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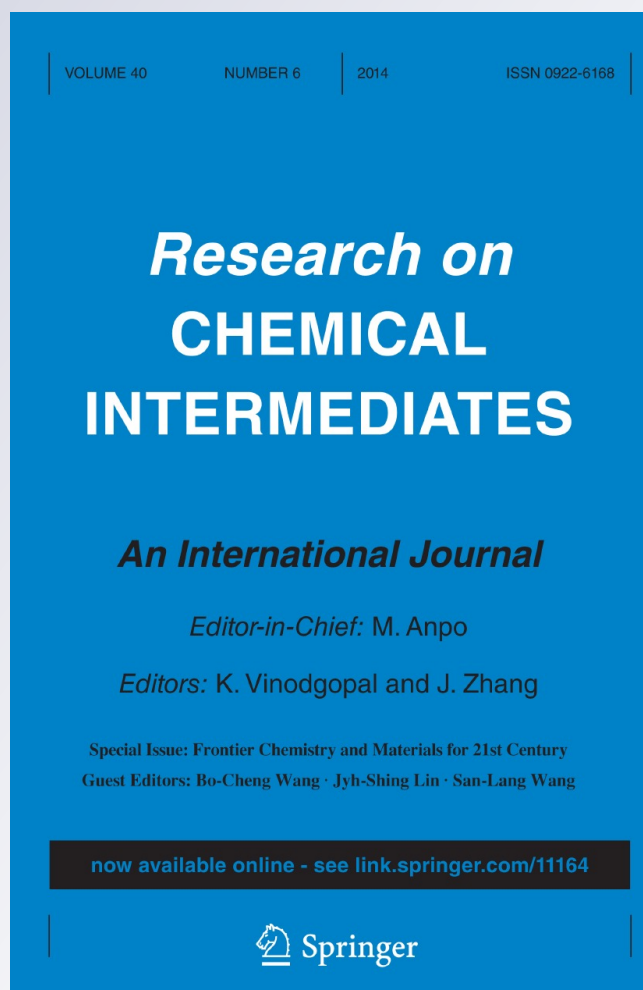
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A new member of tetranuclear dinitrosyl iron complexes (DNICs) with 2-mercaptothiazoline ligand: synthesis, structure and properties

Chien-Hong Chen · Jheng-Hong Wang ·
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Abstract A new tetranuclear dinitrosyliron complex $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]_4$ (**2**), each of a Fe center coordinated with two S or two N, was prepared by CO replacement from the reduced precursor $(\text{CO})_2\text{Fe}(\text{NO})_2$ with 1 equiv of $\text{HSC}_3\text{H}_4\text{SN}$ (2-mercaptothiazoline) in the presence of $\text{O}_{2(\text{g})}$. The structure of **2** is similar to $[(\text{Imid-}i\text{Pr})\text{Fe}(\text{NO})_2]_4$ (Imid- $i\text{Pr}$ = 2-isopropylimidazole) (Hess et al. J Am Chem Soc 133:20426–20434, 2011), and both complexes comprise a quadrilateral plane of irons with corresponding ligands, $\text{SC}_3\text{H}_4\text{SN}^-$ or $\text{Imid-}i\text{Pr}^-$, bridging the edges and two nitrosyl ligands capping the irons at the corners. An additional equiv of $\text{SC}_3\text{H}_4\text{SN}^-$ was added to **2**, which results in the mononuclear $\{\text{Fe}(\text{NO})_2\}^9$ ($(\text{SC}_3\text{H}_4\text{SN})_2\text{Fe}(\text{NO})_2^-$ (**3**), in the manner of N bound- $[\text{SC}_3\text{H}_4\text{SN}]$. Reaction of $(\text{TMEDA})\text{Fe}(\text{NO})_2$ (TMEDA = tetramethylethylenediamine) and complex **3** leads to the formation of complex **2**. Dinuclear complex $[(\mu\text{-C}_5\text{H}_7\text{N}_2)\text{Fe}(\text{NO})_2]_2$ (**4**) can be synthesized by the ligand displacement of $\text{SC}_3\text{H}_4\text{SN}^-$ to $\text{C}_5\text{H}_7\text{N}_2^-$ (3,5-dimethylpyrazolate) of **2** (Chong et al. Can J Chem 57:3119–3125, 1979). Complexes **2–4** were characterized by IR and UV–Vis. The molecular structures of **2** and **3** were determined by X-ray single crystal diffraction.

