Chapter 17

Applications of Paramagnetic NMR Spectroscopy for Monitoring Transition Metal Complex Stoichiometry and Speciation

Debbie C. Crans[1], Luqin Yang[1], Ernestas Gaidamauskas[1], Raza Khan[1], Wenzheng Jin[1], and Ursula Simonis[2]

[1]Department of Chemistry, Colorado State University, Fort Collins, CO 80523–1872
[2]Department of Chemistry and Biochemistry, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132–4163

Although it is well established that paramagnetic NMR spectroscopy is a powerful tool to derive structural information, the methodology is still not yet universally applied to paramagnetic small molecule complexes. In this paper paramagnetic ^{1}H NMR spectroscopy is investigated as a convenient method for the experimental inorganic chemist to elucidate solution structures and speciation of small molecule metal complexes derived from 2,6-pyridinedicarboxylic acid as ligand. Spectra of complexes with O_h geometry, in which the spin states of the metal ion range from d^3 (Cr^{3+}), d^5 (Fe^{3+}), d^6 (Fe^{2+}), d^7 (Co^{2+}) to d^8 (Ni^{2+}), were recorded and analyzed. For all complexes the ^{1}H NMR spectra give well-resolved, easy detectable lines, which depending on the spin state and electron relaxation time of the metal ion and the pH of the solution can be fairly broad. Regardless, the spectra allow complexes of 1:1 and 1:2 stoichiometries to be distinguished in spite of the metal nucleus short nuclear correlation and relaxation times, and the magnitude of the hyperfine shift spread. The pH stability profile and the ability of the complexes to undergo ligand exchange reactions were also investigated for each of the complexes. This work demonstrates that paramagnetic ^{1}H NMR spectroscopy is very useful for characterizing small molecule complexes and their solution chemistry without requiring a detailed analysis of the hyperfine shifts and relaxivities.

Introduction.

NMR spectroscopy remains one of the major tools for examining solution structures of inorganic complexes and for determining their purity and identity. Although NMR spectroscopy is most commonly used to characterize diamagnetic inorganic compounds (*1*), it is well established that NMR spectroscopy provides valuable information on complex structure and spin and oxidation states of the metal ion. Most paramagnetic NMR applications focus on large biomolecules (*2-18*), however, paramagnetic NMR spectroscopy can also be a powerful tool in small molecule chemistry, providing valuable information on solution species (*19-28*). In this work we describe the application of paramagnetic ^1H NMR spectroscopy to characterize the structures and speciation of a series of related small molecule metal complexes. The ^1H NMR spectra presented here were recorded to ultimately determine the effects of first row transition metal complexes on streptozotocin (STZ)-induced diabetic rats (*29-33*). To this end, the structure and stability of a series of 2,6-pyridinedicarboxylate (dipicolinate) complexes were investigated (Fig. 1) (*29-33*). The complexes contain five first row transition metal ions, namely Cr^{3+} (d^3), Fe^{3+} (d^5), Fe^{2+} (d^6), Co^{2+} (d^7) and Ni^{2+} (d^8), in which each of the metal ions has at a minimum two unpaired electrons (Fig. 2). These complexes are, thus, paramagnetic. In spite of the fast nuclear relaxation times and short correlation times of the complexes, it was possible to characterize unambiguously all complexes of either 1:1 or 1:2 stoichiometry and to investigate their pH stability, thereby demonstrating the general applicability of paramagnetic NMR spectroscopy to the characterization of such complexes. It will be shown that all complexes with comparable electron relaxation times of the metal ion (Cr^{3+} and Fe^{3+} vs. Co^{2+}, Fe^{2+} and Ni^{2+}) exhibit similar paramagnetic shift trends in spite of their different electron relaxation times, Fermi contact, dipolar coupling and relaxation mechanisms. These shifts can be attributed to either the formation of a mono- or a bis-dipicolinate complex.

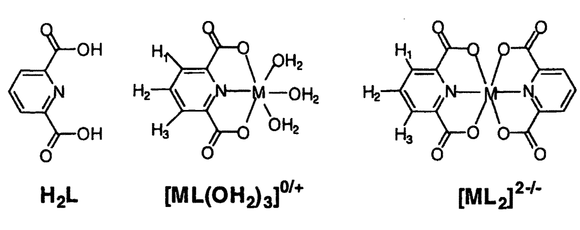

Fig. 1. The structures of ligand, the 1:1 and 1:2 dipicolinate complexes and the proton numbering schemes are shown. Both the 1:1 and 1:2 complex are presumed to coordinate dipic^{2-} in a tridentate manner based on experimental evidence for this series of complexes described elsewhere in detail (31). Other possible structural alternatives exist but are not discussed further here.

The interactions of the spin of the nucleus under investigation and the spins of the unpaired electrons of the metal ion greatly affect the relaxation times of the complexes (*14-17, 34, 35*). The nuclear relaxation times of transition metal ions are very short, and, thus, spectra with a large chemical shift range are obtained (Fig. 3). Depending on the relaxation times of the nucleus under investigation, the resonances are typically much broader than those of diamagnetic complexes (Fig. 3). The broadness of the signals leads to a decrease in peak height, which can affect the signal-to-noise ratio. To avoid a decrease in signal-to-noise ratio, it is essential, that the spectral parameters be adjusted according to the short nuclear relaxivities. Selection of proper acquisition parameters does not always guarantee that all signals can be detected. For some complexes the relaxation times are so short that their resonance lines are rendered undetectable or are hardly discernable from the baseline due to their broadness. Depending on the electronic spin state of the complex, which imparts a certain geometry onto the complex, a wide range of resonance shifts can be observed, which depending on the degree of unpaired electron spin delocalization into ligand orbitals can span a range of hundreds of ppm (*14-17, 36, 37*).
The much greater differences that are observed for the chemical shift range of paramagnetic compounds than of the corresponding diamagnetic complexes, and their origins have been discussed in detail by several authors (*14, 16, 17*). Furthermore, the optimization of spectral parameters to obtain spectra with good signal-to-noise ration and differences between the analysis of NMR spectra of diamagnetic and paramagnetic compounds have been described in detail elsewhere (*14-17*). The objective of this paper is to describe the practical applicability of ^{1}H NMR spectroscopy to paramagnetic complexes to encourage the novice investigator to use this technique to derive structural information without having to analyze hyperfine shifts and patterns. We will show that the resonance assignment and complex quantization is straightforward for the complexes under investigation. The signals can be assigned unambiguously by a titration study in which spectra are recorded at different metal ion:ligand ratios. However, additional structural information can be obtained such as whether the complexes are coordinated by one or two dipicolinate ligands. Furthermore, the determination of the chemical shift ranges of the complexes allows characterization of the spin states. In addition, qualitative and quantitative data can be obtained by peak integration, and if used cautiously, it is an effective tool in characterizing the stability of the complex.

