known that Au(I) phosphine complexes can interact with biological thiols. We have shown that thiols in model systems induce chelation of the bridged compounds; therefore, it seems very likely that the conversion in plasma and serum is thiol-induced.

Reactive thiols are present in many in vivo sites apart from blood plasma.[28] Therefore, $[Au(dppe)_2]^+$ is likely to be a major metabolite of the bridged-digold complexes in cells. $[Au(dppe)_2]^+$ itself does not react significantly with thiols.

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Registry No. GSH, 70-18-8; NaStg, 105177-81-9; $[(AuCl)_2(dppe)]$, 18024-34-5; $[Au(dppe)_2]Cl$, 19624-67-0; $[(AuStg)_2(dppe)]$, 10593-29-0.

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Proton Site Exchange in $(\mu\text{-H})_3M_3(CO)_9(\mu_3\text{-CH})$ (M = Ru, Os)

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Recent work in this laboratory indicated that the CH and μ-H protons in $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$ undergo site exchange, as evidenced by scrambling of a deuterium label.[1] At room temperature, this exchange is slow, but at temperatures above 80 °C, it can be observed by spin saturation transfer.[2] In this note we present a complete description of the variable-temperature NMR experiments performed on this compound. We have also briefly examined the ruthenium analogue in order to form a more complete comparison with recent data reported for the corresponding iron system.[3]

Saturation transfer methods probe the competition between chemical exchange and spin-lattice relaxation; determination of relaxation rates, by separate inversion-recovery experiments, allows quantitation of exchange rates.[4] For an intramolecular exchange, where cross relaxation (as evidenced by a nuclear Overhauser enhancement) may be present, the modified Bloch equations describing the return to equilibrium for homonuclear spins I and S after a perturbation are[5]

$$dI_z/dt = -\rho_I(I_z - I_\infty) - \sigma(S_z - S_\infty) - k_I I_z + k_S S_z \qquad (1)$$

$$dS_z/dt = -\rho_S(S_z - S_\infty) - \sigma(I_z - I_\infty) - k_S S_z + k_I I_z \qquad (2)$$

where ρ_I and ρ_S = relaxation rate constants, σ = cross relaxation rate constant, k_I and k_S = exchange rate constants, I_z and S_z = instantaneous values of magnetization during recovery, and I_∞ and S_∞ = final values of magnetization after recovery.

The solutions to these equations are double exponential in form, unlike the single exponential obtained in the absence of exchange or cross relaxation. Except for certain special cases, such as exchange between sites with equivalent values of T_1 ($=1/\rho$), NOE ($=\sigma/\rho$), and population[5] or the apparent absence of NOE,[6] accurate determination of exchange rates requires extensive computer fitting of data from selective inverstion-recovery experiments to the solutions to eq 1 and 2[7] or an analogous procedure on data from NOESY 2D-NMR experiments.[8] The spin system in $(\mu\text{-H})_3M_3(CO)_9(\mu_3\text{-CH})$ (M = Ru, Os) also represents a special case. Because of the large difference in relaxation rates between the sites, nearly single-exponential recovery curves are obtained from selective inversion-recovery experiments at temperatures below the onset of exchange.[9] This allows relaxation rate determination by using only data fitting routines commonly found in commercial NMR spectrometer software packages, thereby simplifying the exchange rate calculation.

Experimental Section

All NMR experiments were done on a Nicolet Magnetics NT-360 spectrometer with an 1180 computer and a 293B pulse programmer. All T_1 experiments were performed with the fast inversion-recovery sequence,[10] a symmetric five-element composite 180° pulse,[11] alternating phase of the 90° pulse, and a nonlinear three-parameter least-squares fit.[12] The NOE values were determined by difference techniques.[13] All experimental measurements were assumed to be subject to errors of ±20%. Sample temperatures were checked by replacement with a tube containing a thermocouple junction and solvent.