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Introduction

One of the approaches of the current drug discovery research is to design a complex with two or more medicinal functions [1]. For example, a dansyl derivative [Ds-DAB = *N*-(2-Aminophenyl)-5-(dimethylamino)-1-naphthalenesulfonic Amide] was prepared and used as a fluorescent chemosensor for peroxynitrite (ONOO^-) detection [2]. 2-Mercaptobenzimidazole has been explored as an inhibitor for the synthesis of cellular DNA and RNA [3]. Interest in nitric oxide (NO) derives from its physiological and biological functions in living organisms [4–7], the protein-bound dinitrosyliron complexes (protein-bound DNICs) and low-molecular-weight DNICs (LMW-DNICs), and has been suggested in vivo and in vitro, respectively [8–16]. Both DNICs are possibly identified and characterized by their distinctive electron paramagnetic resonance (EPR) signals at $g = 2.03$. Recently, the biological protein-bound DNIC has been well characterized by an X-ray diffraction study via the addition of a dinitrosyl diglutathionyliron complex into human glutathione transferase P1-1 protein [17]. DNICs are also known to play an important role in storage and transfer NO in vivo and in vitro. In fact, much evidence obtained in animal models suggests that DNICs can indeed act as regulatory and cytotoxic agents depending on the concentration of NO required by cells or tissues [18].

In order to develop a bifunctional medicine (an inorganic NO donor with a targeting probe), heterocyclic analogs of 2-mercaptobenzimidazole, such as 1,2,4-triazole-3-thione, 1-methyl-imidazole-2-yl, 3-amino-5-mercapto-1,2,4-triazole, 3-mercapto-1,2,4-triazole, 5-mercapto-1-methyl-1*H*-tetrazole, and 2-mercapto-benzothiazole were adopted to synthesize the DNIC complexes [19–23]. Several coordination modes of thioamide with metals are shown in Chart 1b and two possible tautomeric forms of the 2-mercaptothiazoline are shown in Chart 1a. Basically, these type of ligands can bind to metals in a mono- or a bidentate manners through S and N atoms to form a monomer or a cluster, but when it binds to the $\text{Fe}(\text{NO})_2$ units, only mononuclear and dinuclear DNICs can be found in the literature to date. In this work, a new tetrameric dinitrosyliron complex (DNICs) $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]_4$ (**2**) and monomeric $[\text{cation}][(\text{SC}_3\text{H}_4\text{SN})_2\text{Fe}(\text{NO})_2]$ (**3**), $\text{SC}_3\text{H}_4\text{SN}$ = 2-mercaptothiazoline; cation = Ph_4P^+ and Et_4N^+ , have been synthesized. The formation and interconversion of **2** and **3** were studied by IR. Structural identification of **2** and **3** was carried out by X-ray single crystal diffractometer. Cyclic voltammetry (CV) data of **2** was also compared with earlier synthesized tetranuclear DNIC $[(\text{Imid-}i\text{Pr})\text{Fe}(\text{NO})_2]_4$ (Imid-*i*Pr = 2-isopropylimidazole) [24].

Experimental

Infrared spectra of the nitrosyl $\nu(\text{NO})$ stretching frequencies were recorded on a Thermo FT-IR Nicolet iS5/iD1 spectrophotometer/Bruker Alpha spectrophotometer

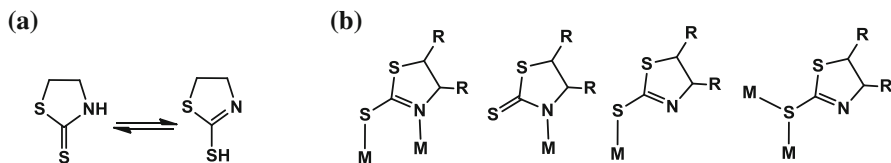


Chart 1 **a** Tautomeric forms of 2-mercaptothiazoline. **b** Binding modes of thioamide ligand with $M = \text{Fe}(\text{NO})_2$ fragments

with sealed solution cells (0.1 mm) and KBr windows. UV/Vis spectra were recorded on a Thermo Genesys 10S spectrophotometer. X-band EPR spectrum was recorded on a Bruker EMX spectrometer equipped with a Hewlett-Packard 5246 L electronic counter. CV was carried out with a CH Instruments electrochemical analyzer 611C. A three-electrode system consisted of a glassy carbon working electrode, a platinum wire auxiliary electrode, and a 0.1 M Ag/Ag^+ reference electrode. All CV data were recorded with the scan rate of 0.1 V/s in THF solution with tetrabutylammonium hexafluorophosphate as the supporting electrolyte. All potential values are reported versus ferrocene/ferrocenium ion (Fc/Fc^+). Analyses of carbon, hydrogen, and nitrogen were obtained with a CHN analyzer (Heraeus).

