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Stabilization of a Zn(II) Hydrosulfido Complex Utilizing a Hydrogen-Bond Accepting Ligand

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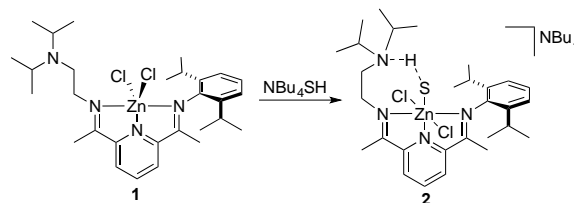
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Hydrogen sulfide (H₂S) has gained recent attention as an important biological analyte that interacts with bioinorganic targets. Despite this importance, stable H₂S or HS[−] adducts of bioinorganic metal complexes remains rare due to the redox activity of sulfide and its propensity to form insoluble metal sulfides. We report here reversible coordination of HS[−] to Zn(didpa)Cl₂, which is enabled by an intramolecular hydrogen bond between the zinc hydrosulfido product and the pendant tertiary amine of the didpa ligand.

Although historically known for its malodour and toxicity, hydrogen sulfide (H₂S) has joined nitric oxide (NO) and carbon monoxide (CO) as a physiologically important gasotransmitter.¹ Complicating its reactivity with different bioinorganic targets, H₂S has multiple protonation states, participates in complex redox chemistry, and is highly metallophilic.^{2–3} For example, the high affinity between zinc and sulfide (ΔG_f° -48.11 kcal/mol, sphalerite)⁴ limits generation of stable sulfide-ligated products, but has also been leveraged as a sulfide sequestration strategy in quantification and detection methods.^{5–6} Consequently, stable zinc hydrosulfido complexes remain rare,^{7–11} with reported examples including (tris)pyrazolylborate zinc hydrosulfide (TpZnSH) complexes, supported by the steric protection from the Tp ligand.^{7–8} Complementing the use of steric protection, secondary-coordination sphere interactions have also been used to stabilize metal-sulfide species with other metals, such as iron.¹² Additionally, these stabilizing forces are hypothesized to be important in the mechanism of carbonyl sulfide fixation by carbonic anhydrase.^{13–14}

Toward increasing our understanding of the solution state stabilization of metal hydrosulfido complexes, we viewed that a ligand scaffold with a pendant hydrogen-bond (H-bond) acceptor would provide a viable scaffold for Zn-SH

stabilization. We noted that the pyridinediimine (PDI) ligand scaffold didpa (([2,6-(ⁱPrC₆H₃)N=CMe)(N(ⁱPr)₂C₂H₄)N=CMe)C₅H₃N]) has been demonstrated to function as an H-bond *donor* when the pendant diisopropylamine is protonated and used to stabilize metal halogen hydrogen bonds (MHHBs), with calculated MHHB strengths of ~6 kcal/mol for [Zn(Hdidpa)Cl₂][PF₆].¹⁵ Additionally, the protonated form of the ligand can also function as an H-bond *donor* to stabilize rare Fe-OH species.¹⁶ Although ligands displaying hydrogen-bond *donors* in the secondary coordination sphere are now frequently used in bioinorganic model complexes,^{17–18} hydrogen-bond *accepting* ligands are rare.^{19–23} On the basis of these properties, we reasoned that the didpa ligand could function as an H-bond *acceptor* in its neutral form to provide a suitable ligation environment for metal hydrosulfido stabilization.



Scheme 1. Reaction of Zn(didpa)Cl₂ (**1**) with NBu₄SH to generate hydrosulfide adduct **2**.

