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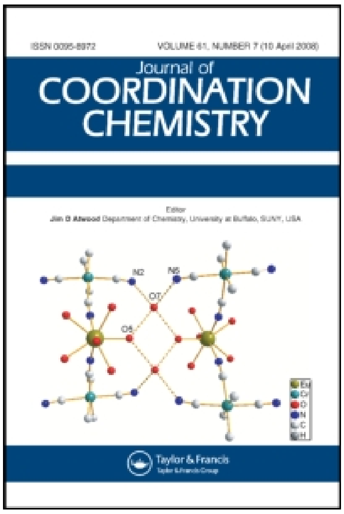

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Kinetics and mechanism of the acid-catalyzed substitution reactions of $[Fe_6S_9(SEt)_2]^{4-}$

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Kinetic studies on the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ and PhS^- in the presence of $[NHEt_3]^+$ to form $[Fe_6S_9(SPh)_2]^{4-}$ are consistent with an acid-catalyzed dissociative mechanism involving rapid protonation of the cluster at both an ethanethiolate and μ_n-S, followed by rate-limiting dissociation of the coordinated ethanethiol, and finally rapid attack of PhSH at the vacant site to form the product. Analysis of the kinetic data gives the pK_a of $[Fe_6S_9(SEt)_2]^{4-}$ as 17.9, in line with other synthetic Fe–S-based clusters and consistent with protonation of a μ_n-S in the cluster core. Further kinetic studies have indicated that Cl^-, CN^-, Bu^tNC, or imidazole can bind and influence the lability of the cluster.

Keywords: Mechanism; Protonation; Substitution; Clusters

1. Introduction

Studies on synthetic Fe–S-based clusters help to establish the fundamental reactivities of this class of molecule and also aid in understanding the reactivity of natural Fe–S-based clusters [1, 2]. One reaction which is common to essentially all synthetic Fe–S-based clusters is protonation. This fundamental reaction not only labilizes the synthetic clusters toward substitution, but is also implicated in the action of certain natural Fe–S-based clusters, notably the nitrogenases.

The nitrogenases are a class of enzymes that convert dinitrogen into ammonia by a sequence of proton and electron transfer steps [3]. There are three types of nitrogenases, distinguished by the metal content of the active site. The most common and extensively studied of the nitrogenases is the so-called Mo-based nitrogenase. The active site in this nitrogenase is called the FeMo-cofactor and is a structurally unique Fe–S-based cluster of the composition $MoFe_7S_9X$(*R*-homocitrate), where X is C, N, or O (figure 1) [4]. The other nitrogenases involve similar active sites but where, it is believed, the Mo has been replaced by V (V-based nitrogenase) or Fe (Fe-only nitrogenase) [5]. In the absence of dinitrogen, all three nitrogenases reduce protons to dihydrogen. The introduction of dinitrogen suppresses the production of dihydrogen, but not entirely. Thus, the limiting stoichiometry of the Mo-based nitrogenase is that shown in equation (1), whilst the limiting stoichiometries of the V-based and Fe-only

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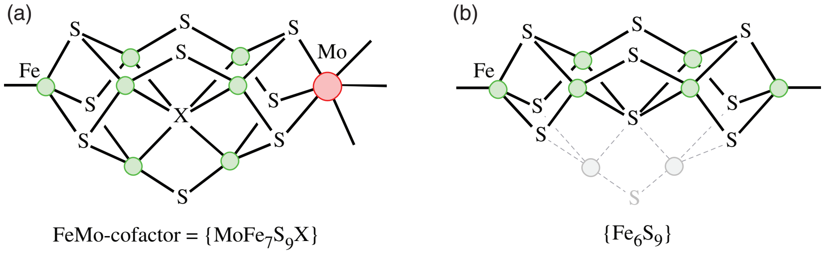

Figure 1. Structures of the cluster cores in FeMo-cofactor of nitrogenase (a) and $[Fe_6S_9(SR)_2]^{4-}$ (R = Et or Bu^t, (b)). The dashed bonds, metals, and S shown in pale grey on the structure in (b) is included to emphasize the structural similarities between FeMo-cofactor and $[Fe_6S_9(SR)_2]^{4-}$.

nitrogenases involve the production of even more dihydrogen. It seems intuitively reasonable that the formation of dihydrogen involves initial protonation of the cluster and this has been explored by calculations [6].