Crystallography

Crystallographic data and structure refinements parameters of complexes $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]_4$ (**2**) and $[\text{cation}][(\mu\text{-SC}_3\text{H}_4\text{SN})_2\text{Fe}(\text{NO})_2]_4$ (cation = Et_4N^+ (**3a**) and Ph_4P^+ (**3b**)) are summarized in the Supplementary Information (Tables S1–S6). Each crystal was mounted on a glass fiber and quickly coated in epoxy resin. Unit-cell parameters were obtained by least-squares refinement. Diffraction measurements for complexes **2** and **3** were carried out on a Nonius Kappa CCD and Bruker SMART Apex CCD diffractometers using graphite-monochromated $\text{Mo K}\alpha$ radiation ($\lambda = 0.7107 \text{ \AA}$). Least-squares refinement of the positional and anisotropic thermal parameters for the contribution of all non-hydrogen atoms and fixed hydrogen atoms was based on F^2 . A SADABS absorption correction was made. The SHELXTL structure refinement program was employed [31–35]. Graphics and publication materials were plotted out by Mercury v.2.3 [36].

Preparation of $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]_4$ (**2**)

An amount of 40 mL of THF solution of freshly prepared 6.0 mmol $(\text{CO})_2\text{Fe}(\text{NO})_2$ was added to a Schlenk flask containing 2-mercaptothiazoline (0.730 g, 6.0 mmol). The reaction solution was stirred for 2 h at room temperature and monitored with FTIR. The IR spectrum showing ν_{NO} stretching frequencies at $1,997(\text{s}) \text{ cm}^{-1}$ (ν_{CO}), $1,750(\text{vs})$, $1,706(\text{vs}) \text{ cm}^{-1}$ (ν_{NO}) (THF) was considered to the formation of $(\text{SC}_3\text{H}_5\text{SN})(\text{CO})\text{Fe}(\text{NO})_2$ (**1**). Then, about 80 mL air was injected to the dark-brown solution at room temperature. After stirring the reaction solution for 8 h at room temperature, large amounts of dark-brown solid was yielded and dissolved with

adequate THF. The THF solution was filtered through Celite and dried under vacuum to afford a dark-brown solid. Then, the solid was washed with 10 mL EtOH to afford complex **2** (Yield: 0.073 g, 52 %). Diffusion of diethyl ether into CH₂Cl₂ solution of complex **2** at −20 °C led to dark-brown crystals suitable for single-crystal X-ray diffraction. IR ν_{NO} : 1,789(s), 1,735(vs) cm^{−1} (ν_{NO}) (THF); 1,789(vs), 1,734(s), 1,715(s) cm^{−1} (ν_{NO}) (KBr). Absorption spectrum (THF) [λ_{max} , nm(ϵ , cm^{−1}M^{−1})]: 241(35,653), 265(32,918), 342(9,837), 530(3,000). EPR (THF) at 298 K: $g = 2.027$; at 77 K: $g = 2.023$. Anal. Calcd for C₁₂H₁₆Fe₄N₁₂O₈S₈: C, 15.39; H, 1.72; N, 17.95. Found: C, 15.72; H, 1.88; N, 17.16.

Preparation of [cation][(SC₃H₄SN)₂Fe(NO)₂] (**3**) (cation = Et₄N⁺ (**3a**), Ph₄P⁺ (**3b**))

