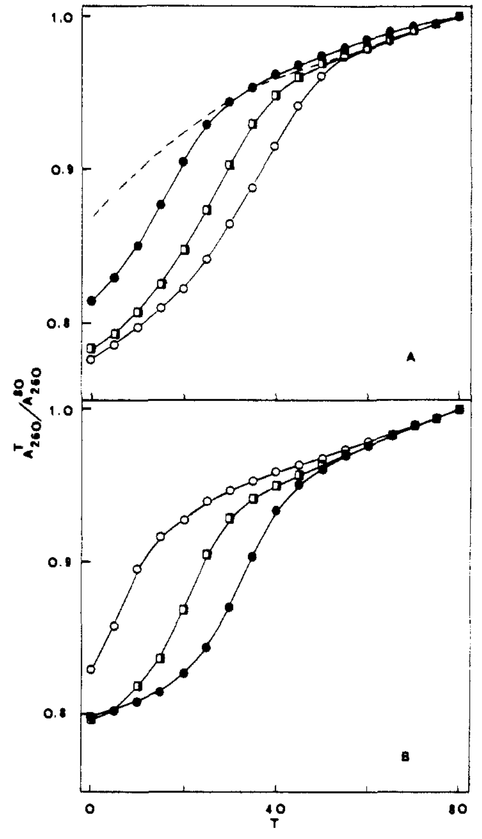

Figure 3. Absorbance profile at pH 5.6 (0.01 M phosphate buffer): A, **3** + **4** (1:1 mole equivalents) in 1 M NaCl (●), 0.1 M NaCl (◨), no NaCl (○); B, **3a** + **4** (1:1 mole equivalents) in 1 M NaCl (●), 0.1 M NaCl (◨), no NaCl (○). The dashed line in A gives absorbance data for **3** + **3a** (1:1 mole equivalents) at pH 5.6, no NaCl.

of hybrids involving ribonucleotide polymers.

An ability to modulate sensitivity to changes in ionic strength by controlling the ratio of plus and minus charges in the probe is demonstrated by the experiments with **2** (Figure 2). In this case, in which the charges in the probe are balanced, binding to polydA is essentially independent of the salt concentration.

The most revealing data are those for interaction of the mixed-base probe, **3**, and the natural counterpart, **3a**, with target **4**. Use of the less hindered anchoring moiety (–NH– in place of $-N(CH_3)-$) favors binding and the weaker basic group (morpholino in place of dimethylamino) allows greater control over protonation. Thermal dissociation curves (pH 5.6) are sigmoidal and clearly demonstrate reversal in the effect of salt concentration on binding affinity (Figure 3). With an increase in concentration of NaCl from 0 to 0.1 to 1.0 M, T_m[6] values for the complex of cationic analogue **3** decreased from 32.5° to 27.5° to 15° whereas the T_m values for the complex of oligonucleotide **3a** increased from <10° to 22.5° to 38°. The difference in affinities of the cationic and natural probes at low salt concentration is especially striking. Lack of significant interaction in a control experiment with an equimolar mixture of **3** and **3a** (non-complementary oligomers) confirmed that proper base pairing as well as electrostatic attraction is necessary for formation of a stable hypochromic complex from the cationic and anionic oligomers.

In addition, we found that the binding properties of the morpholino probe could be selectively influenced by pH changes. Thus, an increase in pH to 7.0 had little effect on the affinity of **3a** for **4** (T_m < 10° in 0 M NaCl, T_m 20° in 0.1 M NaCl) but strongly destabilized the complex between **3** and **4** (T_m 17° in 0 M NaCl, T_m 12° in 0.1 M NaCl). This effect reflects a low extent of protonation of the morpholino groups at pH 7 (see electrophoresis data in Table I).

These findings open new possibilities for designing oligonucleotide probes and may have relevance in controlling processes in biochemical and biological systems.

Acknowledgment. This research was supported by Grants GM10265 and AI24846 from the National Institutes of Health.

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Tautomerization Involving M-H-M and C-H-M Interactions in Capped Trimetal Clusters. Promotion of the C-H-M Interaction in a Mixed-Metal Cluster

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Agostic hydrogens, hydrogens bridging carbon and transition-metal centers, are now well-known structural features of mono- and polynuclear transition-metal compounds.[1,2] Although the factors promoting an E–H–M interaction (E = main group atom) in the capped trimetal cluster system are complex,[3] it is self-evident from a comparison of $Fe_3(CO)_9EH_n$, E = C, n = 4, and E = B, n = 5, that the effective nuclear charge difference between the metals and the capping atom is one factor that plays a large role in the formation E–H–M interactions.[4] Hence, we have sought isoelectronic clusters with endo hydrogens, which differ only in the identity of the metal atoms.