Treatment of Zn(didpa)Cl₂ (**1**) with H₂S gas failed to produce any reaction, however treatment of **1** with NBu₄SH²⁴ in either DCM (Figure 1) or MeCN (Figure S1) resulted in a significant change in the UV-Vis spectrum. The shoulder at 313 nm decreased in intensity with a concomitant increase in absorbance at 280 nm and a well-anchored isosbestic point at 296 nm. A Job plot was consistent with 1:1 binding of HS[−] to **1** (Figure 1, inset). In addition, titration with OH[−] resulted in 1:1 binding (Figure S15). Based on these results, and because chloride abstraction was not required for HS[−] binding, we propose that HS[−] binds to **1** to generate six-coordinate [Zn(didpa)Cl₂SH][−] (**2**, Scheme 1). All attempts to isolate a solid or grow single crystals suitable for X-ray structural determination of **2** resulted in precipitation of a white

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amorphous powder after prolonged standing. Supporting the associative formation of a six-coordinate product, titration of **1** with excess Cl^- showed similar spectral changes by UV-Vis spectroscopy (Figures S3 and S4), and the Job plot was consistent with 1:1 binding (Figure S13). Attempts to isolate and crystallize the six-coordinate 1:1 adduct of Cl^- and **1**, with a range of different Cl^- sources (Bu_4NCl , Ph_4PCl , PPNCl) resulted in simple recrystallization of the starting chloride salt and **1**, presumably due to the reversibility of the process.

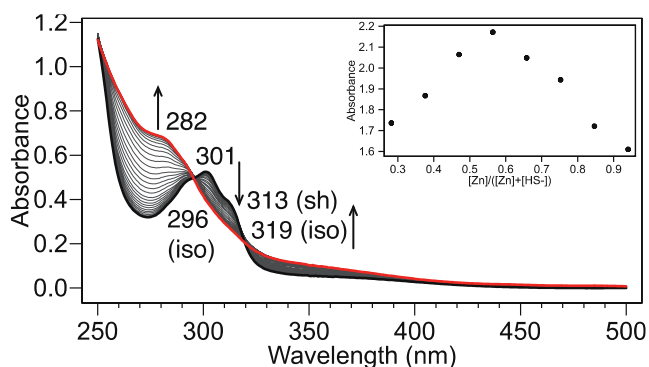


Figure 1. Titration of $\text{Zn}(\text{didpa})\text{Cl}_2$ (87.3 μM , CH_2Cl_2 , black) with NBu_4SH (0.1 equiv. increments up to 6 equiv., red). The inset shows the Job plot of **1** with NBu_4SH in MeCN at a total concentration of 420 μM . The observed break is consistent with 1:1 binding.

To gain further insights into the HS^- binding, we used ^1H NMR spectroscopy to investigate the stability of **2** and the role of hydrogen-bonding in the complex. Treatment of **1** with 1.5 equiv. of NBu_4SH in CD_3CN resulted in significant changes in the ^1H NMR spectrum. The resultant spectrum did not match that of the free ligand,¹⁵ suggesting that addition of HS^- does not remove Zn from the didpa ligand (Figure 2). Upon HS^- addition, the pyridine and other aryl resonances of **1** shifted significantly in a pattern consistent with loss of free rotation of the 2,6-diisopropylphenyl group of the ligand. Similarly, the isopropyl resonance at 1.00 ppm, corresponding to the isopropyl methyl groups of the pendant amine, shifts downfield and bifurcates. Each of these spectral changes indicated a significant change in the primary coordination sphere of the zinc and are consistent with formation of a six-coordinate complex in which the Zn-SH moiety is hydrogen bonded to the pendant diisopropylamine (Scheme 1).

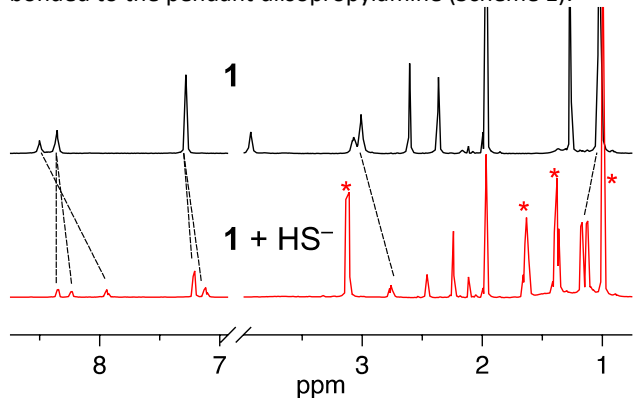


Figure 2. ^1H NMR spectra of **1** (11.8 mM in CD_3CN) before (top, black) and after (bottom, red) addition of 1.5 equiv. of NBu_4SH . Peaks denoted with a (*) correspond to the NBu_4^+ counterion.