The complex **2** (0.234 g, 0.25 mmol) and [Na][SC₃H₄SN] (0.141 g, 1.0 mmol) were loaded into a Schlenk tube and dissolved in THF (10 mL). The reaction mixture was stirred for 2 h at room temperature and added to a Schlenk flask containing [Et₄N][Br] (0.257 g, 1.2 mmol)/[Ph₄P][Br] (0.402 g, 0.95 mmol). After being stirred for 5 h at room temperature, the mixture was filtered through Celite to remove the insoluble solid [Na][Br] and concentrated to 2 mL under vacuum. Then, diethyl ether was added to the dark-brown solution to precipitate complex **3a** (Yield: 0.377 g, 78.0 %)/complex **3b** (Yield: 0.619 g, 90 %). Diffusion of Hexane into THF solution of complex **3a/3b** at −20 °C led to dark-brown crystals suitable for single-crystal X-ray diffraction. Complex **3a**: IR ν_{NO} : 1,769(s), 1,704(vs) cm^{−1} (ν_{NO}) (THF); 1,751(s), 1,677(vs) cm^{−1} (ν_{NO}) (KBr). Absorption spectrum (THF) [λ_{max} , nm(ϵ , cm^{−1}M^{−1})]: 238(16,843), 264(15,588), 345(3,745), 530(1,824). EPR (THF) at 298 K: $g = 2.030$; at 77 K: $g = 2.027$. Anal. Calcd for C₁₄H₂₈FeN₅O₂S₄: C, 34.85; H, 5.85; N, 14.51. Found: C, 35.08; H, 5.85; N, 14.34. Complex **3b**: IR ν_{NO} : 1768(s), 1705(vs) cm^{−1} (ν_{NO}) (THF); 1764(s), 1681(vs) cm^{−1} (ν_{NO}) (KBr).

Reaction of [Et₄N][(SC₃H₄SN)₂Fe(NO)₂] (**3a**) with (TMEDA)Fe(NO)₂ (TMEDA = tetramethylethylenediamine)

The complex **3a** (0.097 g, 0.2 mmol) and (TMEDA)Fe(NO)₂ (0.072 g, 0.2 mmol) were loaded into a Schlenk tube and dissolved in THF (10 mL). The reaction mixture was stirred for 3 h at room temperature and monitored with FTIR. The IR spectrum showing ν_{NO} stretching frequencies at 1,789(s), 1,734(vs) cm^{−1} (ν_{NO}) (THF) was assigned to the formation of complex **2**. After being filtered through Celite to separate insoluble [Et₄N][I], the filtrate was dried under vacuum to afford a dark-brown solid. Then, the solid was washed with EtOH to afford complex **2** (Yield: 0.049 g, 58 %).

Reaction of [(μ-SC₃H₄SN)Fe(NO)₂]₄ (**2**) with [Na][C₅H₇N₂] (3,5-dimethylpyrazolate sodium salt)

The complex **2** (0.094 g, 0.1 mmol) and [Na][C₅H₇N₂] (0.047 g, 0.4 mmol) were loaded into a Schlenk tube and dissolved in hexane (10 mL). The reaction solution

was stirred for 48 h at room temperature and monitored with FTIR. The IR spectrum showing ν_{NO} stretching frequencies at 1,806(s), 1,790(vs), 1,738(s), 1,724(vs) cm^{-1} (ν_{NO}) (hexane) was assigned to the formation of complex $[(\text{C}_5\text{H}_7\text{N}_2)_2\text{Fe}(\text{NO})_2]_2$ (**4**). Then, the resulting solution was filtered through Celite and dried under vacuum to afford a dark-brown solid. The dark-brown solid was washed with MeOH twice to afford complex **1** (Yield: 0.0760 g, 90.0 %).

Reaction of $[(\mu\text{-C}_5\text{H}_7\text{N}_2)\text{Fe}(\text{NO})_2]_2$ (**4**) with 2-mercaptothiazoline

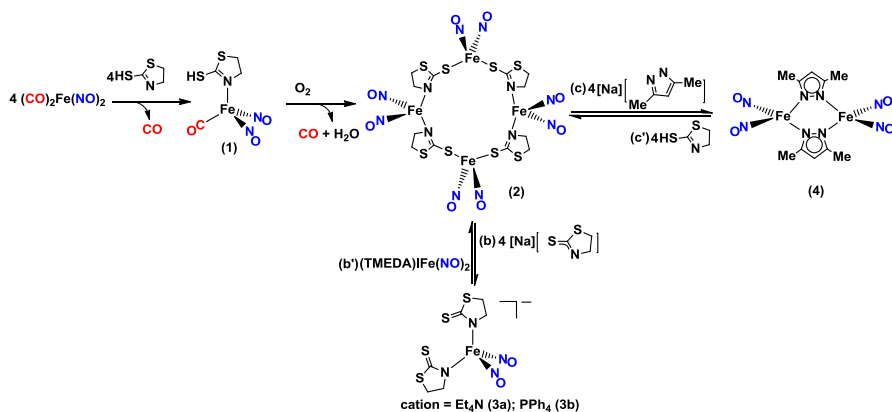
The complex **4** (0.169 g, 0.4 mmol) and 2-mercaptothiazoline (0.195 g, 1.6 mmol) were loaded into a Schlenk tube and dissolved in THF (5 mL). The reaction solution was stirred for 48 h at room temperature and monitored with FTIR. The IR spectrum showing ν_{NO} stretching frequencies at 1,787(s), 1,734(vs) cm^{-1} (ν_{NO}) (THF) was assigned to the formation of complex **2**. Then, 5 mL hexane was added to the resulting solution to precipitate a dark-brown solid. The solid was washed with EtOH twice to afford complex **2** (Yield: 0.115 g, 61 %).

