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Solid-State ^{109}Ag NMR: A Sensitive Environmental Probe for Silver Thiolates

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Ag$^+$ exhibits a rich biological chemistry, serving as a widely-used antibacterial agent,[1] a transcriptional initiator in plants[2] and mammals,[3] a specific target of plasmid-conferred resistance,[4] and a redox-inactive probe for Cu$^{2+/+}$ sites in metalloproteins.[5] Cysteine thiolates are the principal biological ligands for Ag$^+$. Unfortunately, sensitive spectroscopic probes of well-characterized Ag$^+$ complexes with any ligand are exceedingly scarce: neutral compounds are usually very insoluble and nonmolecular,[6] while charged complexes formed with anionic ligands like thiolate undergo rapid exchange, diminishing the information content of otherwise sensitive methods. For example, though solution ^{109}Ag chemical shifts span a 1500 ppm range,[7] exchange and signal averaging in solution cause a single resonance to be observed for $[Ag(CN)_2]^-$, $[Ag(CN)_3]^{2-}$, and $[Ag(CN)_4]^{3-}$,[8] compounds with vastly different Ag$^+$ environments. Solid-state ^{109}Ag NMR[9-11] is not subject to these drawbacks, but data on biologically-significant or structurally-characterized[12] complexes are lacking. The solid-state ^{109}Ag NMR measurements on well-defined Ag$^+$ thiolate model complexes reported herein remedy this situation and demonstrate a sensitivity that greatly surpasses that available with all reported solid-state spectroscopic probes of similar species.[13-15]

Figure 1 shows cross-polarization, magic-angle spinning (CPMAS) ^{109}Ag NMR spectra for a solid sample of $Ag_5[S(CH_2)_3NMe_2]_3[S(CH_2)_3NHMe_2]_3\}(ClO_4)_2$ (Me = CH_3) (**1**) obtained at spinning speeds of 3.7 kHz (top) and 4.1 kHz (bottom). Previous crystallographic analysis of **1** revealed a novel trigonal bipyramid array of metal atoms enclosed within a regular trigonal prism of bridging thiolate ligands,[16] with two different Ag environments: digonal linear coordination for three symmetry-related Ag$^+$ ions and trigonal planar geometry for the remaining pair of symmetry-related Ag$^+$ ions. Accordingly, we find two isotropic peaks at 1228 ppm (isoA) and 826 ppm (isoB) (Table 1), with spinning sidebands for each so indicated in Figure 1. Chemical shift parameters for each Ag environment were determined using Herzfeld−Berger analysis (Table 2).[17] The larger chemical shift anisotropy ($\Delta\sigma$) and very small asymmetry (η) associated with isoB are consistent with linear, two-coordinate Ag, while the peak for the trigonal coordination site (isoA) exhibits a smaller anisotropy.

We have obtained spectra for several other homoleptic solid Ag thiolates and find the observed chemical shifts to be

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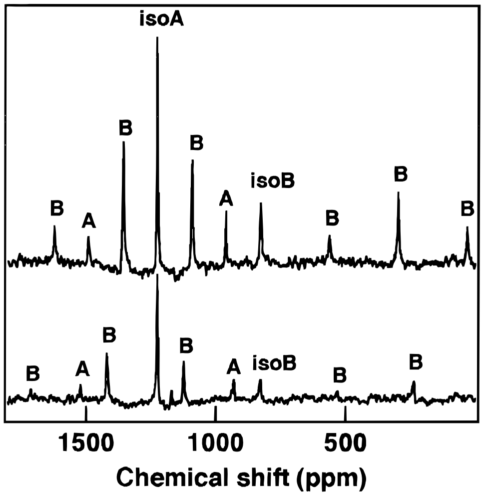

Figure 1. ^{109}Ag CP MAS NMR spectra of **1** at frequencies of 13.852 MHz for ^{109}Ag and 297.372 MHz for ^{1}H. Acquisition parameters: pulse delay, 3.5 s; contact time, 15 ms; ring-down delay, 80 μs. Top: spinning rate, 3.7 kHz; 22 240 transients. Bottom: spinning rate, 4.1 kHz; 8192 transients. Chemical shifts are referenced indirectly to $AgNO_3$ in H_2O (0.0 ppm). Silver acetate was used as the secondary reference (382.7, 401.2 ppm).[11]

Table 1. Ag Coordination Numbers and ^{109}Ag CP MAS NMR Isotropic Shifts of Various Silver Thiolates

	compound[a]	Ag coordn no(s)[b]	σ_{iso} (ppm)[c]
1	$[Ag_5L_3(LH)_3](ClO_4)_2$	3 AgS_2 2 AgS_3	1228, 826
2	$[Ph_4P]_2[Ag_4(SCH_2C_6H_4CH_2S)_3]\cdot 6MeOH$	4 AgS_3	1230, 1220, 1203,[d] 1083[d]
3	$AgS(CH_2)_3CH_3$	AgS_3	962, 952
4	$(Me_4N)_2[Ag_5(SPh)_7]$[e]	1 AgS_2 4 AgS_3	1141,[d] 980[d]
5	Ag_2(1,5-pentanedithiolate)[f]	?	~900−1300
6	$(Me_4N)_2[Ag_6(SPh)_8]$	4 AgS_3 2 AgS_4	none obsd
7	$(AgSC_6H_{11})_{12}$	4 AgS_2 8 AgS_3	none obsd
8	$[AgSCMeEt_2]_n$	AgS_2	none obsd
9	silver glutathione[f]	?	none obsd
10	$[PPh_3Me]_2[AgI_3]$	AgI_3	675