Dipicolinate complexes were selected to illustrate that ^{1}H NMR spectra can be recorded for most of the first row transition metal ions (Cr^{3+} (d^3), Fe^{3+} (d^5), Fe^{2+} (d^6), Co^{2+} (d^7) and Ni^{2+} (d^8)). Previously, paramagnetic NMR studies were reported for characterizing the reaction chemistry of complexes with the metal ions Fe(II) (*2, 19, 22, 26, 27, 38-41*), Fe(III) (*9, 11, 21, 25, 32, 39, 40, 42-47*), Co(II) (*4, 20, 24, 31, 41, 48-51*), Ni(II) (*6, 12, 23, 28, 51-56*) and Cr(III) (*25, 30 57-61*) including the analysis of electron relaxation times, reaction mechanisms, and electron-nuclear correlation times. Dipicolinic acid contains two acidic protons (pK_a values of 2.0 and 4.5 (*62*)), and deprotonation in the presence of

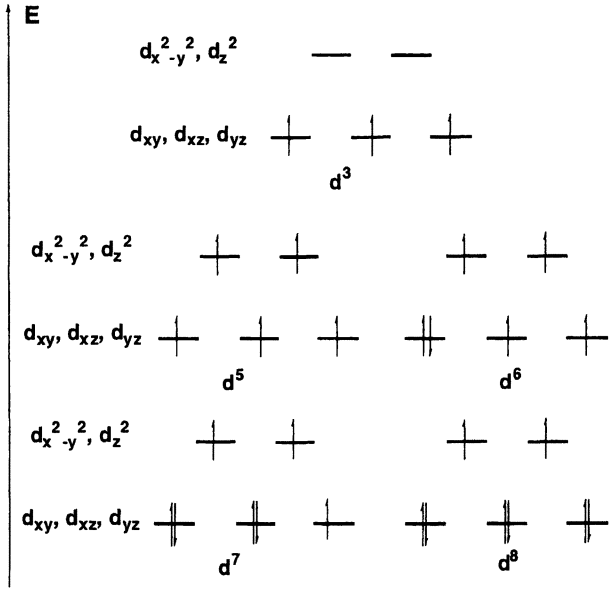

Fig. 2. The d^3, d^5, d^6, d^7 and d^8 high spin states for the complexes with O_h geometry under investigation.

metal ions leads to complex formation with Cr(III), Fe(III), Fe(II), Co(II) and Ni(II). As will be discussed below in more detail, the ^{1}H NMR spectra shown in Fig. 3 reflect the different spin states of the metal ion, their nuclear relaxation processes, and the differences in stabilities of the dipicolinate complexes. It will also be shown that distinction between the 1:1 and 1:2 complexes and their quantitation is possible (Fig. 3). The spectroscopic studies presented in this work serve to document the general usefulness of paramagnetic ^{1}H NMR spectroscopy to the experimental synthetic inorganic chemist.

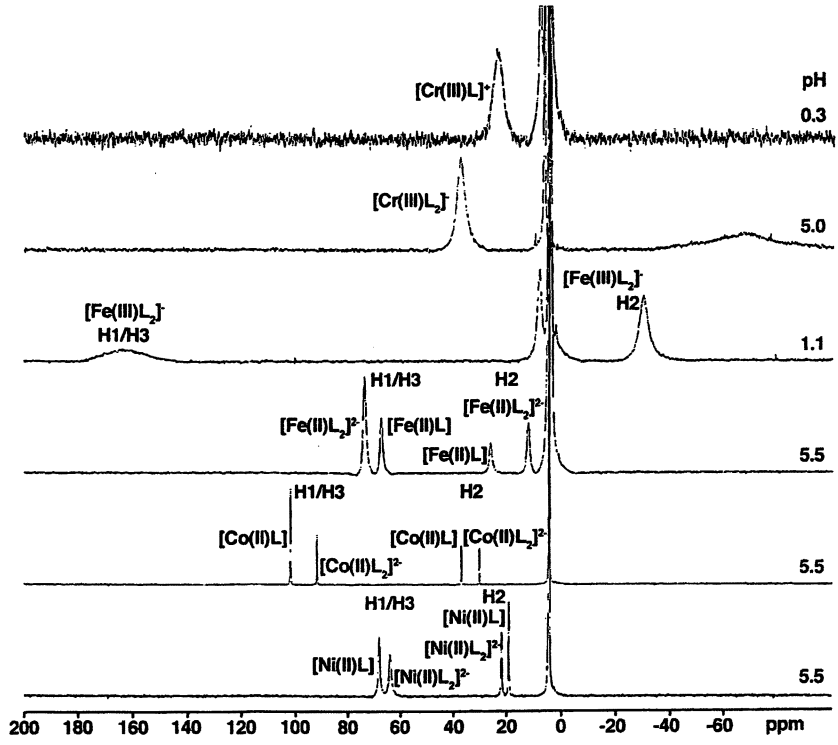

Fig. 3. The paramagnetic ^{1}H NMR spectra are shown of transition metal dipicolinate complexes. The spectra shown are the 1:1 and the 1:2 Cr(III) complex (30), the 1:2 Fe(III) complex (32), the 1:2 and 1:1 Fe(II) complexes (32), the 1:1 and 1:2 Co(II) complexes (31) and the 1:1 and the 1:2 Ni(II) complexes (33).

Materials and Methods.

Preparation of Complexes. The complexes $[Co(dipic)_2Co(H_2O)_5]\cdot 2H_2O$ (*31*), $K_2[Co(dipic)_2]$ (*31*), Co(dipic) (*31*), $[Co(H_2dipic)(dipic)]$ (*31*), $Na_2[Fe(dipic)_2]\cdot 2H_2O$ (*63*), $Na[Fe(dipic)_2]\cdot 2H_2O$ (*63*), $[Fe(dipic)(OH_2)(\mu\text{-}OH)]_2$ (*64*) and $K[Cr(dipic)_2]$ (*30*) where 2,6-pyridinedicarboxylate (dipicolinate) is abbreviated as dipic, were prepared as described previously. The $K_2[Ni(dipic)_2]\cdot 7H_2O$ and $[Ni(dipic)]_2\cdot 2H_2O$ complexes were prepared from 2,6-pyridinedicarboxylic acid (H_2dipic) and $NiCl_2$ as described elsewhere in detail (*33*).