Result and discussion

Synthesis

For the preparation of $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]_4$ (**2**), addition of one equiv of $\text{HSC}_3\text{H}_4\text{SN}$ = 2-mercaptothiazoline to a freshly prepared $(\text{CO})_2\text{Fe}(\text{NO})_2$ in the THF solution (Scheme 1) leads to a color change from dark orange to dark brown. Infrared spectrum shows $\nu(\text{CO})$: 1,997(m); $\nu(\text{NO})$: 1,750(s), 1,706(vs) cm^{-1} in THF, which was assigned to the formation of $(\text{HSC}_3\text{H}_4\text{SN})(\text{CO})\text{Fe}(\text{NO})_2$ (**1**), Fig. 1. Upon injection of dry $\text{O}_{2(\text{g})}$ into the THF solution of **1** under ambient temperature (Scheme 1), the disappearance of the IR CO band and the blue shift of the NO stretching frequencies ($\nu(\text{NO})$: 1,750(s), 1,706(vs) cm^{-1} of **1** shifts to 1,789(s), 1,734(vs) cm^{-1} of **2**; Fig. 1) were attributed to the oxidation of **1** to **2**. In the meantime, water was detected as the by-product. Complex **2** is light and thermally stable under N_2 atmosphere.

Complex **2** was isolated and recrystallized from CH_2Cl_2 /diethyl ether yielding dark brown colored crystals suitable for the X-ray analysis. Addition of 4 equiv of 2-mercaptothiazoline sodium salt and $[\text{Et}_4\text{N}][\text{Cl}]$ or $[\text{Ph}_4\text{P}][\text{Br}]$ to a THF solution of complex **2** led to red shifts of IR $\nu(\text{NO})$ stretching frequencies from 1,789(s), 1,734(vs) cm^{-1} to 1,769(s), 1,704(vs) cm^{-1} , which indicated the formation of anionic $(\text{SC}_3\text{H}_4\text{SN})_2\text{Fe}(\text{NO})_2^-$, (cation = Et_4N^+ (**3a**), Ph_4P^+ (**3b**)) (Scheme 1b). Isolation and recrystallization from THF/hexanes yielded dark brown crystals of **3**. Reaction of complex **3** with $(\text{TMEDA})\text{Fe}(\text{NO})_2$ (TMEDA = tetramethylethylenediamine) in 1:1 stoichiometry in THF at room temperature reproduced complex **2** in good yield. Furthermore, complex $[(\mu\text{-C}_5\text{H}_7\text{N}_2)\text{Fe}(\text{NO})_2]_2$ (**4**) can be synthesized by reaction of complex **2** and 4 equiv of $[\text{Na}][\text{C}_5\text{H}_7\text{N}_2]$ (3,5-dimethylpyrazolate sodium salt) in THF solution (Scheme 1c). Interestingly, excess amounts of 2-mercaptothiazoline was required (ca. molar ratio $\sim 1:4$) to regenerate complex **2** from **4** (Scheme 1c') [25].