$$N_2 + 8H^+ + 8e \longrightarrow 2NH_3 + H_2 \quad (1)$$

In a series of studies, synthetic Fe–S-based clusters have all been shown to protonate, leading to the suggestion that similar protonation occurs on the cofactors of the nitrogenases. However, the synthetic clusters studied to date are principally cuboidal, containing the $\{MFe_3S_4\}$ core (M = Fe, Mo, W, or V) [2], and although these clusters contain some of the same structural elements as cofactor, the cofactors are sufficiently structurally different that there is the concern that different reactivity may operate in the cofactor. Currently, the laboratory synthesis of the cofactors is yet to be realized. However, as shown in figure 1, $[Fe_6S_9(SR)_2]^{4-}$ (R = Et or Bu^t) [7] is a much closer structural analog to cofactor than, for example, cuboidal clusters, such as $[Fe_4S_4(SR)_4]^{2-}$. Herein, we report kinetic studies in MeCN investigating: (i) the substitution reaction of $[Fe_6S_9(SEt)_2]^{4-}$ with PhS$^-$ in the presence of $[NHEt_3]^+$ and (ii) the binding of various small molecules and ions to $[Fe_6S_9(SEt)_2]^{4-}$ and the effect that the bound substrates have on the substitution kinetics and mechanism. These studies show that $[Fe_6S_9(SEt)_2]^{4-}$ exhibits the same characteristics of substitution, protonation, and binding of small molecules and ions as other synthetic Fe–S-based clusters.

2. Experimental

All manipulations were routinely performed under an atmosphere of dinitrogen using standard Schlenk or syringe techniques as appropriate. All solvents were dried and distilled under dinitrogen immediately prior to use. Acetonitrile was distilled from calcium hydride, while methanol was distilled from $Mg(OMe)_2$. Tetrahydrofuran and diethyl ether were dried by the distillation of the pre-dried solvents from sodium/benzophenone or sodium, respectively. ^{1}H NMR spectra were recorded on a 300 MHz Bruker NMR spectrometer fitted with a wide bore cavity to hold larger NMR tubes operating at 121.5 MHz.

The following chemicals were purchased from Aldrich and used as received: $FeCl_2$, $FeCl_3$, NEt_3, C_6H_5SH, $Na[BPh_4]$, Na, S_8 $[NEt_4]CN$, Bu^tNC, imidazole, and Me_3SiCl. $[NEt_4]Cl \cdot H_2O$ was dried prior to use by heating and stirring at 80°C *in vacuo* for 5 h.

$[NHEt_3]BPh_4$ [8] and $[NEt_4]SPh$ [9] were prepared by literature methods and characterized by elemental analysis and ^1H NMR spectroscopy. Anal. Calcd for $[NHEt_3]BPh_4$ (%): C, 85.5; H, 8.61; N, 3.32. Found (%): C, 85.6; H, 8.70; N, 3.28. NMR: δ 1.2 (t, CH_3CH_2); δ 3.03 (q, CH_3CH_2); δ 6.3 (br, NH); δ 6.9–7.3 (m, Ph) [8]. Anal. Calcd for $[NEt_4]SPh$ (%): C, 70.3; H, 10.5; N, 5.9. Found (%): C, 71.0; H, 10.5; N, 5.7. NMR: δ 1.2 (t, CH_3CH_2); δ 3.1 (q, CH_3CH_2); δ 6.6–7.2 (m, Ph)} [9].

$[NEt_4]_4[Fe_6S_9(SEt)_2]$ was prepared by the method of Hagen *et al.* [7] as black, shiny, crystalline plates. The ^1H NMR spectrum of the cluster showed, in addition to the peaks due to $[NEt_4]^+$, the broadened, shifted peaks characteristic of paramagnetic compounds at δ 16.2 (broad, Fe–SCH_2CH_3) and δ 2.9 (broad, Fe–SCH_2CH_3). In some spectra the peak at δ 2.9 is obscured by one of the peaks attributable to $[NEt_4]^+$. The UV–Vis absorption spectrum of $[NEt_4]_4[Fe_6S_9(SEt)_2]$ is essentially featureless: $\lambda_{max} = 430$ nm (shoulder, $\varepsilon = 3.2 \times 10^4\,dm^3\,mol^{-1}\,cm^{-1}$) and $\lambda_{max} = 550$ nm (shoulder, $\varepsilon = 1.4 \times 10^4\,dm^3\,mol^{-1}\,cm^{-1}$). Anal. Calcd for $[NEt_4]_4[Fe_6S_9(SEt)_2]$ (%): C, 34.1; H, 7.1; N, 4.4. Found (%): C, 33.8; H, 7.1; N, 4.2.

The product of the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ ($0.5\,mmol\,dm^{-3}$), PhS^- ($5\,mmol\,dm^{-3}$), and $[NHEt_3]^+$ ($10\,mmol\,dm^{-3}$) in CD_3CN was established by mixing the reagents, then recording the ^1H NMR spectrum. Within the time necessary to record the first spectrum (a few minutes), the peak at δ 16.2 due to $[Fe_6S_9(SEt)_2]^{4-}$ had disappeared and new peaks attributable to $[Fe_6S_9(SPh)_2]^{4-}$ at δ 8.2 (*m*-H), δ 5.9 (*o*-H), and δ 5.3 (*p*-H) are observed. These peaks are identical to those reported in the literature for $[Fe_6S_9(SPh)_2]^{4-}$ [7]. The UV–Vis absorption spectrum of $[Fe_6S_9(SPh)_2]^{4-}$ is featureless: $\lambda_{max} = 430$ nm (shoulder, $\varepsilon = 3.4 \times 10^4\,dm^3\,mol^{-1}\,cm^{-1}$) and $\lambda_{max} = 550$ nm (shoulder, $\varepsilon = 2.5 \times 10^4\,dm^3\,mol^{-1}\,cm^{-1}$).