Solution Preparation. Unless otherwise noted, the samples for NMR analysis were prepared by dissolving crystalline complexes and free ligand in deuterium oxide. The composition of the solutions varied and depended on whether the complex was prepared in the presence and absence of free ligand or solutions of metal ion and free ligand depending on complex stability profile. When necessary the pH was adjusted with DCl or NaOD solutions. The pH values reported are those measured and not adjusted for the presence of D_2O. In some cases (such as solutions containing Fe(II) at pH $\geq$ 9.1 or Fe(III) at pH $\geq$ 5.0) insoluble species (presumably including metal hydroxides) were removed, and supernatant solutions were used to acquire the ^1H NMR spectra.

NMR Spectroscopy. ^1H NMR spectra were recorded on Varian INOVA–300 and 400 spectrometers operating at 300.118 and 400.107 MHz, respectively, and temperatures of 300 $\pm$ 1K. The ^1H NMR spectra were recorded with the standard pulse sequence (INOVA/s2pul) using a spectral width of 200-250 kHz, a data size of 2048-24000 points, a relaxation delay of 50-100 ms to yield acquisition times between 0.5-1.2 s for Co(II) (*31*), 0.12 s for the Ni(II) (*33*), 0.1 s for the Fe(II) (*32*), 0.05 s for the Fe(III) (*32*), and 0.9 s for the Cr(III) (*30*) compounds. After Fourier transformation and apodization with a 2 to 20 Hz exponential line broadening factor, depending on the specific complex, the data were phase corrected to yield the NMR spectra. Chemical shifts are referenced relative to the residual HOD peak of D_2O at 4.80 ppm or external DSS (sodium salt of 3-methyl(silyl)propane sulfonic acid).

The 2D ^1H chemical exchange (EXSY) NMR spectra were recorded on the Varian INOVA-300 NMR spectrometer operating at 300.138 MHz and at 293 $\pm$ 1 K using the standard pulse sequence (INOVA/noesy) (*31*). The 2D maps were acquired in D_2O using 128 complex pairs in t_1 (States-TPPI) 32 signal averaging transients each over a spectral bandwidth ranging from 31000 Hz to 39000 Hz with 4096 complex pairs in t_2. Recycle delays ranged from 0.01-0.3 s. Mixing times of 0.015-0.8 s were used and optimized for each of the complexes to obtain maximum cross peak intensity. The data were processed with Gaussian apodization fit to the linear predicted data in t_1 and Gaussian weighted apodization in t_2. After zerofilling and Fourier transformation, the final 2D spectral matrix consisted of 4 K $\times$ 4 K complex pairs.

Results and Discussion.

Complexes of Cr(III), Fe(II), Fe(III), Co(II), and Ni(II) with dipicolinic acid were prepared as described previously (*30, 31, 33, 63, 64*). Both 1:1 and 1:2 complexes are formed with each of the metal ion assuming that $dipic^{2-}$ coordinated to the metal ion in a tridentate manner as has been shown previously for the Co-complexes (*31*). Although other possible modes of binding have been described (*31*), the NMR spectra presented below support formation of complexes with the stoichiometries 1:1 and 1:2 as is shown in Fig. 1. Below we will describe in detail each complex, but at this point some general statements will be made for all the transition complexes investigated. The ^1H NMR spectra of the dipicolinate complexes are shown in Fig. 3; the free ligand in the absence of any paramagnetic metal ion gives rise to a pH dependent spectrum with three signals resonating from 7 to 9 ppm (*29*) and this spectrum is, thus, not shown. However, the resonances of free ligand are observed in the spectrum of $[Fe(III)(dipic)_2]^-$ as one broad signal (at ~8 ppm) and one close to the HOD signal (~5 ppm). Although the electronic spin states of the metal ion in these complexes vary dramatically, several similarities are apparent. Regardless of the reported solid state structure of the respective complexes, the observed aqueous solution species in the absence of evidence to the contrary is anticipated to coordinate to the metal ion in a tridentate manner to form dipicolinate complexes of both 1:1 and 1:2 stoichiometries (Fig. 1). The two sets of resonances in the ^1H NMR spectra are attributable to either the 1:1 or the 1:2 complex (Fig. 3). For each complex we have carried out studies, in which the metal to ligand ratio has been monitored by examining the concentration dependences and/or Job plots, respectively. The complex obtained in solution at a high metal to ligand ratio has been attributed to a 1:1 complex. The second complex formed upon decreasing the metal to ligand ratio and in the presence of a 2-fold ligand (and larger) excess is assigned to the 1:2 complex.

Considering the chemical shifts for all 10 complexes, it can be concluded that in the case of the Cr(III), Fe(II) and Fe(III) dipic complexes the chemical shifts for the resonances of the 1:2 complex are further downfield than for 1:1 complex. This pattern is reversed for the Ni(II) and Co(II) complexes. For these complexes the signals of the 1:1 complex are downfield from those of the 1:2 complex. Whereas in diamagnetic complexes the chemical shifts reflect the electron density provided to the ligand by the metal ion, a similar interpretation cannot be used for these paramagnetic complexes, since upfield and downfield shifts are related to the contact interactions, i.e., the transfer of unpaired electron spin density into ligand orbitals, the dipolar interaction, and/or the mechanisms of unpaired electron spin polarization. Regardless of the effects contributing to the chemical shifts of paramagnetic complexes, a study in which the metal ion:ligand ratio is varied will provide information on the stoichiometry of the complex. In addition, a correlation of signal linewidth and chemical shift with

distance between the proton and metal center will unambiguously assign many of the signals.

Independent of complex stoichiometries all dipicolinate complexes span a much greater chemical shift range (Table I) than the corresponding diamagnetic complex $[VO_2dipic]^-$ (*29*). All complexes have two signals for the three dipic-protons and fail to show the pH dependence of the free ligand reflecting the sequential deprotonation of H_2dipic. Protons H1 and H3 in the complexes are chemically equivalent and give rise to the most downfield shifted signals in each of the complexes (Fig. 3). This resonance is expected to be the most downfield shifted, since protons H1 and H3 are closest to the paramagnetic metal ion center, and, thus, are influenced the most by the presence of the unpaired electrons. The signal of H2 is shifted less and gives rise to the other peak observed for the complexes of either 1:1 or 1:2 stoichiometry, which is consistent with the greater distance to the paramagnetic center. Examining the spectra in Fig. 3, the magnitude of the paramagnetic shifts and the broadness of the resonance signals correlate with the number of unpaired electrons and the electron relaxation time of the metal ion. However, it should be pointed out the distance to the paramagnetic center and the number of unpaired electrons are only two factors that influence the paramagnetic shifts. In general, paramagnetic shifts are governed by contact and dipolar interactions. In terms of the contact shift, the hyperfine coupling controls the chemical shift, whereas for the dipolar shift, the distance and the angle of the distance vector and the magnetic susceptibility tensor contribute to the chemical shift.

