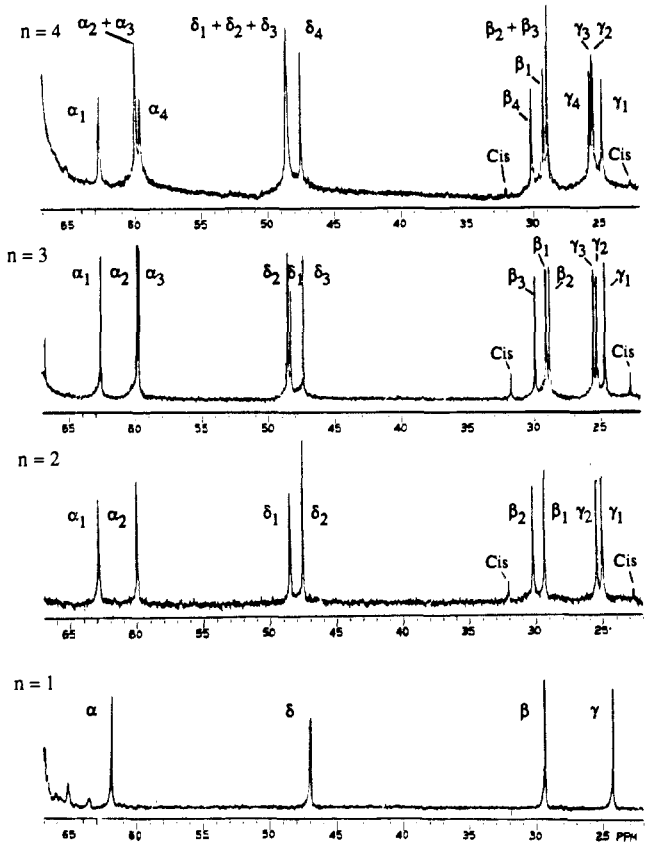


Figure 5. The expanded ^{13}C NMR spectrum of proline ring carbons in the $[(NH_3)_5Co^{III}(Pro)_nH]^{3+}$, n = 1–4, complexes.

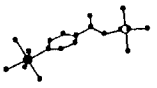
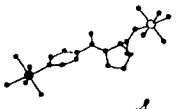
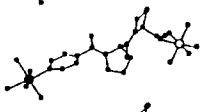
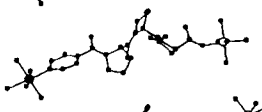
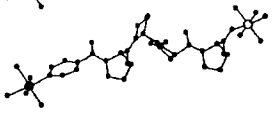
In the ^1H NMR of the $[(NH_3)_5Co(Pro)_n]^{3+}$ complexes in 0.01 M DCl, the cis α protons and the trans α protons are well separated and similar to those of polyproline in D_2O at pH 4 where the cis α protons appear at 4.3–4.4 ppm and the trans α protons at 4.7 ppm downfield from TSP(d_4).[18b] The chemical shifts of the α protons for both the cis and trans forms are listed in Table IV. From the integration of the ^1H NMR signals, the percent of trans conformer for the $[(NH_3)_5Co(Pro)_n]^{3+}$ complexes was calculated to be 86%, 88%, and 95% (±3%), for n = 2–4, respectively.

Discussion

Characterization and Stability of the $Os^{III}LRu(NH_3)_5$, L = iso(Pro)$_n$, Complexes. The osmium(III)–ruthenium(III) binuclear complexes were synthesized from the corresponding mononuclear osmium(III) complexes and a mixture of the $[Ru(NH_3)_5(OH_2)]^{3+}$ and $[Ru(NH_3)_5(OH_2)]^{2+}$ in aqueous acidic solution. The substitution of ruthenium(III) onto the C-terminus of the peptide is catalyzed by the presence of ruthenium(II). The HPLC retention times of the three components, $[Ru(NH_3)_5(OH_2)]^{3+}$, $[Os(NH_3)_5(peptide)]^{3+}$, and $[(NH_3)_5Os^{III}LRu^{II}(NH_3)_5]^{5+}$ (Figure 2), facilitated their separation, identification, and the study of their decomposition. Furthermore, the retention times of the Os–L–Ru complexes were similar to the corresponding Os–L–Co complexes characterized and studied earlier.[11b,c]

Low concentrations of acetonitrile (ca. 1%) were used throughout the electrochemical and kinetic studies to inhibit the catalytic decomposition of the binuclear complexes by small concentrations of $[Ru(NH_3)_5(OH_2)]^{2+}$.[30] After reduction of the binuclear complexes, aquation of the ruthenium occurs with $t_{1/2} \sim$ 50–100 ms.[31] Acetonitrile rapidly scavenges the $[(NH_3)_5RuOH_2]^{2+}$ generated from the aquation reaction of the binuclear complex to form $[(NH_3)_5RuNCCH_3]^{2+}$. The higher reduction potential of $[(NH_3)_5RuNCCH_3]^{2+}$ (relative to $[(NH_3)_5RuOH_2]^{2+}$) prevents any further decomposition of the binuclear complexes (the reverse of eq 2).