2.1. *Kinetic studies*

All kinetic studies were performed using an Applied Photophysics SX.18 MV stopped-flow spectrophotometer, modified to handle the air-sensitive solutions, connected to a RISC pc. The temperature was maintained at 25.0 ± 0.1°C using a Grant LTD 6G thermostat tank with combined re-circulating pump. The solutions of the cluster and the reactants were prepared under an atmosphere of dinitrogen and transferred to the spectrophotometer *via* gas-tight, all-glass syringes. The solutions of all the reagents were prepared by dilution from freshly made stock solutions in MeCN and used within 1 h.

The absorbance-time traces were fitted to a single exponential curve using the Applied Photophysics software. The observed rate constants (k_{obs}) presented in the figures are the average of at least three experiments. All experiments were performed under pseudo first-order conditions with the concentration of all the reagents in excess over the concentration of the cluster. The dependences of k_{obs} on the concentrations of nucleophiles and acids were established from the plots presented in the text. The error bars on the kinetic data presented in the figures show errors corresponding to 10%. The observed rate constants (k_{obs}) are presented in the "Supplementary material"

The absorbance changes monitored on the stopped-flow apparatus for the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ and an excess of PhS^- and $[NHEt_3]^+$ correspond to the formation of $[Fe_6S_9(SPh)_2]^{4-}$. The initial absorbance corresponds to that of $[Fe_6S_9(SEt)_2]^{4-}$. Over protracted periods (several minutes) further spectroscopic changes are evident, presumably corresponding to the decomposition of $[Fe_6S_9(SPh)_2]^{4-}$ to form $[Fe_4S_4(SPh)_4]^{2-}$, which has been reported in [7].

3. Results and discussion

3.1. *Reaction of $[Fe_6S_9(SEt)_2]^{4-}$ with PhS^- in the presence of $[NHEt_3]^+$*

The kinetics of the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ and PhS^- in the presence of an excess of $[NHEt_3]^+$ ($[NHEt_3^+]/[PhS^-] > 1$) have been studied using stopped-flow spectrophotometry. ^{1}HNMR spectroscopy indicates that the product of the reaction is $[Fe_6S_9(SPh)_2]^{4-}$ [equation (2)]. The presence of $[NHEt_3]^+$ is essential because in its absence no substitution occurs.

$$\left[Fe_6S_9(SEt)_2\right]^{4-} + 2PhS^- \xrightarrow{[NHEt_3]^+} \left[Fe_6S_9(SPh)_2\right]^{4-} + 2EtS^- \qquad (2)$$

In order to fully define the mechanism, it is important to appreciate the nature of the solution species. In MeCN solution, mixing $[NHEt_3]^+$ and PhS^- results in the protolytic equilibrium shown in equation (3) and, in the presence of an excess $[NHEt_3]^+$, this equilibrium lies to the right. Consequently, under these conditions, the nucleophile is PhSH as all PhS^- is converted into PhSH, and the concentration of free $[NHEt_3]^+$ and NEt_3 present can be calculated using the relationships $[NHEt_3^+]_{free} = [NHEt_3^+] - [PhS^-]$ and $[NEt_3]_{free} = [PhS^-]$, as has been described before [2].

$$[NHEt_3]^+ + PhS^- \rightleftharpoons NEt_3 + PhSH \qquad (3)$$

The kinetics of the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ and PhSH in the presence of $[NHEt_3]^+$ exhibits a first-order dependence on the concentration of the cluster, as indicated by exponential absorbance-time traces. This first-order dependence on the concentration of the cluster is confirmed by studies where the concentration of the cluster was varied in the range 0.12–0.016 mmol dm^{-3}, whilst keeping the concentrations of PhS^- (1.25 mmol dm^{-3}) and $[NHEt_3]^+$ (10 mmol dm^{-3}) constant. Under these conditions the observed rate constant did not change ($k_{obs} = 0.25 \pm 0.06\,s^{-1}$).

