

Determination of the Exchange-Coupling Constant of an Fe³⁺–Fe³⁺ Pair in a Cubane-Type Iron–Sulfur Cluster

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Received April 14, 1997

Revised Manuscript Received July 2, 1997

Biological systems extensively employ iron–sulfur clusters with cuboidal Fe₃S₄ and cubane-type Fe₄S₄ cores for electron transport, catalysis, or other functions such as oxygen sensing and DNA regulation.^{1,2} The operative redox couples of protein-bound clusters are [Fe₃S₄]^{1+,0}, [Fe₄S₄]^{3+,2+}, and [Fe₄S₄]^{2+,1+}. Because electronic structure is essential to reactivity, a variety of physicochemical techniques have been employed to characterize the electronic configurations of these clusters. Mössbauer, ENDOR, and NMR studies have revealed that the iron sites of these clusters are either localized Fe²⁺ or Fe³⁺ or they belong to valence-delocalized Fe^{2.5+}Fe^{2.5+} pairs.^{2,3} These delocalization patterns profoundly influence the magnetic properties of the clusters. The low-lying electronic states of Fe₃S₄ and Fe₄S₄ clusters are generally spin multiplets arising from exchange-coupled iron sites. For an Fe₄S₄ cluster, the spin states depend on as many as six exchange-coupling constants, J_{ij} . Additionally, the presence of delocalized Fe^{2.5+}Fe^{2.5+} pairs requires consideration of double exchange,^{4–6} adding at least one parameter, B , per mixed-valence pair. The large number of unknowns has made a determination of the J -values exceedingly unreliable. For instance, for structurally similar Fe³⁺Fe³⁺ pairs in [Fe₄S₄]³⁺ and [Fe₃S₄]¹⁺ clusters, J -values ($J = J_{\text{ferric-ferric}}$) ranging from 40 to 797 cm⁻¹ have been reported ($H = JS_1 \cdot S_2$),^{7–15} while X α calculations have yielded $J = 795$ cm⁻¹ for [Fe₄S₄]³⁺.⁶ NMR studies of the β -CH₂ cysteinate protons

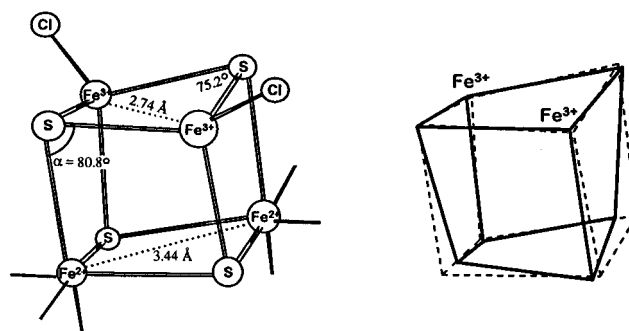


Figure 1. Left: Fe₄S₄Cl₂ portion of **2**, showing selected bond distances (Å) and angles.¹⁸ Right: Fe₄S₄ portion of **2**, (dashed) shown in the same orientation as on the left, superimposed with [Fe₄S₄]³⁺ core of *C. vinosum* HiPIP.¹⁹ The Fe³⁺Fe³⁺ pair of HiPIP, as identified with NMR by Banci *et al.*,³¹ is matched with Fe³⁺Fe³⁺ of **2**. The diagram was generated with Chem3D by superimposing the two structures without scaling.

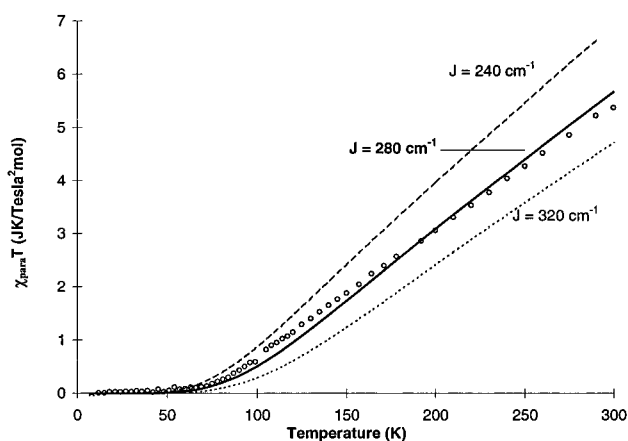


Figure 2. $\chi_{\text{para}}^M T$ vs T plot for 1.0 Tesla data of cluster **1**. The plotted data were obtained by removing contributions of the sample holder, ligand, TIP, and Fe³⁺ impurity. The solid line is a theoretical curve generated from eq 1 for $J = 280$ cm⁻¹ and $g = 2.00$. For comparison, theoretical curves for $J = 240$ cm⁻¹ and $J = 320$ cm⁻¹ are also shown.