Table III. Intramolecular Electron-Transfer Rates, Activation Parameters, and Os–Ru Distances for the $[(NH_3)_5Os^{II}iso(Pro)_nRu^{III}(NH_3)_5]^{4+}$, n = 0–4, Series

Os ▨ Ru	n	k (s^{-1})	$\Delta H^{\ddagger}$ kcal/mol	$\Delta S^{\ddagger}$ cal/deg*mol	M–M' Dist Å
	0	$>5 \times 10^9$	—	—	9.0
	1	3.1×10^6	4.2	-15	12.1 – 12.3
	2	3.7×10^4	5.9	-19	14.4 – 15.1
	3	3.2×10^2	7.4	-23	17.8 – 18.3
	4	~50	—	—	20.9 – 21.5

The electrochemical results show that the potential difference between the ruthenium(II/III) and osmium(II/III) centers is relatively constant throughout the series. This potential difference is equated to the driving force in these intramolecular electron-transfer reactions, since they are carried out in aqueous media where the distance dependence of the driving force is expected to be negligible.

Proline Conformation and Estimation of Distance between Donor and Acceptor. The solid-state structure of *trans*-polyproline is shown in Figure 1. On the basis of this structure, end-to-end distances between the C- and N-terminal of the proline residues can be calculated.[29] Because this study is concerned with low molecular weight proline oligomers, further evidence for the structure of these low molecular weight oligomers is desirable. The trans configuration in low molecular weight oligomers in the solid state is clearly demonstrated in the crystal structures of [(*tert*-butyloxy)carbonyl]tetra-*l*-proline benzyl ester and [(*tert*-amyloxy)carbonyl]tri-*l*-proline.[37] The structures of these low molecular weight proline oligomers are very similar to the fiber structure of *trans*-polyproline. The compounds investigated in this study are inorganic analogues of these derivatives, where the two ends of the prolines have been derivatized with transition-metal complexes as donors and acceptors. Although crystal structures of the inorganic complexes studied here are not available, their solid-state structures are expected to closely resemble these corresponding organic oligoproline peptide derivatives.

The solution conformation of the cobalt polyprolines was determined by ^{13}C and proton NMR. The carbon resonances were assigned by comparison of $[Co(NH_3)_5(Pro)_n]^{3+}$ with $[Co(NH_3)_5(Pro)_{n+1}]^{3+}$, assuming that the chemical shift changes the most for the α and δ carbons close to the site where oligomerization takes place. Studies of the ^{13}C spectra in small proline peptides[23-26] showed that the relaxation line (T_1) for the *cis*-X-*l*-proline bonds is very similar to that for molecules with *trans*-X-*l*-proline bonds. Since the *cis*- and *trans*-proline conformers do not exchange rapidly, the amount of cis or trans conformer could be determined from the ^{13}C resonances at different chemical shifts.

Mandelkern and co-workers have analyzed the conformation of poly(l-proline) and poly(γ-hydroxy-l-proline) by proton and ^{13}C NMR spectra.[26] From the NMR analysis and the experimental determination of the end-to-end average distance[14] in proline polymers (MW 10000) using intrinsic viscosity measurements, they concluded that the majority (>97%) of the solution conformations of these polymers resemble those found in the solid state. In analogy to this early work, the proton and ^{13}C NMR analysis reported here shows that ~95% of the cobalt tetraproline exists in the extended trans form. However, this analysis does not preclude the presence of several very closely related *trans*-polyproline conformers that exchange rapidly on the NMR time scale. The existence of such conformers would result in variation of the end-to-end distances at very fast time scales.