The Cr(III) complexes contain three unpaired electrons, and, consequently, the chemical shifts of the two resonances span a large chemical shift range of 100 ppm with the resonance spread ranging from – 70 to + 40 ppm, (Table I). The high spin Fe(III)-dipicolinate complexes contain five unpaired electrons and their signals spread by 190 ppm from -30 to 160 ppm (Table I). The large resonance spread reveals electron spin delocalization from metal ion orbitals into ligand orbitals although a fraction of the electron spins remains localized on the metal ion.

Table I. ^1H Chemical Shifts of Paramagnetic Metal Dipicolinate Complexes

M^{z+}	*[ML]*		*[ML_2]*	
	H1/H3	*H2*	*H1/H3*	*H2*
Cr^{3+}	-50	24	-70	35
Fe^{3+}	NA[a]	-16	160	-30
Fe^{2+}	68	27	74	13
Co^{2+}	101	36	93	31
Ni^{2+}	68	20	64	22

[a]- not distinct from the baseline.

The corresponding high spin Fe^{2+} complex contains four unpaired electrons. The NMR lines are much sharper, and the chemical shift range (10 to 80 ppm, Table I) is smaller than that observed for the signals of the Fe(III) complex. The smaller chemical shift range and the sharper lines correlate well with the reduced electron spin density of Fe(II). The high spin Co(II)-dipicolinate complexes with three unpaired electrons have a resonance spread of 30 - 110 ppm, which is similar to the one of the complex of the Cr(III) ion that has also three unpaired electrons. However, the Co(II) complex, has much sharper lines than the Cr(III) complexes, which is expected, since the metal centered dipolar relaxation is smaller for the Co(II) complex. In accordance with its two unpaired electrons and its smaller electron relaxation time, the resonances are the least shifted for the Ni(II) complex and span a range from 20 to 70 ppm. The line widths are the narrowest observed in this series of complexes making the NMR spectra of the Co(II) and Ni(II) complexes the easiest to observe. These observations are in agreement with results of Bertini and coworkers who reported that the metal ions most suitable for recording NMR spectra with relatively narrow lines are high-spin tetrahedral Ni(II), penta- and hexacoordinate high-spin Co(II), and high-spin Fe(II) (*14*). Thus, it can be concluded that the electron-nuclear interactions are such that the two signals of the dipicolinate complexes can be easily observed, and that the two sets of signals observed in the spectra for the 1:1 and 1:2 complexes are sufficiently different to be unambiguously distinguished.

Examination of the spectra in Fig. 3, indicates that Cr(III) and Fe(III) complexes yield spectra that are distinct from Fe(II), Co(II) and Ni(II) complexes. The spectra in question contain upfield, shifted resonances for H2, which reflects differences in the delocalization mechanisms of the spins of the unpaired electrons (*14-17*). At first, the discussion below focuses on the Co-complexes. These complexes have been studied in detail (*31*). Following this discussion, the Ni-complexes (*33*), the Fe-complexes (*63, 64*), and finally the Cr-complexes will be described (*30*).

The d^7 Co-dipicolinate complexes. Dissolving 9.0 mM [Co(H_2dipic)(dipic)] and varying the pH from 1.8 to 12.8 result in the spectra shown in Fig. 4 (*31*). In the pH range of 2.5 to 12.8 one major complex is observed. Since little free ligand is present, the observed shifts at 30.6 (H2) and 92.6 (H1/H3) ppm can be attributed to the $[Co(dipic)_2]^{2-}$ complex. In addition to paramagnetic line width broadening, peak broadness can also result from exchange broadening (see Fig. 4) (*1, 65*). As described in detail elsewhere, this class of complexes was subjected to detailed characterization both in the solid state and in solution. In the solid state X-ray crystallography and IR spectroscopy both showed the tridentate coordination of $dipic^{2-}$, $Hdipic^-$ and H_2dipic in most complexes (*31*). Below pH 2, the 1:1 complex is observed giving rise to signals at 36 (H2) and 101 (H1/H3) ppm.

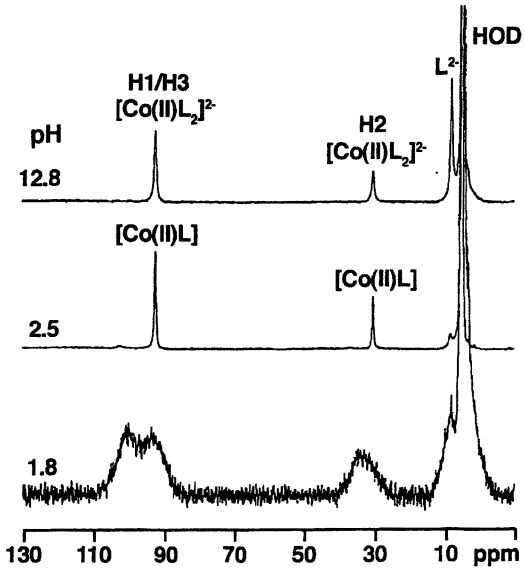

Fig. 4. ^{1}H NMR spectra of solutions of 9.0 mM [Co(H_2dipic)(dipic)] at pH 12.8, 2.5 and 1.8. Reproduced from reference 31.
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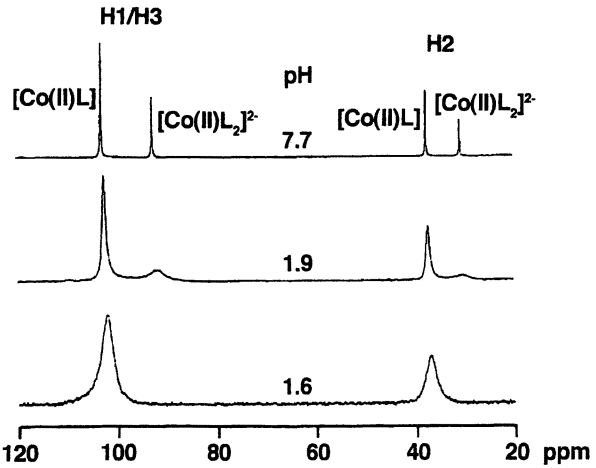

Fig. 5. ^{1}H NMR spectra of solutions of 28 mM [Co(dipic)] at pH values of (from the top) 7.7, 1.9 and 1.6. Reproduced from reference 31.
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In Fig. 5 the spectra are shown of 28 mM [Co(dipic)] at acidic pH. At low pH the 1:1 complex remains the most stable one, however, as the pH is increased, the concentration of the 1:2 complex increased suggesting that at higher pH, the 1:2 complex is the most stable one.