As shown in figure 2, a plot of k_{obs} against the ratio $[NHEt_3^+]/[NEt_3]$ shows that k_{obs} exhibits a non-linear dependence on the ratio, such that at low values of $[NHEt_3^+]/[NEt_3]$ the rate is first order, but at high values of $[NHEt_3^+]/[NEt_3]$ the rate is independent of the ratio. The data presented in figure 2 cover a wide concentration range of PhSH (1.0–7.5 mmol dm^{-3}) but all data fit to a single curve, indicating that the rate of the reaction is independent of the concentration of PhSH. A further important feature of these kinetics is that the rate depends only on the ratio of $[NHEt_3^+]/[NEt_3]$ and not on the absolute concentrations of either $[NHEt_3]^+$ or NEt_3. The data in figure 2 can be analyzed by the usual plot of $1/k_{obs}$ *versus* $[NEt_3]/[NHEt_3^+]$ [10], and hence the rate law shown in equation (4) can be derived. This rate law is consistent with an acid-catalyzed dissociative substitution mechanism. However, as we have discussed in the studies with cuboidal Fe–S-based clusters containing terminal thiolates, the protonation chemistry is probably more complicated than indicated by these kinetics [2].

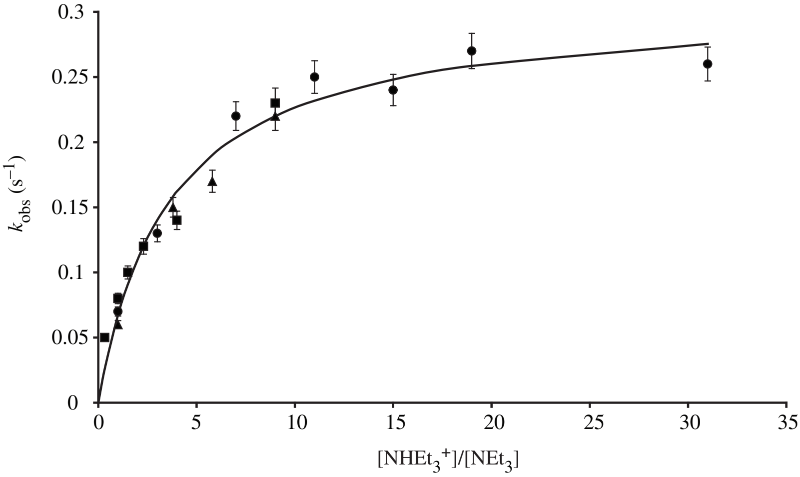

Figure 2. Kinetics of the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ (0.05 mmol dm^{-3}) and PhSH in the presence of $[NHEt_3]^+$ in MeCN at 25.0°C. Data show the dependence of k_{obs} on the ratio, $[NHEt_3^+]_{free}/[NEt_3]_{free}$. The data points correspond to $[PhS^-] = 1.25\,mmol\,dm^{-3}$ (●), $[PhS^-] = 2.5\,mmol\,dm^{-3}$ (▲), and $[NHEt_3^+] = 10\,mmol\,dm^{-3}$, $[PhS^-] = 1–7.5\,mmol\,dm^{-3}$ (■). The curve fit to the data is that defined by equation (4).

The kinetics indicate a single protonation of the cluster and the protonation equilibrium constant, K_1, and derived pK_a, indicates protonation of a μ_n-S (*vide infra*). However, as we have discussed before [2], it seems unlikely that the μ_n-S sites are more basic than the ethanethiolate sulfur. We propose that the initial protonation occurs at the ethanethiolate sulfur and that this protonation equilibrium lies strongly in favor of $[Fe_6S_9(SEt)(SHEt)]^{3-}$. However, protonation of the ethanethiolate is not labilizing because the protonation weakens the S-to-Fe σ-donation, but strengthens the Fe-to-S π-backbonding. The net effect is little change in the lability between the coordinated ethanethiolate and ethanethiol. Only further protonation of the cluster, this time at a μ_n-S, could labilize the cluster toward dissociation of the ethanethiol, and this is the protonation detected in the kinetics. Presumably, the origin of this labilization is because the protonation of μ_n-S diminishes the Fe-to-S π-backbonding to the ethanethiol ligand.

The mechanism for the acid-catalyzed substitution reaction incorporating both protonation of the ethanethiolate ligand and a μ_n-S is shown in figure 3. In this mechanism, the protonation of the cluster core (K_1) labilizes the cluster to dissociation of the ethanethiol group which is lost in the rate-limiting step (k_2). Subsequently, PhSH attacks the vacant site on the terminal Fe site to complete the substitution. If protonation is a rapidly established equilibrium and dissociation of the thiol ligand is rate-limiting then the associated rate law for this mechanism is shown in equation (5). Comparison of equations (4) and (5) gives $K_1 = 0.28 \pm 0.03\,s^{-1}$ and $k_2 = 0.31 \pm 0.03\,s^{-1}$.