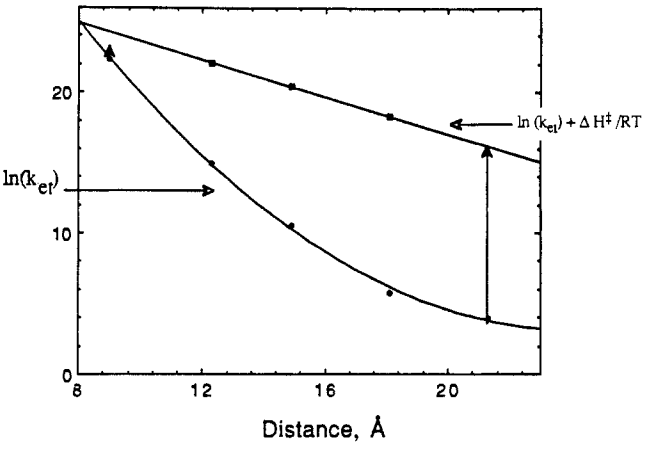


Figure 6. A plot of ln k_{et} vs distance (lower) and ln $k_{et} + \Delta H^{\ddagger}/RT$ vs distance (upper) for $[(NH_3)_5Os^{III}LRu^{III}(NH_3)_5]^{4+}$, L = iso(Pro)$_n$, n = 0–4, series.

On the fluorescence time scale, Stryer[19] has demonstrated that for energy transfer across polyprolines from $n = 5$ to $n = 12$ the efficiency of energy transfer decreases with the increasing number of proline residues yielding a 50% transfer efficiency at 34.6 Å and shows the r^{-6} dependence predicted by Forster[20] for weak dipole–dipole coupling. The circular dichroism spectra of $[Co(NH_3)_5(Pro)_n]^{3+}$, n = 3, 4, show the *helical* structure characteristic of oligoproline peptides ($n \geq 3$).[11c,24,36] The CD spectra[11c] of the $[Co(NH_3)_5(Pro)_4]^{3+}$ in the ultraviolet is similar to that of *trans*-polyproline.[36] In summary the NMR, fluorescence energy transfer, and CD studies all demonstrate that oligoproline peptides, and, specifically, the cobalt oligoprolines studied here possess reasonably rigid structures with well-defined end-to-end distances.

Distance Dependence of Long-Range Intramolecular Electron Transfer in the Osmium–Ruthenium Complexes. Table III summarizes the intramolecular electron-transfer rates and the distances

(34) Schanze, K.; Sauer, K. *J. Am. Chem. Soc.* **1988**, *110*, 1180.
(35) (a) Faraaggi, M.; DeFelippis, M. R.; Klapper, M. H. *J. Am. Chem. Soc.* **1989**, *111*, 5141. (b) Klapper, M. H. Private communication.
(36) Helbecque, N.; Loucheux-Lefebvre, M. H. *Int. J. Peptide Protein Res.* **1982**, *19*, 94.
(37) (a) Matsuzaki, T. *Acta Crystallogr.* **1974**, *B30*, 1029. (b) Kartha, G.; Ashida, T.; Kakudo, M. *Acta Crystallogr.* **1974**, *B30*, 1861.

between the osmium and the ruthenium centers in five different molecules, Os–L–Ru, L = iso(Pro)$_n$, n = 0–4 prolines. Although molecules with more than four prolines can be synthesized, the measurement of intramolecular rate constants is not possible because of competition by intermolecular reactions, thus the Os–L–Ru series is limited to the molecules studied here.

A very important result of these rate measurements is the large change of the rate of intramolecular electron transfer *by more than eight orders of magnitude across the series* (Table III). Because these Os–L–Ru complexes have very similar driving force and inner-sphere reorganization energies, this variation in rate must be attributed to the difference in the electronic coupling between the two metal centers and the change in the outer-sphere reorganizational energy as the distance (and the number of proline residues) increases.[29]

For n = 0 prolines, the Os–iso–Ru intramolecular electron-transfer rate is extremely fast and only a lower limit of $k > 5 \times 10^9$ s^{-1} could be obtained. It should be noted that Os–iso–Ru is a conjugated molecule with significant coupling between the osmium and the ruthenium. With this large coupling this molecule is expected to undergo adiabatic intramolecular ET with a reduced activation barrier.[2c] The large drop in rate from n = 0 to n = 1 (more than a factor of 10^3) may be attributed to the increase in the distance and the loss of direct conjugation of the two metal centers Os^{II}($5d^6$) and Ru^{III}($4d^5$).