Spectra of four different Co(II)-dipic complexes $K_2[Co(dipic)_2]$, $[Co(dipic)_2Co(H_2O)_5]\cdot 2H_2O$, Co(dipic), and $[Co(H_2dipic)(dipic)]$ are shown in Fig. 6 (*31*). The spectrum obtained by dissolution of $K_2[Co(dipic)_2]$ illustrates the stability of this 1:2 complex. At neutral pH (the spectrum is shown at pH 7.3 in Fig. 6) only this complex, which has sharp lines, is observed. Dissolution of solid $[Co(dipic)_2Co(H_2O)_5]\cdot 2H_2O$ at pH 6.4 results in the formation of both the 1:2 and the 1:1 complex. The sharp NMR lines suggest that these complexes are not interconverting, at least not at pH 6.4. Dissolution of the 1:1 material ([Co(dipic)]) resulted in a solution containing the 1:1 complex at pH 1.6. However, the resulting broad lines indicate that this complex is undergoing ligand exchange at low pH. The latter observation is supported by dissolution of $[Co(H_2dipic)(dipic)]$ at low pH. At pH 1.8 this complex resulted in a solution containing two broad lines with chemical shifts assigned to both the 1:1 and 1:2 complexes. These spectra clearly show the presence of two complexes, and the pH of the solution defines the stability of each of the complexes. These studies demonstrate as previously has been reported that ^1H NMR spectra of Co(II) complexes are very informative (*4, 20, 24, 41, 48-51*).

The dynamics of the complexes were investigated using variable temperature and 2D EXchange SpectroscopY (EXSY) spectroscopy as has been

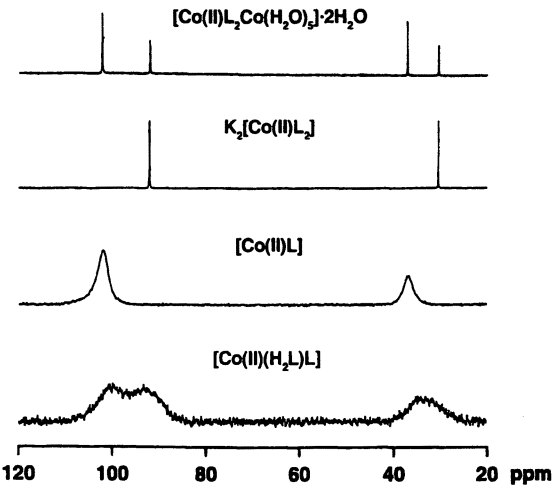

Fig. 6. ^1H NMR spectra of solutions of 14.0 mM $[Co(dipic)_2Co(H_2O)_5]\cdot 2H_2O$ (pH 6.4), 10 mM $K_2[Co(dipic)_2]$ (pH 7.3), 28 mM [Co(dipic)] (pH 1.6) and 9.0 mM $[Co(H_2dipic)(dipic)]$ (1.8). Reproduced from reference 31.

lescribed previously (*1, 31, 67-69*). Variable temperature studies showed that at ɔoth low pH and high pH, the signals shifted and the line widths increased ɔonsistent with the system approaching coalescence (data not shown). In ɜolutions of $[Co(dipic)_2]^{2-}$ and $dipic^{2-}$ the EXSY experiment is specifically ıddressing the question if free ligand will exchange with ligand coordinated to ɨhe Co(II) as shown in eq 1. The ligand exchanging with complex both at low ɪnd high pH was confirmed by the cross peaks between ligand and complex ɔrotons observed in the EXSY maps (Fig. 7). A representative ^1H EXSY ɜpectrum is shown of a solution containing 28 mM $[Co(dipic)_2]^{2-}$ and 27 mM H_2dipic at pH 3.3. The observation of cross peaks between the proton signal for ɨhe 1:2 complex and free ligand documents exchange between these species. Ɽhe fundamental reaction between Co^{2+} and free ligand is not favorable in terms ɔf entropy. The reaction between the 1:2 complex and free ligand is shown in ɜq 1 and this reaction is likely to take place in solutions with excess ligand. By ɾecording the ^1H EXSY spectra at varying pH the ligand exchange was shown to ɔe pH-dependent as described in detail elsewhere (*31*).

$$[Co(dipic)_2]^{2-} + \mathbf{dipic}^{2-} \rightleftharpoons [Co(dipic)(\mathbf{dipic})]^{2-} + dipic^{2-} \qquad (1)$$

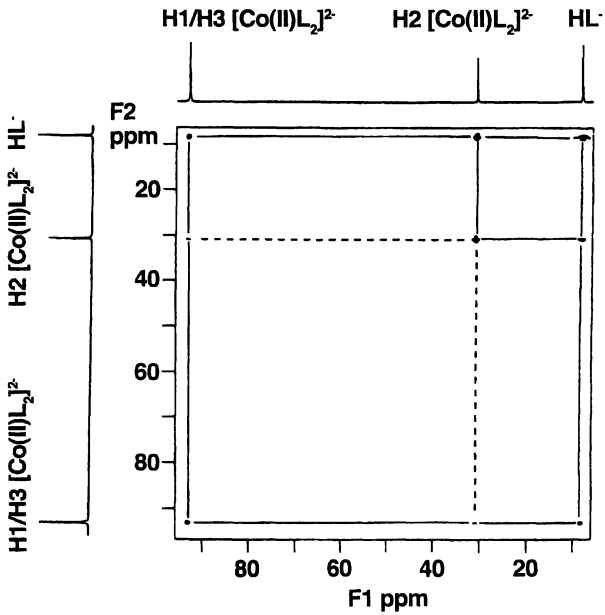

Fig. 7. ^1H EXSY maps of a solution containing 28 mM $[Co(dipic)_2]^{2-}$ and 27 mM H_2dipic at pH 3.3. Reproduced from reference 31.
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By examining the ligand exchange in solutions with higher Co^{2+}:$dipic^{2-}$ ratios, evidence for a different ligand exchange reaction was observed. The ^1H EXSY spectrum in Fig. 8 of 8.8 mM [Co(dipic)] and 5.1 mM $[Co(dipic)_2]^{2-}$ at pH 6.4 revealed cross-signals between $[Co(dipic)_2]^{2-}$ and [Co(dipic)]. This spectrum illustrates that these complexes interconvert with each other as is shown in eq 2. Since little ligand is observed under these conditions, ligand exchange between complexes is not observed. The EXSY maps (Fig. 7 and 8) demonstrate that the 1:2 complex is kinetically labile since ligand exchange does take place between the 1:2 complex and ligand or the 1:1 complex.