The compounds $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$[14] and $(\mu\text{-H})_3Ru_3(CO)_9(\mu_3\text{-CH})$[15] were prepared by literature methods. Solutions for the NMR experiments were prepared in perdeuteriated solvents (Aldrich, *o*-xylene (M = Os) or toluene (M = Ru)), degassed by freeze-pump-thaw sequences, and sealed in tubes under a partial atmosphere of nitrogen. A separate sample of the osmium compound was prepared in the same manner and sealed under a partial atmosphere of carbon monoxide. Although this sample was not examined as extensively as the sample sealed under nitrogen, no differences in relaxation rates or exchange rates were observed.

Results and Discussion

Nonselective inversion-recovery measurements of the "T_1's" for the CH and μ-H sites in the osmium compound at ambient temperature gave 11.3 and 2.02 s, respectively, for single-exponential data fits. The respective nuclear Overhauser enhancements were 32% and 2%. Because of the cross relaxation present, the inversion-recovery curve of the methylidyne site was expected to be biexponential. This was demonstrated by selective inversion-recovery experiments, which gave 13.0 and 2.08 s for the CH and μ-H sites, respectively. These values were taken to be the "true" values of T_1, i.e., the inverse of the desired quantity ρ. The different values of T_1 reflect the dipole-dipole relaxation mechanism of the protons, a process that is very sensitive to internuclear distances, and the μ-H sites are over 1 Å closer to each other than to the CH site.[16]

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$$I_z = C_1 \exp(\lambda_1 t) + C_2 \exp(\lambda_2 t) + I_\infty$$

where $\lambda_{1(2)} = 0.5(-(\rho_I + k_I + \rho_S + k_S) + (-) \{[(\rho_I + k_I) - (\rho_S + k_S)]^2 - 4(k_S - \sigma)(\sigma - k_I)\}^{1/2})$ and C_1 and C_2 are dependent on the initial values of the magnetization I_0 and S_0. Equation 2 has a similar solution. When $\rho_I \gg \rho_S$ and $k = 0$, then $-\lambda_1 \cong \rho_S$ and $-\lambda_2 \cong \rho_I$. For the 6-fold difference in ρ_I and ρ_S in this system, these approximations are good to within 1%. For the selective inversion-recovery sequence, C_1 is forced to zero, permitting calculation of λ_2 (and thus ρ_I) from a single exponential data analysis.

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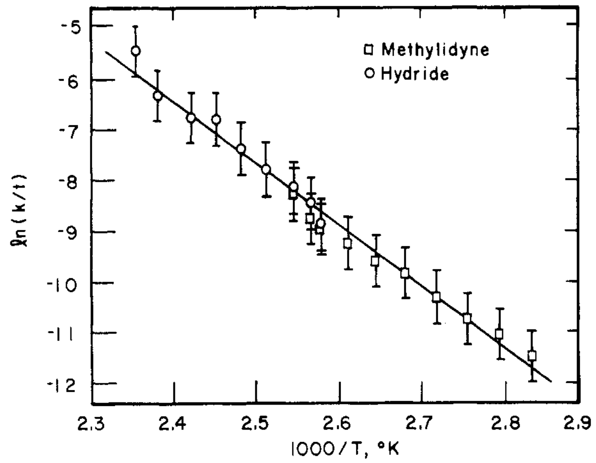

Figure 1. Eyring plot of spin saturation transfer rate data for $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$.

Variable-temperature measurements of the T_1 and NOE values below the onset of exchange (ca. 80 °C) were also fully consistent with dipole–dipole relaxation. The NOE showed no temperature dependence, indicating that the ratio σ/ρ was constant. A plot of log T_1 vs. log (η/T) was accurately linear with slope of -1[17] where η is the viscosity of the medium (taken to be that of the solvent, *o*-xylene-d_{10}, for this dilute solution)[18] and T is the absolute temperature. This relation between T_1 and η/T was used to predict the relaxation (ρ) and cross relaxation (σ) rates in the exchange region, where direct measurement would require extensive computation. If ρ and σ are known, only steady-state spin-saturation transfer experiments are needed to calculate the exchange rate, from the relation[5]

$$I_\infty'/I_\infty = (\rho + n\sigma)/(\rho + k) \qquad (3)$$

where I_∞' is the steady-state signal intensity of the observed site with the other site irradiated, I_∞ is the signal intensity without irradiation, and n is the number of equivalent spins being irradiated.