Low temperature ^1H NMR investigations provided additional information about the structural flexibility of the scaffold and the presence of the coordinated hydrosulfide. Although we were unable to observe an appreciable signal corresponding to the coordinated HS^- at room temperature, we expected that lowering the temperature would not only enable HS^- observation, but also lock the conformation of the ligand ethylene backbone of the ligand. Consistent with these expectations, cooling to -35°C in CD_3CN strengthened the resonance at 11.05 ppm, matching the general chemical shift expected for partial protonation of the nitrogen as an H-bond acceptor.²⁵ For comparison, the ^1H NMR spectrum of the previously reported $[\text{Zn}(\text{Hdidpa})\text{Cl}_2][\text{PF}_6]$ displays an N-H resonance at 8.50 ppm in CD_2Cl_2 .¹⁵ The downfield shift in the N-H resonance observed in that system is due to the protonated diisopropylamine of the didpa ligand acting as an H-bond donor and forming an intramolecular MHHB with a chloride ligand. The downfield shift observed for **2** is consistent with the diisopropylamine acting as an H-bond acceptor, likely accepting a hydrogen bond from the Zn-ligated SH moiety.²⁶

Additionally, we observed that the broad peak centered at 3.6 ppm corresponding to the ethylene bridge decoalesced upon cooling. The presence of the internal hydrogen bond between the sulfhydryl group and the tertiary amine significantly limits the flexibility of the secondary coordination sphere, resulting in a sharpening in the signal produced by the ethylene linker, methine protons, and methyl groups (Figure S10). Supporting the presence of an intramolecular SH hydrogen bond, a ^1H NOESY experiment at -35°C revealed cross peaks between the SH and the ethylene, methine, and methyl signals of the tertiary amine linker (Figure S4).

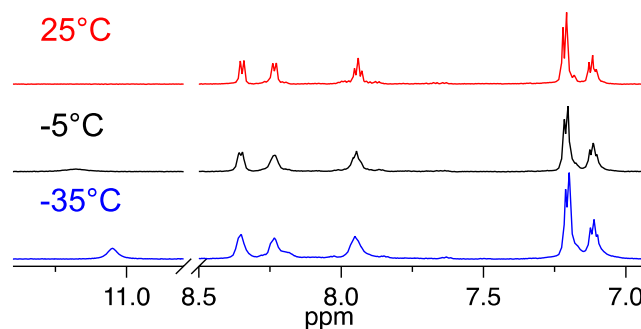


Figure 3. Variable temperature ^1H NMR spectra of 11.4 mM $\text{Zn}(\text{didpa})\text{Cl}_2$, and 1.5 equiv. NBu_4SH in CD_3CN . Cooling to -35°C results in sharpening and an upfield shift of the broad SH peak to 11.05 ppm. See Figure S11 for a zoom of the SH peak.

Although the N---HS interaction was not observed by solution state FTIR, we note that the N-H stretch involved in hydrogen bonding in the $[\text{Zn}(\text{Hdidpa})\text{Cl}_2][\text{PF}_6]$ system is also absent in solution FTIR spectra.¹⁵ The N-H stretch in the N---HS moiety is likely severely broadened or obscured, which is common in many hydrogen bonding systems.²⁵

To demonstrate the reversibility of **2**, and to provide evidence for the formation of a six-coordinate complex, we performed a displacement experiment by ^1H NMR. Treatment

of **1** with 1.5 equiv. of NBu_4SH resulted in the formation of **2** with characteristic shifts in the aryl peaks, and broad absorbance at 3.6 ppm (Figure 5). Upon addition of 20 equiv. of NBu_4Cl , the aryl protons maintained the same configuration; however, the broad absorbance at 3.6 ppm resolved, characteristic of the Cl^- adduct of **1** (Figure S6).²⁷