$$\frac{-d\left[Fe_6S_9(SEt)_2^{4-}\right]}{dt} = \frac{\left\{(0.086 \pm 0.005)[NHEt_3^+]\right\}\left[Fe_6S_9(SEt)_2^{4-}\right]}{1 + (0.28) \pm 0.03[NHEt_3^+]/[NEt_3]} \tag{4}$$

$$\frac{-d\left[Fe_6S_9(SEt)_2^{4-}\right]}{dt} = \frac{\left\{K_1k_2[NHEt_3^+]/[NEt_3]\right\}\left[Fe_6S_9(SEt)_2^{4-}\right]}{1 + K_1[NHEt_3^+]/[NEt_3]} \tag{5}$$

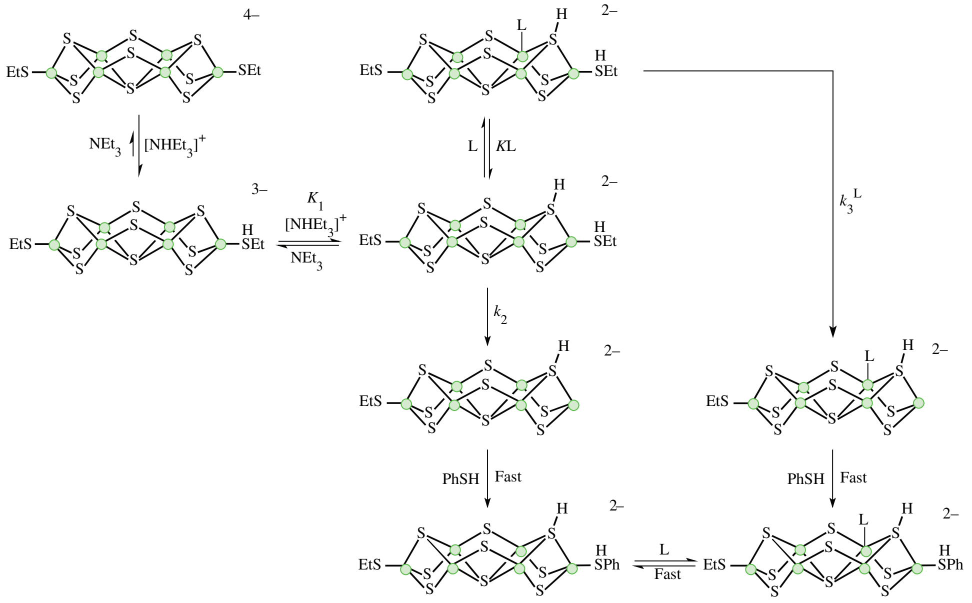

Figure 3. Mechanism for the substitution reactions of the terminal thiolate-ligands on $[Fe_6S_9(SEt)_2]^{4-}$ with PhSH in the presence of $[NHEt_3]^+$ (solvent = MeCN). Also shown is the pathway for substitution observed when L = Cl^-, CN^-, Bu^tNC, or imidazole binds to the cluster.

3.2. *Substitution and protonation characteristics of Fe–S-based clusters*

We will now consider the kinetic features we have observed in the studies reported herein, for $[Fe_6S_9(SEt)_2]^{4-}$, and compare the results with those from the earlier studies on the other synthetic Fe–S-based clusters.

The kinetic data for the reaction of $[Fe_6S_9(SEt)_2]^{4-}$ with PhSH in the presence of $[NHEt_3]^+$ allows the determination of the equilibrium constant for the protonation of the cluster (K_1). As the pK_a of $[NHEt_3]^+$ is 18.46 in MeCN [11], we can calculate that for $[Fe_6S_9(SEt)_2]^{4-}$ pK_a = 17.9. This value is consistent with the pK_as determined for other synthetic Fe–S-based clusters, which all fall in the range pK_a = 17.9–18.9 [2]. A series of studies have shown that the pK_a of synthetic Fe–S-based clusters is insensitive to the composition of the cluster core, the terminal ligands, and the charge on the cluster. This observation is consistent with the protonation occurring at the cluster core μ_n-S sites. In $[Fe_6S_9(SEt)_2]^{4-}$ there are three types of μ_n-S: μ_2-S, μ_3-S, and μ_4-S (figure 1). Although our data do not allow us to identify which sulfur is protonated, the similarity of the pK_a of $[Fe_6S_9(SEt)_2]^{4-}$ with those of other synthetic Fe–S-based clusters indicates that the protonation of $[Fe_6S_9(SEt)_2]^{4-}$ exhibits no special characteristics, and there is no evidence for any unexpected protonation chemistry associated with this cluster.

A general characteristic of the substitution reactions of synthetic Fe–S-based clusters is that when the terminal ligands are thiolates, the substitution generally occurs by a dissociative mechanism at a rate independent of the concentration of the nucleophile [2]. In contrast, when the terminal ligands are chlorides, an associative pathway usually operates. The dissociative substitution mechanism for $[Fe_6S_9(SEt)_2]^{4-}$ follows this pattern. Earlier it was proposed that one of the factors discriminating between the associative and dissociative substitution mechanisms in cuboidal clusters is that the more bulky thiolate disfavor the binding of the nucleophile [2], and thus the dissociative mechanism is enforced. Clearly, $[Fe_6S_9(SEt)_2]^{4-}$ is appreciably less congested than $[Fe_4S_4(SEt)_4]^{2-}$ and it seems unlikely that steric factors are significant. Rather, a more subtle feature may influence the choice of mechanism.