$$[Co(dipic)_2]^{2-} + [Co(\mathbf{dipic})] \rightleftarrows [Co(dipic)(\mathbf{dipic})]^{2-} + [Co(dipic)] \qquad (2)$$

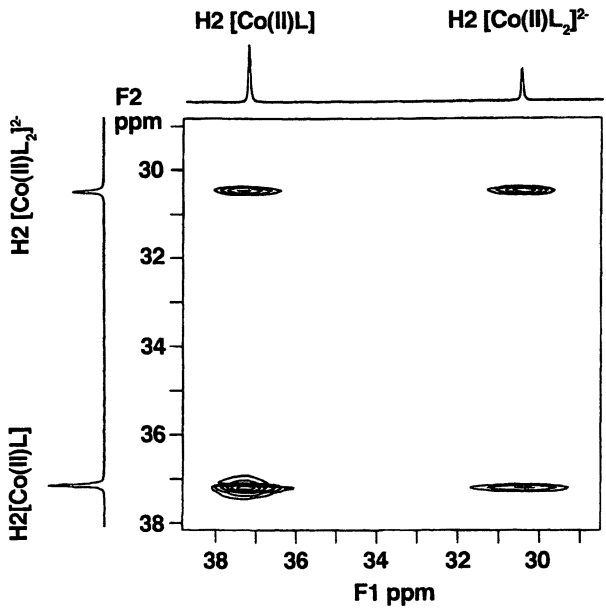

Fig. 8. ^1H EXSY map of a solution containing 8.8 mM [Co(II)dipic] and 5.1 mM $[Co(II)(dipic)_2]^{2-}$ at pH 6.4. Reproduced from reference 31.
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The d^8 Ni-dipicolinate complexes. The spectrum is shown of a solution containing 22 mM $K_2[Ni(dipic)_2]$ (*33*) and 34 mM H_2dipic from pH 10.4 to 1.8 (Fig. 9). In the presence of excess ligand in this entire pH range only the 1:2 complex is observed with signals at 22.1 and 63.7 ppm. However, when dissolving $[Ni(dipic)]_2$ (which contains a 1:1 ratio of ligand and Ni(II)) at pH 5.5 (Fig. 3), both the 1:1 complex with signals at 19.5 and 67.9 ppm and the 1:2 complex are observed. Two species are observed upon preparation of 14 mM

$K_2[Ni(dipic)_2]$ at pH 1.2; both the 1:2 complex and free ligand form (eq.3) (no 1:1 complex). These studies show that the 1:2 complex is very stable over a wide pH range analogous to $[Co(dipic)_2]^{2-}$.

The ^1H NMR spectra of a Ni-complex solution at acidic pH were measured at temperatures ranging from 298 K to about 345 K. As was observed in case of the Co(II) ion, the temperature dependent studies confirm that $[Ni(dipic)]_2$ is in exchange with free ligand, since the ligand and complex signals approach coalescence with increasing temperatures. This observation was confirmed by the formation of cross peaks in the ^1H EXSY map (Fig. 10).

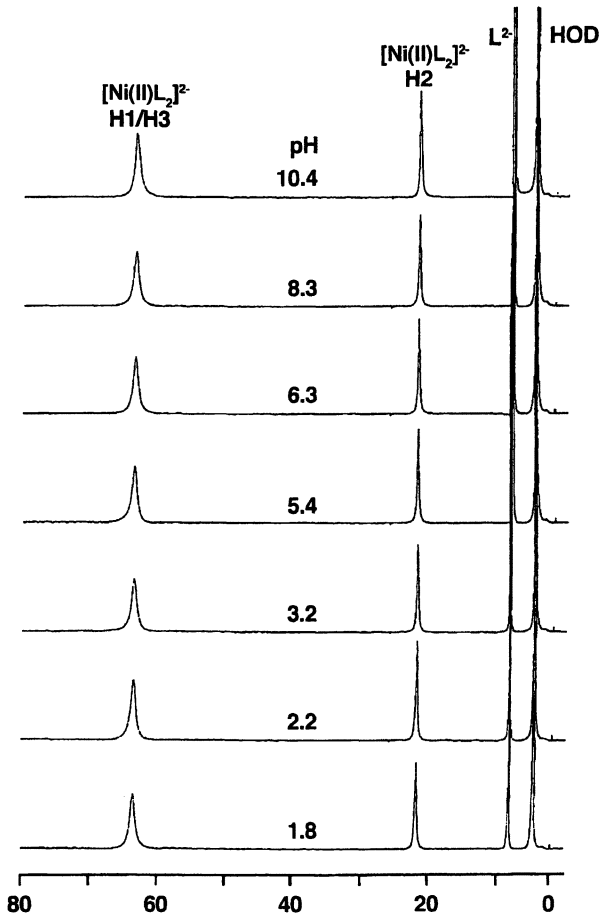

Fig. 9. ^1H NMR spectra of solutions containing 22 mM $K_2[Ni(dipic)_2]$ and 34 mM H_2dipic at varying pH values (10.4, 8.3, 6.3, 5.4, 3.2, 2.2 and 1.8).