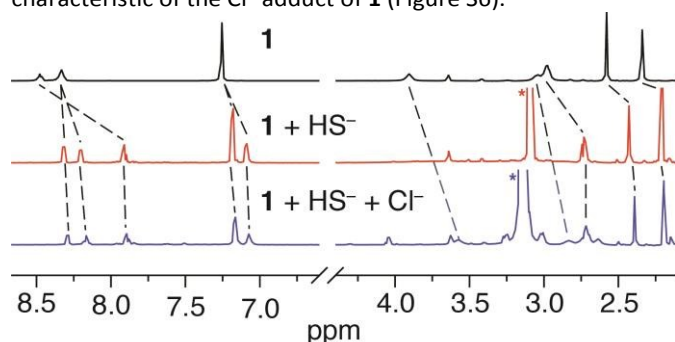
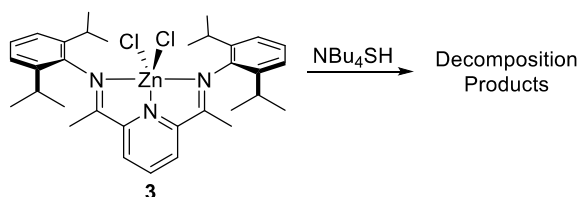


Figure 5. ^1H NMR spectrum of 10.3 mM **1** (black), upon addition of 1.5 equiv. of NBu_4SH (red) is characteristic for **2**. Addition of 20 equiv. of NBu_4Cl produces the spectrum characteristic of the Cl^- adduct.

To further determine whether the internal hydrogen-bond was necessary for stabilization of the zinc-sulfido product, we also titrated a Zn-pyridinediimine compound which does not possess the pendant amine hydrogen-bond acceptor (Scheme 2). Upon addition of 0.5 equiv. of HS^- to a solution of $\text{Zn}(\text{iprPDI})\text{Cl}_2$ (**3**) ($\text{iprPDI} = 2,6\text{-(2,6-}i\text{Pr}_2\text{C}_6\text{H}_3\text{N=CMe)}_2\text{C}_5\text{H}_3\text{N}$) a white precipitate (ZnS) was immediately observed, along with a significant change in the NMR spectrum. The shifts in the NMR spectrum and formation of precipitate continued until 1 equiv. of HS^- was added, after which no more changes were observed (Figure S7). The resultant solid was isolated, washed with acetonitrile to remove any excess free sulphide, then acidified and subjected to the methylene blue assay, which provided a positive response for acid-labile sulfur and was consistent with ZnS formation.²⁸ These data illustrate the importance of the hydrogen-bond acceptor in the stabilization of the zinc-sulfido complex, as the pendant amine in **1** is vital in this system.



Scheme 2. Reaction of **3** with NBu_4SH shows decomposition, demonstrating the importance of the H-bond acceptor in **2**.

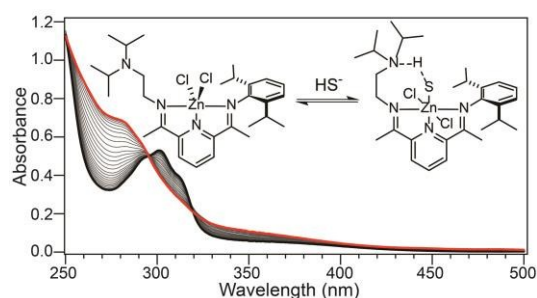
In conclusion, we have shown the stabilization of a rare synthetic zinc hydrosulfide complex stabilized by a hydrogen bond accepting ligand. Removal of the hydrogen bonding ability of the ligand resulted in decomposition and ZnS precipitation, highlighting the importance of the second coordination sphere in stabilizing the zinc hydrosulfido adduct.