3.3. *Binding of L = Cl^-, CN^-, N_3^-, Bu^tNC, or imidazole to $[Fe_6S_9(SEt)_2]^{4-}$*

We have investigated the binding of various small molecules and ions (generically referred to as substrate = L) to $[Fe_6S_9(SEt)_2]^{4-}$. The binding of substrates to Fe–S-based clusters is often difficult to detect spectroscopically because of small to negligible spectroscopic changes associated with the formation of the adducts. Consequently, we have used a kinetic approach to detect the binding of substrates to the clusters which rely on the observation that the bound substrate affects the lability of the cluster [2, 12]. In this approach, the effect that a substrate has on the rate of substitution is monitored, and the analysis of the kinetic data allows us to determine how many substrates are bound, measure the binding affinity of the substrate, and the effect the bound substrate has on the rate of substitution.

The rate of the reaction of $[Fe_6S_9(SEt)_2]^{4-}$ with PhS^- (1.25 mmol dm^{-3}) in the presence of $[NHEt_3]^+$ (10 mmol dm^{-3}) is affected by the addition of L = Cl^-, CN^-, Bu^tNC, and imidazole, as shown by the data in figure 4, where it is evident that the binding of Cl^- and CN^- inhibit the substitution while imidazole increases the rate of substitution and Bu^tNC has only a slight (inhibitory) effect. An important feature of these data is that, whilst the binding of Cl^-, CN^-, and Bu^tNC suppress the rate of substitution of the cluster, they do not completely stop the substitution. Thus, at high concentrations of the substrate, when all clusters in solution have a substrate bound, the rate of the substitution reaction does not become zero, but is finite. The kinetic behavior shown in figure 4 is consistent with the mechanism shown in figure 3 where, after protonation of the cluster, substitution of the ethanethiol occurs but, in addition, binding of L to the cluster (K_L) competes with this substitution. Consequently, substitution can occur by two pathway: the original k_2 pathway and another where the cluster is both protonated and has L bound (k_3^L pathway). The rate law describing this two pathway mechanism is shown in equation (6) and is derived assuming that both the protonation (K_1) and the binding of L (K_L) are rapidly established equilibria.

$$\frac{-d\left[Fe_6S_9(SEt)_2^{4-}\right]}{dt} = \frac{\left\{\left(K_1k_2[NHEt_3^+]/[NEt_3]\right) + \left(K_1K_Lk_3^L[L][NHEt_3^+]/[NEt_3]\right)\right\}\left[Fe_6S_9(SEt)_2^{4-}\right]}{1+\left(K_1[NHEt_3^+]/[NEt_3]\right)+\left(K_1K_2[L][NHEt_3^+]/[NEt_3]\right)} \tag{6}$$

Equation (6) can be simplified as the values of K_1 and k_2 are known, and the experiments were all performed with $[NHEt_3^+]/[NEt_3] = 7$. Substituting these values into equation (6) gives equation (7).

$$\frac{-d\left[Fe_6S_9(SEt)_2^{4-}\right]}{dt} = \frac{\{(0.20+0.66K_Lk_3^L)[L]\}\left[Fe_6S_9(SEt)_2^{4-}\right]}{1+0.66K_L[L]} \tag{7}$$

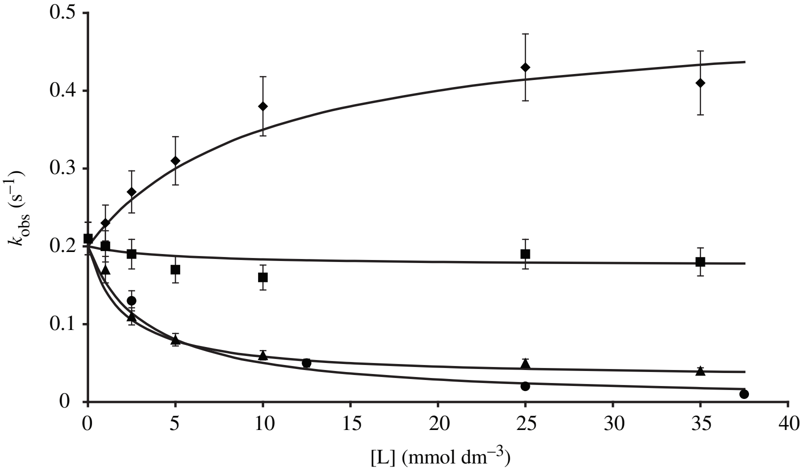

Figure 4. Effects of various molecules and ions (L = Cl$^-$, CN$^-$, Bu^{t}NC, and imidazole) on the kinetics of the reaction between $[Fe_6S_9(SEt)_2]^{4-}$ (0.05 mmol dm^{-3}) and PhSH in the presence of $[NHEt_3]^+$ in MeCN at 25.0°C. Data collected with $[NHEt_3^+]/[NEt_3] = 7.0$ and [PhSH] = 1.25 mmol dm^{-3}. Plots show the dependence of k_{obs} on the concentrations of L. The data points correspond to Cl$^-$ (●), CN$^-$ (▲), Bu^{t}NC (■), and imidazole (◇). The curve fits to the data are those defined by equation (6) and the parameters presented in the text.