The effects of exchange became apparent at 80 °C for the CH site ($k = 3.6 \times 10^{-3}$ s^{-1}) and at 115 °C for the faster relaxing μ-H site. Complete saturation of the CH nuclei occurred at 130 °C, but measurements on the μ-H nuclei were possible up to 152 °C.[19] Figure 1 displays an Eyring plot of the exchange rate constants, from which the activation parameters $\Delta H^\ddagger = 24.0 \pm 1.7$ kcal/mol and $\Delta S^\ddagger = 2.0 \pm 1.8$ cal/(deg mol) were derived.

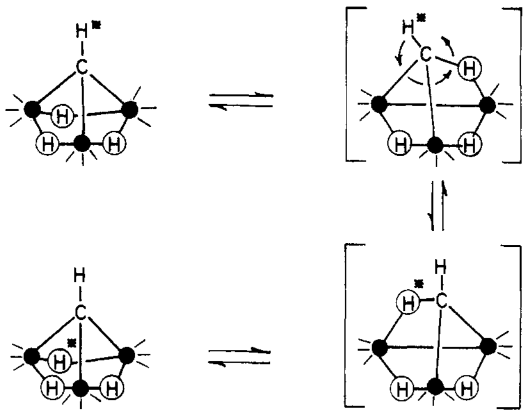

Figure 2. Proposed exchange mechanism for $(\mu\text{-H})_3M_3(CO)_9(\mu_3\text{-CH})$.

For the ruthenium compound, $(\mu\text{-H})_3Ru_3(CO)_9(\mu_3\text{-CH})$, the NOE values for the two sites were identical with those of the osmium compound. The apparent T_1's, measured in toluene-d_8 at ambient temperature, were 15.4 s for the CH site and 2.7 s for the μ-H site. Considering the lower viscosity of toluene compared with *o*-xylene (1:1.33),[18] these values were considered equivalent with the T_1's of the osmium compound. At 34 °C, exchange was evident and $k = 1.1 \times 10^{-2}$ s^{-1}/was determined; from the Eyring equation, $\Delta G^\ddagger(307) = 20.6$ kcal/mol was calculated.

We propose that exchange in $(\mu\text{-H})_3M_3(CO)_9(\mu_3\text{-CH})$ begins by proton transfer from a M–M bond to a M–C bond, producing $(\mu\text{-H})_2M_3(CO)_9(\mu_3,\eta^2\text{-CH}_2)$ (Figure 2). Interchange of the terminal and bridging protons, followed by reversal of the first step, completes the exchange. This proposed intermediate is saturated, consistent with the observation that the presence of CO does not affect exchange in $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$, and the proton migration is closely related to that observed directly in the $H_2Os_3(CO)_{10}(\mu\text{-CH}_2)/HOs_3(CO)_{10}(\mu,\eta^2\text{-CH}_3)$ tautomeric pair.[20] Our proposed intermediate is analogous to one of the isomers observed for "$H_3Fe_3(CO)_9CH$";[3] however, for both the Os_3 and Ru_3 systems this species is sufficiently higher in energy that it is only perceived indirectly. It is likely, also, that $(\mu\text{-H})_2Os_3(CO)_9(\mu_3,\eta^2\text{-CH}_2)$ is an intermediate in the conversion of $(\mu\text{-H})_2Os_3(CO)_{10}(\mu\text{-CH}_2)$ into $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$.[14]

The difference in free energies of activation for the exchange process in the Ru_3 and Os_3 compounds is about 3 kcal/mol. Similar values (3–5 kcal/mol) have been observed for other cases comparing proton migration to/from the metal triangle and a capping group in analogous Ru_3 and Os_3 compounds.[21,22]

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Registry No. $(\mu\text{-H})_3Os_3(CO)_9(\mu_3\text{-CH})$, 64012-09-5; $(\mu\text{-H})_3Ru_3(CO)_9(\mu_3\text{-CH})$, 63280-43-3.

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