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Notes and references

- 1 R. Wang, *Physiol. Rev.*, 2012, 92, 791-896.
- 2 M. D. Hartle, S. K. Sommer, S. R. Dietrich and M. D. Pluth, *Inorg. Chem.*, 2014, 53, 7800-7802.
- 3 C. C. Tsou, W. C. Chiu, C. H. Ke, J. C. Tsai, Y. M. Wang, M. H. Chiang and W. F. Liaw, *J. Am. Chem. Soc.*, 2014, 136, 9424-9433.
- 4 P. Patnaik, *Handbook of Inorganic Chemicals*, McGraw-Hill, New York, 2002.
- 5 J. K. Fogo and M. Popowsky, *Anal. Chem.*, 1949, 21, 732-734.
- 6 E. Galardon, A. Tomas, P. Roussel and I. Artaud, *Dalton Trans.*, 2009, DOI: 10.1039/b907115f, 9126-9130.
- 7 M. Rombach and H. Vahrenkamp, *Inorg. Chem.*, 2001, 40, 6144-6150.
- 8 M. Ruf and H. Vahrenkamp, *Inorg. Chem.*, 1996, 35, 6571-6578.
- 9 M. M. Morlok, K. E. Janak, G. Zhu, D. A. Quarless and G. Parkin, *J. Am. Chem. Soc.*, 2005, 127, 14039-14050.
- 10 N. G. Spiropoulos, E. A. Standley, I. R. Shaw, B. L. Ingalls, B. Diebels, S. V. Krawczyk, B. F. Gherman, A. M. Arif and E. C. Brown, *Inorg. Chem. Acta*, 2012, 386, 83-92.
- 11 S. Kuwata and M. Hidai, *Coord. Chem. Rev.*, 2001, 213, 211-305.
- 12 E. Galardon, T. Roger, P. Deschamps, P. Roussel, A. Tomas and I. Artaud, *Inorg. Chem.*, 2012, 51, 10068-10070.
- 13 J. Notni, S. Schenk, G. Protoschill-Krebs, J. Kesselmeier and E. Anders, *ChemBioChem*, 2007, 8, 530-536.
- 14 F. Namuswe and J. M. Berg, *J. Inorg. Biochem.*, 2012, 111, 146-149.
- 15 M. Delgado, S. K. Sommer, S. P. Swanson, R. F. Berger, T. Seda, L. N. Zakharov and J. D. Gilbertson, *Inorg. Chem.*, 2015, 54, 7239-7248.
- 16 A. J. Kendall, L. N. Zakharov and J. D. Gilbertson, *Inorg. Chem.*, 2010, 49, 8656-8658.
- 17 A. S. Borovik, *Acc. Chem. Res.*, 2005, 38, 54-61.
- 18 S. A. Cook and A. S. Borovik, *Acc. Chem. Res.*, 2015, 48, 2407-2414.
- 19 Y. J. Park, N. S. Sickerman, J. W. Ziller and A. S. Borovik, *Chem. Commun.*, 2010, 46, 2584-2586.
- 20 N. S. Sickerman, Y. J. Park, G. K. Ng, J. E. Bates, M. Hilkert, J. W. Ziller, F. Furche and A. S. Borovik, *Dalton Trans.*, 2012, 41, 4358-4364.
- 21 Z. Shirin and C. J. Carrano, *Polyhedron*, 2004, 23, 239-244.
- 22 C. M. Moore and N. K. Szymczak, *Dalton Trans.*, 2012, 41, 7886-7889.
- 23 E. M. Matson, J. A. Bertke and A. R. Fout, *Inorg. Chem.*, 2014, 53, 4450-4458.
- 24 M. D. Hartle, D. J. Meininger, L. N. Zakharov, Z. J. Tonzetich and M. D. Pluth, *Dalton Trans.*, 2015, 44, 19782-19785.
- 25 T. Steiner, *Angew. Chem. Int. Ed.*, 2002, 41, 48-76.
- 26 B. Brzeninski and G. Zundel, *Journal of Molecular Structure*, 1982, 84, 205-211.
- 27 Based on the number of equivalents of HS^- required to displace the bound Cl^- , we estimate that the binding affinity of HS^- for $\text{Zn}(\text{didpa})\text{Cl}_2$ is similar and not more than 10x greater than that of Cl^- . See Figure S3.
- 28 X. Shen, C. B. Pattillo, S. Pardue, S. C. Bir, R. Wang and C. G. Kevill, *Free Radic. Biol. Med.*, 2011, 50, 1021-1031.



Inclusion of a hydrogen bond accepting motif in the secondary coordination sphere of a pyridinediimine ligand enables formation of a stable Zn-SH adduct. We report here reversible coordination of HS⁻ to Zn(didpa)Cl₂ to form [Zn(didpa)Cl₂SH]⁻, which is stabilized by an intramolecular hydrogen bond between the zinc hydrosulfido product and the pendant tertiary amine of the didpa ligand.