The $Fe_3(CO)_9CH_3R$ (I), R = H, cluster exists as three tautomers in solution: $(\mu\text{-H})_3Fe_3(CO)_9CR$ (Ia); $(\mu\text{-H})_2Fe_3(CO)_9(\mu_3\text{-HCR})$ (Ib); and $(\mu\text{-H})Fe_3(CO)_9(\mu_3\text{-H}_2CR)$ (Ic) in the relative abundances 16:3:1 at 20 °C.[5] On the basis of a comparison of system I with the isoelectronic ferraborane, we would expect that replacing one or two FeH units with Co would favor tautomer Ib over Ia.[6] Indeed neutral mixed metal clusters $FeCo_2(CO)_9CHR$ (II), R = Me, Et, and Ph, are known.[7] In contrast to our prediction, the single endo hydrogen has been assigned a position associated with the trimetal face on the basis of ^1H NMR

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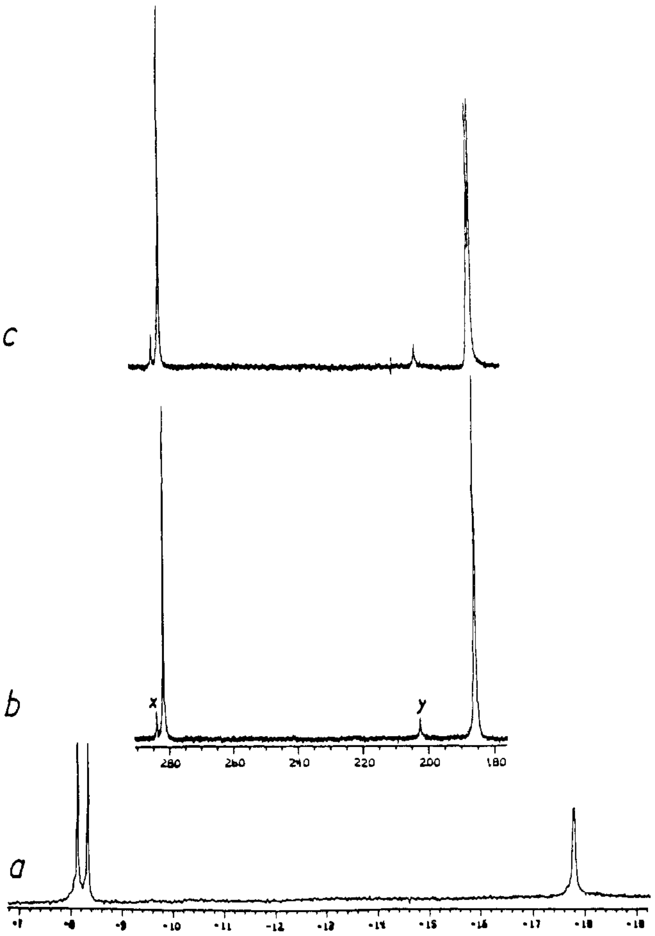
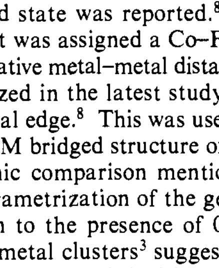
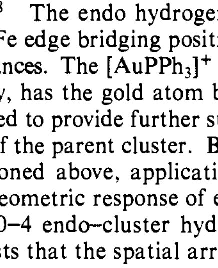


Figure 1. Partial NMR spectra of *II, $FeCo_2(CO)_9$ *CHR, R = Ph, with $\approx$ 98% ^{13}C in the *C position at -35 °C in $C_6D_5CD_3$. (a) ^1H NMR. (b) $^{13}C\{^1H\}$ NMR. (c) ^{13}C NMR. The peaks marked x and y in (b) are $Co_3(CO)_9$ *CPh and $HFeCo_3(CO)_{12}$, respectively.