For n = 1–3 prolines in the Os–L–Ru series, L = iso(Pro)$_n$, increasing the distance between the metal ions results in an incremental decrease in rate of an approximate factor of 10^2 per added proline residue. For these three complexes, it was possible to measure the rate of intramolecular electron transfer without any significant interference from intermolecular reactions. These reactions were also studied at different temperatures to determine the activation parameters for the intramolecular electron-transfer process at different distances. Table III shows how the activation enthalpy ΔH^* increases and the activation entropy ΔS^* decreases for n = 1–3. For the n = 4 complex, the slower rate of intramolecular electron transfer studied was competitive with the intermolecular rate of electron transfer. An approximate rate of 50 ± 20 s^{-1} (Table III) was measured at 25 °C. Because of the large uncertainty in this rate constant, the temperature dependence of the rate was not studied.

The rate constants and temperature dependences for these molecules can be used to explain the large variation in rate in this series by using the following theoretical treatment. The rate constant for intramolecular electron transfer[2] can be expressed as

$$k_{ET} = \kappa_{el}\upsilon_n\kappa_n \quad (8)$$

$$\kappa_n = \exp[-(\lambda + \Delta G^\circ)^2/(4\lambda RT)] \quad (9)$$

$$\upsilon_n\kappa_{el} = 10^{13} \exp[-\beta(r-r_o)] \quad (10)$$

where κ_{el} is the electronic transmission coefficient, r_o is the distance between redox sites at which $\kappa_{el} = 1$, β is the electronic factor which is a constant characteristic of the system, υ_n is the nuclear vibrational frequency, ($\sim 10^{13}$ s^{-1}), κ_n is the nuclear factor, λ is the reorganization energy (with both inner-sphere (λ_i) and outer-sphere (λ_o) contributions), and ΔG° is the standard free energy change of the reaction. As seen in eqs 8–10, electron-transfer rates may be changed by either changing the reorganization energy (λ), the distance (κ_{el}), or the driving force (ΔG°).

For the oligoproline bridged complexes reported here, the dependence of the rate on the outer-sphere reorganization energy, λ_o, can be either estimated from simple expressions of the dielectric continuum model,[2] or it can be experimentally determined from the temperature dependence of the rate of electron transfer for the different proline oligomers.[29] By using a rearranged form of the transition-state expression

$$\ln k_{el} + \Delta H^*/RT = \ln [\kappa_{el}(kT/h)] + \Delta S^*/R \quad (11)$$

and assuming that for the Os^{II}–L–Ru^{III} → Os^{III}–L–Ru^{II} charge shift reaction ΔH^* ($\sim \Delta G^*$) is a measure of the activation barrier for the reaction at different distances, it is possible to obtain the electronic factor β from the slope of the plot of [ln k_{et} + $\Delta G^*/RT$] (also referred to as ln [$\upsilon_n\kappa_{el}$]) vs distance. From the variation of the rate of intramolecular electron transfer with temperature for n = 1–3 (Table II), $\Delta H^*/RT$, and λ, the reorganization energy, were calculated.[29]

Figure 6 shows two plots: the lower plot of ln k_{et} versus distance shows the dependence of the rate on both the nuclear and electronic factors, and the upper plot of [ln k_{et} + $\Delta H^*/RT$] versus distance for n = 2–4 prolines, yields only the electronic factor, β (eq 10) as the slope. The Os–iso–Ru compound is shown on the plot for comparison although the conjugation between the donor and acceptor in this binuclear complex may not qualify it as a weakly coupled system.

A slope of β = 0.65 Å^{-1} is obtained from the plot of [ln k_{et} + $\Delta H^*/RT$] vs distance. This value is slightly smaller than that calculated by Endicott[5] for the Os–L–Co series. The difference, though small, is in the right direction expected for more rapid electron transfer to ruthenium acceptors than to cobalt acceptors.[1] This value of β = 0.65 Å^{-1} is lower than that obtained for saturated polycyclic hydrocarbon systems ($\beta \sim 0.9$ Å^{-1}).[6] The difference between the hydrocarbon and the polypeptide bridging ligands can be related to the interaction of the filled π levels of the polypeptide with the donor and acceptor metal ions. Such electronic coupling models based on "hole" superexchange mechanisms have been proposed by Beretan et al.[38,39] to interpret *through bond* electron transfer in mixed valence ruthenium complexes. Larsen[40] has also calculated the distance dependence of the electronic interaction in polypeptide bridges. His results show that oligoglycine spacers with 1–10 peptide residues decrease the interaction in approximately exponential dependence on distance. These types of theoretical models of Beretan[38,39] and Larsen[40] may be applicable to the current results where a lower β than in the saturated hydrocarbons is obtained, i.e., the difference between the two types of bridging ligands being in the interaction of the orbitals of the donor and acceptors with the bridge. Other models involving the π^* orbitals of peptides may be responsible for the observed smaller β.