The cross peaks observed between the ligand and the protons in complex directly demonstrate exchange between free ligand and $[Ni(dipic)_2]^{2-}$ at acidic pH. No evidence for ligand exchange by EXSY spectroscopy was observed at neutral pH (*33*). These studies demonstrate as previous examples that ^1H NMR spectra of Ni(II) complexes are very informative (*6, 12, 23, 28, 51-56*).

$$[Ni(dipic)_2]^{2-} + \mathbf{dipic^{2-}} \rightleftharpoons [Ni(dipic)(\mathbf{dipic})]^{2-} + dipic^{2-} \qquad (3)$$

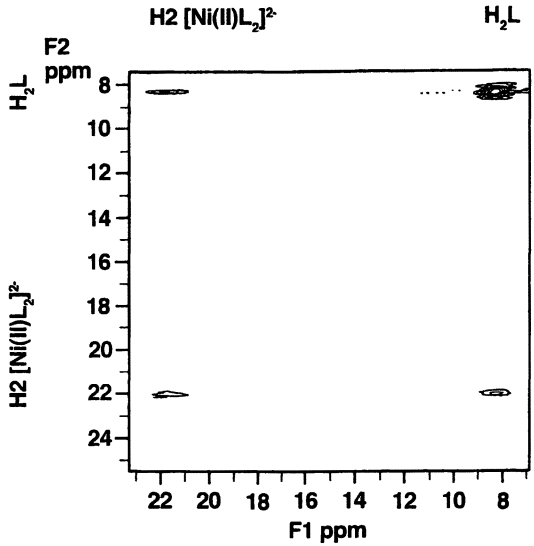

Fig. 10. ^1H EXSY spectrum of a solution of 14 mM $K_2[Ni(dipic)_2]$ at pH 1.2

The d^5 and d^6 Fe-dipicolinate complexes. A number of Fe-dipicolinate complexes were previously prepared and characterized in the solid state (*63, 64*). Several of these complexes were characterized in the solution state and their solution properties investigated using potentiometry and UV-Vis spectroscopy (*66, 70, 71*). In Fig. 11 a solution of 20 mM Fe^{2+} containing varying amounts of dipic-ligand is shown at pH 4.2. The 1:1 complex was the major complex when ligand was present at 7 mM, and the resonances for protons H1, H3 and H2 were observed at 68 and 27 ppm, respectively. As the concentration of ligand was increased the signals attributed to the 1:2 complex at 74 and 12.5 ppm increased. In a pH study, the spectra of a solution containing 20 mM $[Fe(II)(dipic)_2]^{2-}$ were recorded at a pH ranging from 0 and to 12.8 (Fig. 12). The 1:2 complex remains completely intact until about pH 8, when free

ligand is observed in the spectra (Fig. 12). Increasing amounts of ligand in the spectra as the pH is increased show that the 1:2 complex is hydrolytically unstable at alkaline pH. In contrast, the complex is very stable in the acidic pH range and remains in solution down to a pH of about 2.5. Below pH 2 the signals of the complex are significantly broadened indicative of exchange and deprotonation processes, all of which result in reduced complex stability.

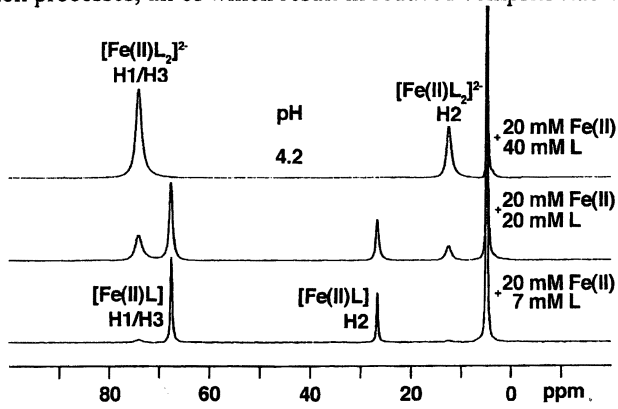

Fig. 11. ^1H NMR spectra of 20 mM Fe^{2+} solutions containing (from the top) 40, 20 and 7 mM dipic at pH 4.2.

In Fig. 12 the peak (–30 ppm) with an asterisk over it grows in at pH 3.5 (and below). This signal is assigned to the 1:2 $[Fe(III)(dipic)_2]^-$ complex with the metal ion in its +3 oxidation state and indicates that, although the Fe(II) complex may be somewhat stable to hydrolysis, it is oxidized at low pH. Since higher pH commonly results in a greater propensity of metal complexes to oxidize, the opposite trend observed here may reflect that the small fraction of Fe(II)-complex which hydrolyzes is rapidly oxidized. The resonances in the ^1H NMR spectra of the Fe(III)-system are more difficult to detect due to the five unpaired electrons of the metal ion when compared to the four unpaired electrons of the metal ion in the Fe(II)-system. The ^1H NMR spectra of 20 mM Fe(III) in the presence of 15, 30 and 40 mM dipicolinate ligand at pH 1.95 resulted in spectra with the signals spanning a range from –30 to 160 ppm depending on the nature of the complex (Fig.13). Two signals were observed at ppm values below 0. In these spectra the proton signals are shifted both upfield and downfield reflecting differences in spin polarization in the delocalization of the unpaired Fe^{3+} spins (*14-17*). The signal of protons H1, H3 centered at 160 ppm is very broad and is difficult to distinguish from the baseline, and is, therefore, not useful for monitoring the existence of the complexes. However, the signal at –16 ppm assigned to the proton H2 accurately report on the nature of the complex existing in solution. As the ligand concentration increases up to 30 mM, a

second signal at –30 ppm emerges. This signal is assigned to the H2 proton of the 1:2 complex, which is the major species in solution with metal ion to ligand ratios of 1:2. Spectra were also recorded of solutions containing Fe(III) complex at various pH values (Fig. 14).

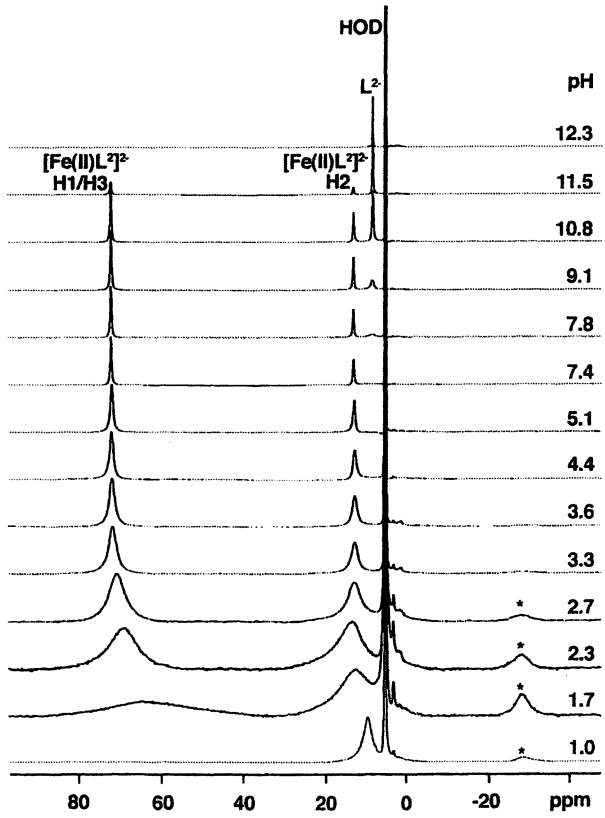

*Fig. 12. ^1H NMR spectra of solutions containing 20 mM $Na_2[Fe(dipic)_2]$ recorded at varying pH values (12.3, 11.5, 10.8, 9.1, 7.8, 7.4, 5.1, 4.4, 3.6, 3.3, 2.7, 2.3, 1.7 and 1.0). The * indicates the presence of the Fe(III) dipicolinate complex.*

These spectra show that the 1:2 complex is stable at acidic pH but not in a solution of basic pH. Above pH 5.0 a brown precipitate formed; supernatant solution spectra show that the Fe(III) was removed by precipitation because the free ligand to complex ratio increases with increasing pH (Fig.14). When comparing the data of the Fe(II)-dipic and Fe(III)-dipic complexes, it can be shown that $[Fe(II)(dipic)_2]^{2-}$ is stable in neutral and slightly alkaline pH regions, whereas $[Fe(III)(dipic)_2]^-$ is stable at acidic pH.