The fits to the data in figure 4 are those defined by equation (7) and the derived values of K_L and k_3^L are as follows. L = Cl$^-$: $K_{Cl} = 454.5 \pm 50\,dm^3\,mol^{-1}$, $k_3^{Cl} = 3.3 \pm 0.4 \times 10^{-4}\,s^{-1}$; L = CN$^-$: $K_{CN} = 757.5 \pm 50\,dm^3\,mol^{-1}$, $k_3^{CN} = 0.03 \pm 0.01\,s^{-1}$; L = Bu^{t}NC: $K_{BuNC} = 303.0 \pm 50\,dm^3\,mol^{-1}$, $k_3^{BuNC} = 0.18 \pm 0.05\,s^{-1}$; and L = imidazole: $K_{Im} = 151.5 \pm 30\,dm^3\,mol^{-1}$, $k_3^{Im} = 0.50 \pm 0.05\,s^{-1}$. The rate law shown in equation (6) adequately fits the data for binding all substrates, as shown in figure 4, and there is no evidence for L binding to the unprotonated cluster.

Consider the values of K_L and k_3^L. Although the binding affinities (K_L) follow the order CN$^-$ > Cl$^-$ > Bu^{t}NC > imidazole, all the substrates have similar binding affinities for the cluster with the tightest binding being only five times larger than the weakest. Thus, the cluster shows no significant discriminatory preference for binding the different substrates. In contrast, when bound the various substrates affect the lability of the protonated cluster in markedly different ways with the value of k_2/k_3^L covering the range 1000–0.62.

The acid-catalyzed dissociative substitution mechanism established for the reactions of $[Fe_6S_9(SEt)_2]^{4-}$ with PhSH in the presence of $[NHEt_3]^+$ is perturbed when L binds to the cluster. As the rate-limiting step in the absence of L is dissociation of the ethanethiol ligand, it seems likely that when L is bound, thiol dissociation is still rate-limiting and the binding of L affects the Fe–S(H)Et bond strength. Furthermore, as might be anticipated, different types of bound substrates with different electron-donating or electron-withdrawing capabilities affect the bond strength differently. It is notable that the anionic substrates (Cl$^-$ and CN$^-$) have the most marked inhibitory effect on the rate of the reaction, whilst the neutral Bu^{t}NC has a very minor inhibitory effect and imidazole actually increases the rate of substitution.

The substitution reactions of $[Fe_6S_9(SEt)_2]^{4-}$ are extremely slow in the absence of acid. It is the protonation of $[Fe_6S_9(SEt)_2]^{4-}$ which labilizes the cluster toward dissociation such that substitution in the presence of acid occurs on the seconds timescale. After L has bound, the reactivity of the resultant $[Fe_6S_9(H)(SEt)(SHEt)L]^{n-}$ must be a combination of the effects of the protonation and the bound L on the lability of the Fe–SHEt bond. Simplistically, when the nucleophiles bind to the protonated cluster, it seems likely that this will, to some extent, modulate the effect of the bound proton. However, it is not easy to quantify the extent to which each nucleophile will negate or complement the labilizing effect of the proton. The so-called E_L values (Cl^-, $E_L = -0.24$; CN^-, $E_L = 0.02$; Bu^tNC, $E_L = 0.45$; imidazole, $E_L = 0.12$) [13] can be used as a quantitative description of whether a ligand is a σ-/π-donor (negative E_L) or a σ-donor/π-acceptor (positive E_L values). However, in considering the reactivities of $[Fe_6S_9(H)(SEt)(SHEt)L]^{n-}$ it seems likely that a crucial factor is the relative positions of the bound proton, bound nucleophile and leaving group. If all three sites are close then it would be anticipated that both nucleophile and proton would effect the lability of the leaving group. In contrast, if the three sites are distant from one another, then the lability of the cluster would be dominated by whether the nucleophile or proton was closest to the leaving group. Without any structural information concerning the sites of protonation and nucleophile binding it is not possible to fully interpret the effects that the various nucleophiles have on the reactivity of $[Fe_6S_9(H)(SEt)(SHEt)L]^{n-}$.