of the [Fe₃S₄]¹⁺ cluster in oxidized *Desulfovibrio gigas* ferredoxin (Fd) II have suggested $J = 300$ cm⁻¹,⁸ while magnetization studies have yielded $J > 200$ cm⁻¹.¹⁴ These values are in disagreement with $J \approx 40$ cm⁻¹ inferred from low-temperature EPR.^{7,16}

Accurate values of J are essential to an understanding of the electronic structures of these clusters. An opportunity for *direct* determination of J for the rhomboidal fragment [Fe₂(μ_3 -S)₂]²⁺ is afforded by the [2:2] site-differentiated clusters [Fe₄S₄L₂(RNC)₆] (L = Cl⁻, ArO⁻, RS⁻) whose [Fe₄S₄]²⁺ cores contain this fragment and two diamagnetic low-spin Fe²⁺S₃(RNC)₃ sites.^{17,18} Unlike in [Fe₃S₄]¹⁺ and [Fe₄S₄]³⁺ cores, the foregoing fragment is not subject to additional intracluster exchange interactions. The clusters [Fe₄S₄(SET)₂(tBuNC)₆]¹⁷ (**1**) and [Fe₄S₄Cl₂(tBuNC)₆]¹⁸ (**2**) have been selected for magnetization studies. Although only the structure of **2** has been determined, **2** and two other clusters contain essentially congruent [Fe₂(μ_3 -S)₂]²⁺ fragments,^{17,18} making highly probable a similar relationship between **1** and **2**. Cluster **1** was chosen because its

(16) The different J -values obtained by EPR ($J \approx 40$ cm⁻¹) and magnetization and NMR studies ($J > 200$ cm⁻¹) point to some fundamental problems which have to be resolved (requiring perhaps amending the spin Hamiltonian with terms describing interactions such as anisotropic exchange).

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ethanethiolate ligands closely resemble cysteinyl ligands. As shown in Figure 1, the structure of the $[\text{Fe}_2(\mu_3\text{-S})_2]^{2+}$ fragment of **2** is virtually superimposable on the corresponding fragment of the $[\text{Fe}_4\text{S}_4]^{3+}$ cluster of the High-Potential Iron Protein (HiPIP) of *Chromatium vinosum*.¹⁹ This relationship extends to the $[\text{Fe}_3\text{S}_4]^{1+}$ cluster of *D. gigas* Fd II.²⁰

We have studied polycrystalline samples of **1** and **2** with a SQUID magnetometer in the temperature range 6–300 K in applied fields of 1.0, 2.0, and 3.0 Tesla. For cluster **1**, a plot of $\chi_{\text{para}}^{\text{M}} T$ vs T is shown in Figure 2. The data shown were obtained by subtracting from the raw data the contributions of the sample holder,²¹ ligand diamagnetism, temperature-independent paramagnetism (TIP), and a mononuclear ferric contaminant.²³ The data were modeled using the expression for the molar magnetic susceptibility of an exchange-coupled dimer

$$\chi_{\text{para}}^{\text{M}} = \frac{N_{\text{A}} g^2 \mu_{\text{B}}^2 \sum_{S=0}^5 S(S+1)(2S+1) \exp(-E_S/kT)}{3kT \sum_{S=0}^5 (2S+1) \exp(-E_S/kT)} \quad (1)$$

where S is the total spin and $E_S = 1/2 J[S(S+1) - 35/2]$ are the energies of $\neq J\mathbf{S}_1 \cdot \mathbf{S}_2 + g\mu_{\text{B}}H \cdot \mathbf{S}$ in zero field, with $S_1 = S_2 = 5/2$. For the fitting procedure, J was treated as a free parameter; g -values were assumed to be isotropic and kept in the range 2.00–2.05.²⁴ After accounting for uncertainties in sample weight, diamagnetic corrections, and g -values, the J -values were determined to be $J = 280 \pm 20 \text{ cm}^{-1}$ for **1** and $J = 240 \pm 15 \text{ cm}^{-1}$ for **2**.²⁵