data at 25 °C.[7] Recently, the structure of the phenyl derivative in the solid state was reported.[8] The endo hydrogen was not located but was assigned a Co–Fe edge bridging position on the basis of relative metal–metal distances. The $[AuPPh_3]^+$ derivative, characterized in the latest study, has the gold atom bridging a metal–metal edge.[8] This was used to provide further support for the M–H–M bridged structure of the parent cluster. Besides the isoelectronic comparison mentioned above, application of our simple parametrization of the geometric response of exo ligand orientation to the presence of 0–4 endo-cluster hydrogens on capped trimetal clusters[3] suggests that the spatial arrangement of the CO ligands and the Ph group are more consistent with the presence of an agostic hydrogen on a CM_2 face (IIb) than the presence of a metal bridging hydrogen (IIa). For these reasons, we have reexamined II seeking evidence for a C–H–M interaction.



IIa



IIb

Cluster *II, R = Ph, with $\approx$98% ^{13}C in the capping position, was prepared and purified by using known reactions.[9] At 20 °C the ^1H NMR spectrum of *II exhibits the broad high-field resonance reported earlier but the width and chemical shift depends on spectrometer field strength, suggesting an exchange process of some type. On lowering the temperature, two resonances of unequal area freeze out (Figure 1). One at δ -8.28 is a doublet (J_{CH} = 59.8 Hz) and the other at δ -17.81 is a singlet. At 20 °C the ^{13}C NMR spectrum shows broad resonances at δ 284 and δ 190. Lowering the temperature causes both signals to sharpen (281.4, s; 189.4 d, J_{CH} = 59.5 Hz). Clearly *II in solution is present as an equilibrium mixture of two tautomers. The *least* abundant tautomer undoubtedly has the structure previously postulated (IIa) whereas the *most* abundant tautomer has an agostic hydrogen (IIb). The large upfield shift in the ^{13}C NMR in going from IIa to IIb was observed previously for Ia and Ib[5] and reflects the methyne environment of IIa vs the methylene environment of IIb.[10] The small J_{CH} in IIb relative to that expected for an unbridged methylene CH demonstrates a relatively strong interaction of the hydrogen with the metal base.[1] An analysis of the ^1H spectra as a function of temperature allows the rate of tautomerization of IIa to IIb to be estimated as 5.7×10^3 s^{-1} as 45 °C,[11,12] which corresponds to a free energy of activation of 13 kcal/mol. Clearly, the conversion of a M–H–M hydrogen to a C–H–M hydrogen is a facile process.

Because of its relevance to bimetallic catalysis,[13] considerable effort has been expended in trying to illucidate the effects of a mixed-metal framework on the reactivity of a bound ligand.[14] The results reported here allow us to comment precisely on the effect of changing metal identity in a capped trimetal framework. The relative abundances of IIa and IIb correspond to 0.25 kcal/mol in free energy favoring the C–H–M tautomer. In I, the energy difference between Ia and Ib is 1.05 kcal/mol, favoring the tautomer with three Fe–H–Fe interactions. The difference, 1.3 kcal/mol, is a measure of the effect of the cobalt atoms. However, it is a minimum value as for I, R = CH_3, only tautomer Ia is observed. Clusters II, R = Me and Ph, have similar ^1H NMR behavior,[7] and comparison of I and II, R = CH_3, unambiguously shows that going from a H_3Fe_3C to a $HFeCo_2C$ core promotes the formation of a C–H–M interaction.

This work reemphasizes the fact that cluster tautomerization is likely in a solution environment,[15] and excessive reliance on solid state structures or analogies can be misleading. The effects of a multinuclear metal site on an organic ligand as metal identity is changed are subtle ones, but, despite the small energies involved, perturbations in the cluster metal content can cause hydrogen atoms to be delivered to or retrieved from a cluster-bound carbon atom. Large structural change with small energy input is the behavior one expects if metal clusters are real models for surface interactions.[16] Finally, in a multinuclear cluster environment, the agostic hydrogen should not be considered an unusual structural feature but one that is easily generated from the right main group–metal atom combination.

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[12] This can be compared to the rate of 3.6×10^{-3} s^{-1} at 115 °C for the exchange of Os–H–Os and C–H hydrogens in $H_3Os_3(CO)_9CH$, which has been postulated to proceed via an intermediate involving a C–H–Os interaction. VanderVelde, D. G.; Holmgren, J. S.; Shapley, J. R. *Inorg. Chem.* **1987**, *26*, 3077.

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