Table IV. Chemical Shifts of α Protons in the [(NH$_3$)$_5$Co^{III}(Pro)$_n$], n = 2–4, Complexes

	H_α cis	H_α trans
[(NH$_3$)$_5$Co(Pro)$_2$]	4.51, 4.36	4.61, 4.42
[(NH$_3$)$_5$Co(Pro)$_3$]	4.67, 4.46, 4.30	4.75, 4.64, 4.36
[(NH$_3$)$_5$Co(Pro)$_4$]	4.49, 4.45, 4.40, 4.26, 4.14, 4.11	4.80, 4.71, 4.62, 4.35[a]

[a] Other α proton lines were obscured by water peaks.

Table V. ^{13}C Resonances of Proline and [(NH$_3$)$_5$Co^{III}(Pro)$_n$], n = 1–4, in the Extended Trans Conformation[a]

complex	–COO	–CON<	C_α	C_β	C_γ	C_δ
proline	175.8		63.1	30.2	25.0	47.3
Co(Pro)	179.2		61.9	29.4	24.3	47.0
			62.8_a	29.2_a	24.9_a	48.4_a
Co(Pro)$_a$(Pro)$_b$	183.9	168.8	59.9_b	30.1_b cis 32.0	25.3_b cis 23.8	47.4_b
			62.8_a	29.2_a	24.8_a	48.6_a
Co(Pro)$_a$(Pro)$_b$-(Pro)$_c$	184.4	169.6_b 172.3_c	60.1_b 59.9_c	28.9_b 30.1_c cis 31.7	25.4_b 25.7_c cis 23.8	48.7_b 47.5_c
			62.7_a	29.2_a	24.8_a	48.7_{a-c}
Co(Pro)$_a$(Pro)$_b$-(Pro)$_c$(Pro)$_d$	184.7	168.4_b 172.2_c 173.0_d	$60.1_{b,c}$ $59.9_{b,c}$ 59.6_d	$28.9_{b,c}$ 30.1_d cis 32.0	$25.5_{b,c}$ $25.4_{b,c}$ cis 23.8	47.5_d

[a] 0.01 M DCl, T = 6 °C, TMS scale, reference: dioxane 67.4 ppm from TMS.

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Table VI. Intramolecular Electron-Transfer Rates Across Oligoprolines

n	$k_{Ru-L-Co}$, s^{-1}	$k_{Os-L-Co}$, s^{-1}	$k_{Os-L-Ru}$, s^{-1}
0	1.2×10^{-2}	1.9×10^{5}	$>5 \times 10^{9}$
1	1.04×10^{-4}	2.7×10^{2}	3.1×10^{6}
2	0.64×10^{-5}	0.74	3.7×10^{4}
3	5.6×10^{-5}	0.04–0.09	3.2×10^{2}
4	1.4×10^{-4}	0.01–0.09	5.0×10^{1}

For the compound Os–iso$(Pro)_4$–Ru, where no temperature dependence was determined, extrapolation of the best fit line through the three experimentally determined points leads to a *rough* estimate for the reorganization energy of 7.3 kcal mol^{-1}, close to the Os–iso$(Pro)_3$–Ru case.

Comparison with Earlier Studies Involving Proline Bridging Groups. The intramolecular electron-transfer rates for the Os–L–Ru series (Table III) can be compared directly to the corresponding Os–L–Co series (Table VI). The electron-transfer rates increase dramatically (more than three orders of magnitude) for the Os–L–Ru series over the corresponding Os–L–Co series. This can be attributed mainly to the much smaller inner-sphere reorganization energy for the $[(NH_3)_5Ru^{III}]$ center than the $[(NH_3)_5Co^{III}]$ center.[1]

Table VI provides a comparison of rates of electron transfer for three similar series of proline oligomers, with different metal ion donors and acceptors.[11] The largest difference among these different series is for $n = 0$; a change of *more than 11 orders of magnitude in rate* has been observed for compounds where the change is in the *metal ion* donor and acceptor. Differences in driving force, inner-sphere reorganizational energy, and the symmetry of the acceptor orbital account for the large rate changes. Slightly smaller differences are observed for $n = 1$ and $n = 2$. These results demonstrate the large changes in rates that can be obtained by systematic changes in the driving force and reorganization energies as well as distances between the donor and acceptor. These large changes reflect the ability to vary ET rates dramatically by using transition-metal ion donors and acceptors and represent the contribution that inorganic chemistry has made in the understanding of ET reactions through organic bridging groups.