Complex **1**, presumably more appropriate for comparison with cysteinate-coordinated $[\text{Fe}_3\text{S}_4]^{1+}$ and $[\text{Fe}_4\text{S}_4]^{3+}$ clusters, has a J -value in agreement with $J \approx 300 \text{ cm}^{-1}$ reported for the $[\text{Fe}_3\text{S}_4]^{1+}$ clusters of *D. gigas* Fd II⁸ and *Rhodospseudomonas palustris* 7Fe Fd.¹⁵ However, for their NMR analyses, Macedo

*et al.*⁸ and Bertini *et al.*¹⁵ lacked data for the magnetic hyperfine constants, A_{iso} , of the cysteinate $\beta\text{-CH}_2$ protons, and they adopted the value $A_{\text{iso}} = 1 \text{ MHz}$. Recent experimental data suggest that the A_{iso} -values of such protons may vary from 1.2 to 3 MHz.^{26,27} J -values may range considerably depending on the values for A_{iso} used in the analysis of the cysteinate $\beta\text{-CH}_2$ proton resonances. For example, using the reported values of A_{iso} the Curie-type resonances considered by Macedo *et al.*⁸ can be modeled with J -values ranging from 300 to 500 cm^{-1} .

Magnetization data of the synthetic complex $[\text{Fe}_4\text{S}_4(\text{SR})_4]^{1-}$ (**3**) ($\text{R} = 2,4,6\text{-}(\text{i-Pr})_3\text{C}_6\text{H}_2$)¹⁰ have been fit using models that include contributions from Heisenberg–Dirac–van Vleck exchange and double exchange. From these data Jordanov *et al.*¹⁰ determined $J = 797 \text{ cm}^{-1}$ and $B = 592 \text{ cm}^{-1}$. Using a modified model, Belinskiy *et al.* obtained from the same data $J = 730 \text{ cm}^{-1}$ and $B = 40 \text{ cm}^{-1}$.²⁸ Because the J -value of **1** is much smaller than those reported for **3**, we wondered whether the data of **3** could be fit with a smaller J . Using the model of Jordanov *et al.*¹⁰ we found that the magnetization data above 50 K can be modeled, within the experimental uncertainties, with a smaller value for J (350 cm^{-1}) provided that B is kept large ($\approx 900 \text{ cm}^{-1}$).²⁹

The question arises to what extent the J -values obtained here are representative for those of biological clusters. The $[\text{Fe}_2(\mu_3\text{-S})_2]^{2+}$ fragment of **2** (and probably **1**) matches closely the corresponding fragments in the clusters of HiPIP and Fd II; a minor difference concerns the $\text{Fe}^{3+}\text{-S-Fe}^{2+}$ angles (α in Figure 1) of **2** which are 5° larger than the corresponding angles in HiPIP and Fd II. A comparison of the properties of the $\mu_2\text{-S}$ bridged (planar) $[\text{Fe}_2\text{S}_2]^{2+}$ cores and the $\mu_3\text{-S}$ bridged (dihedral angle = 158.3°) $\text{Fe}^{3+}\text{-S}_2\text{-Fe}^{3+}$ fragment of **2** reveals exchange couplings of similar strengths (J -values of 296–316 cm^{-1} have been reported for $[\text{Fe}_2\text{S}_2]^{2+}$ synthetic complexes¹²). With the caveat that cancellation of different contributions to J could occur, these observations suggest to us that exchange coupling is dominated by the bridged structure and that the slight increase in α associated with the enhanced Fe–Fe distances between the two low-spin ferrous sites in **1** and **2** (Figure 1) has a minor influence on the J -value of the $\text{Fe}^{3+}\text{-Fe}^{3+}$ pair.

In conclusion, we provide here precise values of $J_{\text{ferric-ferric}}$ for **1** and **2**. These are the first directly determined J -values for $[\text{Fe}_2(\mu_3\text{-S})_2]^{2+}$ fragments incorporated in a cubane-type cluster, and are relevant to $J_{\text{ferric-ferric}}$ values in protein-bound cuboidal $[\text{Fe}_3\text{S}_4]^{1+}$ and cubane-type $[\text{Fe}_4\text{S}_4]^{3+}$ clusters. Indeed, we suggest that $J_{\text{ferric-ferric}} \approx 300 \text{ cm}^{-1}$ be adopted as the initial value for fitting the magnetic data of such clusters.

Acknowledgment. We thank Drs. B. Lamotte and J.-M. Mousca for valuable suggestions. This research was supported by NIH Grants GM 22701 (E.M.) at Carnegie Mellon University and GM 28856 (R.H.H.) at Harvard University.

Supporting Information Available: Tabulated magnetization data for complexes **1** and **2** (3 pages). See any current masthead page for ordering and Internet access instructions.

JA971171F

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