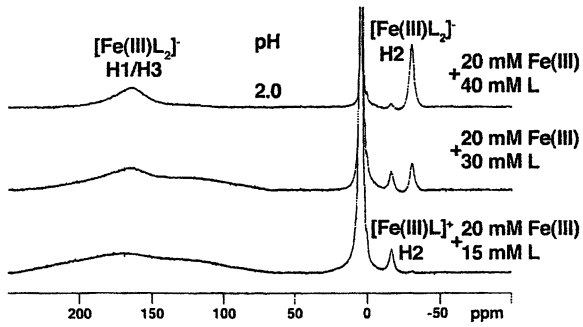

Fig. 13. ^{1}H NMR spectra of 20 mM Fe^{3+} solutions containing (from the top) 40, 30 and 15 mM dipic at pH 2.0±0.2.

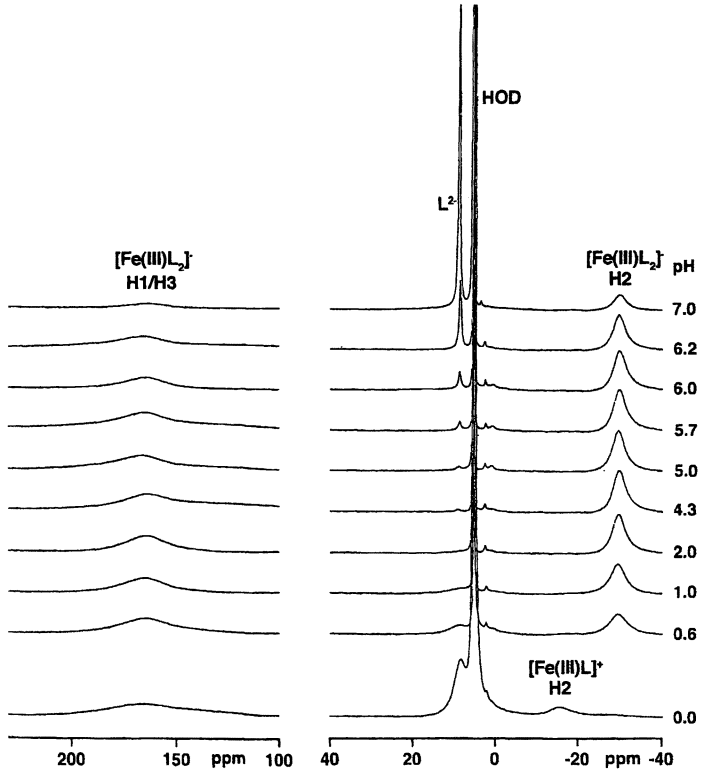

Fig. 14. ^{1}H NMR spectra of solutions containing 20 mM Na[Fe(dipic)$_2$] recorded at varying pH values (7.0, 6.2, 6.0, 5.7, 5.0, 4.3, 2.0, 1.0, 0.6 and 0.0).

The d^3 Cr-dipicolinate complexes. Dissolution of K[Cr(dipic)$_2$] results in a spectrum with signals at –70 ppm and 35 ppm at a pH of about 5 (Fig. 15). As the pH of this solution is decreased to pH 0.9 and 0.4, two new signals are observed at –50 and 24 ppm (Fig. 15). Since free ligand also is formed, the new signals are assigned to the 1:1 species. The chemical shifts of the complex were monitored from pH 1 to 10, and no change in complex identity was observed. In this pH range the 1:2 complex was stable in solution, and no change was detected in the chemical shifts of the two protons, suggesting that neither deprotonation takes place in the pH range from 2-10, nor is ligand exchange observed. However, these studies showed that only at pH below 1 did the 1:1 complex become a stable species in solution. A variable temperature study was performed to confirm whether ligand exchange was occurring. Although the signals were shifting as if they approached coalescence with the uncomplexed ligand signal, examination of the line width showed that the continuous decrease was not consistent with a ligand-exchange process.

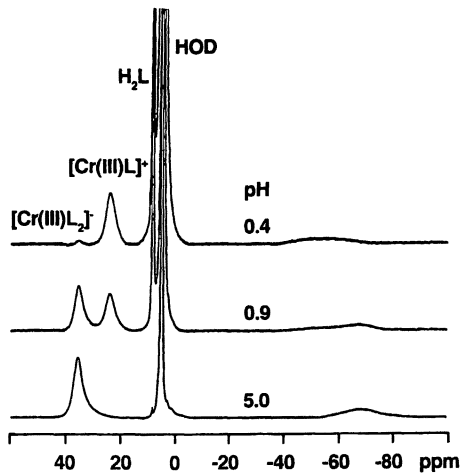

Fig. 15. ^{1}H NMR spectra of solutions containing 45.3 mM K[Cr(dipic)$_2$] at pH 0.4, 0.9, and 5.0.

Summary. In this manuscript we have shown that paramagnetic ^{1}H NMR spectroscopy is an effective tool in investigating complex stoichiometry and speciation in Cr(III), Fe(II), Fe(III), Co(II) and Ni(II) dipicolinate complexes with O_h geometries. We demonstrated that spectra can be obtained for a wide range of metal ion electronic spin states, and although only minimal information is available regarding relaxation mechanisms, the species existing in solution and their quantization can be derived. Despite the significant differences in line widths and extensive line broadening that occurs for some of the complexes, this

method can be characterized as generally applicable to this type of structural and stability analysis.

Acknowledgement.

DCC thanks the American Diabetes Association and NIH (The Institute for General Medicine at The National Institutes of Health) for funding. We thank Dr. Christopher D. Rithner for technical assistance.

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