For the $n = 3$ and $n = 4$ prolines, large divergences among the same series of complexes begin to emerge. For $n = 3$ in the Co–L–Ru series, the rate is so slow that conformational exchange dominates the observed rate constant. For the corresponding Os–L–Co series, the rates proceed more rapidly than the corresponding Ru–L–Co reaction for $n = 1$ and 2. For $n = 3$ and 4 the reactions are slow and it can be argued that the observed rate reflects the availability of different conformers that can contribute to the rate of electron transfer (eq 12). Recently, however, correction for the nuclear factor (similar to the procedure outlined earlier) showed that the deviation from linearity of ln k vs distance in the Os–L–Co series can be accounted for without invoking multiple conformations with different rates.[5]

The availability of different conformers in the Os^{II}–L_s–Ru^{III} series and their contribution to the observed rate can be represented in eq 12

$$Os^{II}\text{–}L_s\text{–}Ru^{III} + Os^{III}\text{–}L_f\text{–}Ru^{III} \rightarrow Os^{III}\text{–}L_s\text{–}Ru^{III} + Os^{II}\text{–}L_f\text{–}Ru^{III} \xrightarrow{k_{et}} Os^{III}\text{–}L_f\text{–}Ru^{II} \quad (12)$$

where L_s and L_f represent slow and fast reacting conformers of the proline oligomers. The rate of this exchange reaction can be calculated from the $Os^{II/III}$ self-exchange rate constant. At concentrations of $\sim 10^{-5}$ M the upper limit for this reaction is $k_{obs} = 10\ s^{-1}$. For the Os–L–Ru series at concentrations lower than 10^{-5} M, interchange resulting from eq 12 is not expected to contribute to the observed rate because electron transfer occurs on a faster time scale.

To verify the above analysis it is necessary to increase the rate of electron transfer, in order to measure the rate at even longer distances (greater than 3 and 4 proline spacers) without interference from intermolecular reactions. Increasing the driving force is one simple method for increasing these rates in a related series of molecules. The objective for studying these new molecules will be to clarify the contribution of the through-bond pathway and the role of λ_{out} in determining the rate of electron transfer in complexes when the metal-to-metal separation is greater than 20 Å.

During the course of our work, Schanze and Sauer[34] reported on the fluorescence quenching of polyproline-bridged ET complexes containing quinone acceptors and $Ru^{II}(bpy)_2L$ donors (bpy is 2,2′-bipyridine). They concluded that ET reactions occur rapidly in these systems, $\sim 10^5\ s^{-1}$ for $n = 4$ prolines, the longest distance examined. Their results, however, were complicated by the presence of multiple conformations (and therefore different distances) in the polyproline bridges. This conformational variability is introduced by the use of nonaqueous solvents required to maintain the solubility and stability properties of their complexes.[34] The advantage of the systems described in the current study is that the polyproline complexes are soluble and stable in aqueous solution where the proline oligomers exist in the predominantly all-trans conformation.

Recently Klapper et al.[35] studied the rate of intramolecular ET in a series of complexes of the type Trp–$(Pro)_n$–Tyr and Tyr–$(Pro)_n$–Trp where Trp and Tyr are tryptophan and tyrosine residues and $n = 1$–3. One-electron oxidation of these peptides produced the indolyl radical which in turn oxidizes the tyrosine side chain by inter- and intramolecular electron-transfer pathways. The rate of intramolecular electron transfer for the Tyr–$(Pro)_n$–Trp with $n = 1$–3 changed by less than a factor of four. This small dependence of rate on distance is very surprising and may imply additional mechanisms of intramolecular electron transfer involving the peptides are operating. Further investigations using proline oligomers with ($n = 4$–6) may shed more light on this unexpected observation.[35b]

The results of the work described here can be extrapolated to predict reasonably fast rates of electron transfer (ca. in the msec time scale) *across metal–metal distances of 40* Å, if the driving force and reorganization energy are appropriately controlled in complexes similar to the ones reported here. Work is continuing in our laboratory to further probe the mechanisms of electron transfer on these extremely long-range electron-transfer reactions.

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