Earlier studies [12] on the cuboidal $[Fe_4S_4(SEt)_4]^{2-}$ and $[\{MoFe_3S_4(SEt)_3\}_2(\mu\text{-}SEt)_3]^{3-}$ showed that binding of small molecules and ions (Cl^-, CO, and N_2O) occurs to these cuboidal clusters and in all cases inhibit the rate of the acid-catalyzed substitution of the Fe–SEt groups. At the time, we commented that with these cuboidal systems the data were insufficiently good to establish whether binding L inhibited the substitution entirely or it just altered the rate of substitution and substitution still occurs with L bound. In the light of our results with $[Fe_6S_9(SEt)_2]^{4-}$, it is now clear that the binding of substrates to synthetic Fe–S-based clusters does not switch off substitution entirely but merely changes the rate of substitution through an electronic effect modulating the labilizing influence of the protonation.

4. Conclusions

The studies on the reaction of $[Fe_6S_9(SEt)_2]^{4-}$ with PhS^- in the presence of $[NHEt_3]^+$, described herein, are consistent with the substitution reactions of the terminal thiolate ligands occurring by an acid-catalyzed dissociative mechanism, with the cluster exhibiting similar protonation and substitution chemistry to that of the other synthetic Fe–S-based clusters that have been studied, including cuboidal and binuclear systems [2]. A variety of small molecules and ions (Cl^-, CN^-, Bu^tNC, and imidazole) have been observed to bind to $[Fe_6S_9(SEt)_2]^{4-}$ by the perturbation they afford to the rate of the substitution reaction with PhS^- in the presence of $[NHEt_3]^+$. The bound molecules or ions can either inhibit the substitution reaction (Cl^-, CN^-, or Bu^tNC) or accelerate the substitution (imidazole).

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References

[1] S.C. Lee, R.H. Holm. *Chem. Rev.*, **104**, 135 (2004).

[2] R.A. Henderson. *Chem. Rev.*, **105**, 2365 (2005); R.A. Henderson. *Coord. Chem. Rev.*, **249**, 1841 (2005).

[3] B.M. Hoffma, D.R Dean, L.C. Seefeldt. *Acc. Chem. Res.*, **42**, 609 (2009); B.K. Burgess, D.J. Lowe. *Chem. Rev.*, **96**, 2983 (1966).

[4] D.C. Rees, F.A. Tezcan, C.A. Haynes, M.Y. Walton, S. Andrade, O. Einsle, J.B. Howard. *Philos. Trans. R. Soc., A*, **363**, 971 (2005).

[5] R.R. Eady. *Chem. Rev.*, **96**, 3013 (1996).

[6] I. Dance. *Aust. J. Chem.*, **47**, 979 (1994); I. Dance. *Chem. Commun.*, 165 (1997); I. Dance. *Chem. Commun.*, 523 (1998); T. Lovell, J. Li, T. Liu, D.A. Case, L. Noodleman. *J. Am. Chem. Soc.*, **123**, 12392 (2001); T. Lovell, J. Li, D.A. Case, L. Noodleman. *J. Am. Chem. Soc.*, **124**, 4546 (2002); T. Lovell, R.A. Torres, W.G. Hau, T. Liu, D.A. Case, L. Noodleman. *J. Biol. Inorg. Chem.*, **7**, 735 (2002); M.C. Durrant. *Biochemistry*, **41**, 13934 (2002); M.C. Durrant. *Biochemistry*, **41**, 13946 (2002); U. Hunter, R. Ahlrichs, D. Coucouvanis. *J. Am. Chem. Soc.*, **126**, 2588 (2004); I. Dance. *Dalton Trans.*, 5977 (2008); I. Dance. *Dalton Trans.*, 5992 (2008).

[7] G. Christou, M. Sabat, J.A. Ibers, R.H. Holm. *Inorg. Chem.*, **21**, 3518 (1982); K.S. Hagen, A.D. Watson, R.H. Holm. *J. Am. Chem. Soc.*, **105**, 3905 (1983).

[8] J.R. Dilworth, R.A. Henderson, P. Dahlstrom, T. Nicholson, J.A. Zubieta. *J. Chem. Soc., Dalton Trans.*, 529 (1987).

[9] R.E. Palermo, P.P. Power, R.H. Holm. *Inorg. Chem.*, **21**, 173 (1982).

[10] R.G. Wilkins. *Kinetics and Mechanisms of Reactions of Transition Metal Complexes*, VCH, Weinheim, Germany (1991).

[11] K. Izutsu. *Acid-Base Dissociation Constants in Dipolar Aprotic Solvents*, Blackwells Scientific, Oxford (1990).

[12] R.A. Henderson, K.E. Oglieve. *J. Chem. Soc., Dalton Trans.*, 1467 (1993); R.A. Henderson, K.E. Oglieve. *J. Chem. Soc., Dalton Trans.*, 1473 (1993).

[13] A.B.P. Lever. *Inorg. Chem.*, **46**, 11145 (2007).