[a] L = $S(CH_2)_3NMe_2$; Ph = C_6H_5; Et = CH_2CH_3. [b] AgS_2 = 2-coordinate, AgS_3 = 3-coordinate, AgS_4 = 4-coordinate. [c] Single values reported were obtained by comparison of spectra obtained at two different spinning speeds. [d] Consists of two or more unresolvable peaks. [e] Dance, I. G. *Aust. J. Chem.* **1978**, *31*, 2195−2206. [f] Reference 15.

remarkably sensitive to differences in environment. For example, all four Ag^+ ions in **2** are trigonally coordinated, but in the idealized C_3-symmetry geometry, the Ag on the 3-fold axis is less distorted than the three similar but nonidentical symmetry-related ions.[18] These structural perturbations are manifested in the NMR spectrum, with a single resonance at 1083 ppm and three closely spaced peaks between 1203 and 1230 ppm. Two isotropic peaks were observed for silver butanethiolate (**3**), a compound whose structure has been described as being three-coordinate on the basis of X-ray powder diffraction studies.[19] The chemical shifts fall at 952 and 962 ppm and were analyzed by the Herzfeld−Berger method (Table 2). The peak at 962 ppm, which exhibits an η of 0, corresponds to symmetric, three-coordinate Ag^+. Comparison of the anisotropies of compounds **1** and **3** suggests that those of **3** more closely resemble two-coordinate than three-coordinate environments. The sensitivity of ^{109}Ag CPMAS NMR to subtle differences in Ag^+−thiolate environments, even within a single coordination number, contrasts sharply with the notable lack of such differentiation in all other solid-state measurements on similar compounds.[13−15]

Table 2. Chemical Shift Parameters for **1** and **3**

1

σ_{iso} (ppm)	σ_{11} (ppm)[a]	σ_{22} (ppm)[a]	σ_{33} (ppm)[a]	$\Delta\sigma$(ppm)[b]	η[b]
1228	968	1109	1607	569	0.44
826	−587	1510	1555	−2120	0.03

3

σ_{iso} (ppm)	σ_{11} (ppm)	σ_{22} (ppm)	σ_{33} (ppm)	$\Delta\sigma$ (ppm)	η
962	−173	1530	1530	−1703	0.00
952	−135	1166	1825	−1631	0.61

[a] These parameters were confirmed by comparison of the experimental data and those plotted with the Herzfeld−Berger subroutine CMA of the program FTNMR, Version 5.1, Hare Research, 1988. [b] For $|\sigma_{11} - \sigma_{22}| < |\sigma_{22} - \sigma_{33}|$, $\Delta\sigma = \sigma_{33} - {}^1/_2\,(\sigma_{11} + \sigma_{22})$ and $\eta = (\sigma_{22} - \sigma_{11})/(\sigma_{33} - \sigma_{iso})$; for $|\sigma_{11} - \sigma_{22}| > |\sigma_{22} - \sigma_{33}|$, $\Delta\sigma = \sigma_{11} - 1/2\,(\sigma_{33} + \sigma_{22})$ and $\eta = (\sigma_{22} - \sigma_{33})/(\sigma_{11} - \sigma_{iso})$.

In comparison with solid-state studies, the only reported solution ^{109}Ag NMR data on Ag^+ thiolate complexes are for silver-substituted yeast metallothionein (Ag_8MT).[20] The coordination environments of the eight Ag^+ ions in this protein are not crystallographically known but, on the basis of heteronuclear multiple quantum coherence transfer (HMQC) experiments, are thought to be a mixture of two- and three-coordinate. The chemical shifts for Ag_8MT range from 790 to 1250 ppm, with only seven distinct Ag environments being detected: two of these resonances, at 790 and 890 ppm, are assigned to two-coordinate Ag, while the downfield shifts from 1000 to 1250 ppm are three-coordinate in nature.[21] In this work, the peaks spanning 950−1230 ppm observed for the trigonal environments of compounds **1**−**3** are in the range of the three-coordinate environments observed for Ag_8MT in solution, with corresponding behavior of the two-coordinate environments in **1**. This provides evidence of a general correlation between solid and solution measurements, illustrating the power of this technique. Additionally, the proposed explanation for the observance of only seven shifts in Ag_8MT is exchange broadening of the eighth resonance,[20] a possibility that may enable the eighth environment to be observed by solid-state ^{109}Ag NMR.

The signal/noise ratio of Ag^+ compounds in Table 1 span a wide range, where **1** and **3** are intense, **2, 4**, and **5** are weak, and **6**−**9** have signal/noise so low as to be not observable. Crystal structures of **6**,[22] **7**,[23] and **8**,[24] suggest this is a consequence of significant structural disorder, leading to a large range of microenvironments.[25] The failure to see the solid-state NMR signature of a tetrahedral heavy metal thiolate

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complex (**6**), expected to have a lower chemical shift anisotropy than two- and three-coordinate analogues, is surprising in light of the excellent data for corresponding Hg^{2+} and Cd^{2+} complexes.[26,27] Finally, a single isotropic peak is observed from a crystalline sample of trigonal $[PPh_3Me]_2[AgI_3]$ (**10**),[28] indicating the utility of ^{109}Ag CPMAS NMR for molecular Ag halides.

Since MT is a small protein and binds multiple Ag^+ ions in rigid, well-defined environments,[5a,c] solid-state ^{109}Ag measurements are feasible, if 100 mg or more of sample is available: Ag_8MT is ≈13% Ag by weight, compared to 37% for **1**. We are currently pursuing this avenue with rabbit liver MT (for which Ag_{12}MT is ≈17% Ag by weight). More generally, since the large majority of solid-state Ag−S compounds are not amenable to X-ray crystallographic analysis, CPMAS ^{109}Ag NMR is likely to be an especially critical aspect of characterization.

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