Scheme 1 Synthesis of Dinitrosyl Iron Complexes (DNICs) **1**, **2**, **3** and **4**

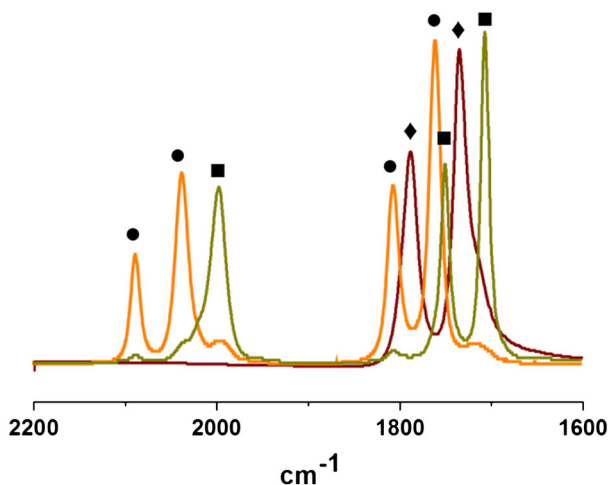


Fig. 1 Overlaid IR spectra of $(\text{CO})_2\text{Fe}(\text{NO})_2$, **1** and **2** in THF solution. [filled circle, orange $(\text{CO})_2\text{Fe}(\text{NO})_2$: $\nu(\text{CO})$: 2,092(m), 2,041(s), $\nu(\text{NO})$: 1,808(s), 1,761(vs) cm^{-1}], [filled square, olive **1**: $\nu(\text{CO})$: 1,997(m), $\nu(\text{NO})$: 1,750(s), 1,706(vs) cm^{-1}], [filled diamond, dark brown: $\nu(\text{NO})$: 1,789(s), 1,734(vs) cm^{-1}]. (Color figure online)

Molecular structures

A view of the ball and stick/capped sticks rendition of the molecular structure and packing diagram of **2** is shown in Fig. 2a, b, respectively; full thermal ellipsoid plot of **2** and metric data are provided in the Supplementary Information. The selected bond distances and angles of complex **2** is similar to the published tetranuclear DNIC [(Imid-*i*Pr) $\text{Fe}(\text{NO})_2$]₄ (Imid-*i*Pr = 2-isopropylimidazole) [24] (Table 1). In both structures: (1) the Fe–N–O units are slightly bent, avg. $\sim 165^\circ$, and oriented in toward each other; (2) four irons construct a quadrilateral plane with a very small deviation of Fe from Fe₄ plane; (3) each iron contains two nitrosyl groups and the

$\text{SC}_3\text{H}_4\text{SN}^-$ or Imid-iPr^- ligands bridge the edge of the Fe_4 quadrilateral; and (4) the Fe_4 in complex **2** is more closed to a diamond shape instead of an almost precise square shape in $[(\text{Imid-iPr})\text{Fe}(\text{NO})_2]_4$. We also notice that two sets of dihedral angles of opposite $\text{Fe}(\text{NO})_2$ planes are 51.11° , 6.72° of **2** and 12.52° , 11.85° of $[(\text{Imid-iPr})\text{Fe}(\text{NO})_2]_4$, which is due to the binding mode of $\text{SC}_3\text{H}_4\text{SN}^-$ being more flexible/asymmetrical than the Imid-iPr^- ligand.

The X-ray diffraction analysis yielded the typical tetrahedral structures of [cation] $[(\text{SC}_3\text{H}_4\text{SN})_2\text{Fe}(\text{NO})_2]$, cation = Et_4N^+ (**3a**) and Ph_4P^+ (**3b**), which are shown in Fig. 3. Selected bond distances and angles of complex **3b** are shown in Table 1. The average Fe–NO and N–O bond length of **3b**, 1.688(4) and 1.175(5) Å, falls in the range of 1.661(4)–1.695(3) Å and 1.160(6)–1.178(3) Å, respectively, as observed in the anionic $\{\text{Fe}(\text{NO})_2\}^9$ (Enemark/Feltham electronic notation [26]) DNICs [27]. It is worth noting that two tautomeric forms, thiolate and thione forms, of 2-mercaptothiazoline can be found in complexes **2** and **3**, respectively. We point out that the shortening in the $\alpha\text{-C-N}$ bond distance and the elongation of $\alpha\text{-C-S}$ bond length from 1.318(5) and 1.673(4) Å for **3** to 1.294(4) and 1.722(3) Å for **2** is consistent with the tautomeric thione/amide form of complex **3** (Chart 1a, left) and the thiolate/imine form of complex **2** (Chart 1a, right). Sanina et al. [23] have demonstrated the neutral $\{\text{Fe}(\text{NO})_2\}^9$ mononuclear DNIC $(\text{SC}_2\text{H}_3\text{N}_3)(\text{SC}_2\text{H}_2\text{N}_3)\text{Fe}(\text{NO})_2$ with two 1,2,4-triazol-3-thione ligands, one S atom is a negative charge, bonding to the iron atom is covalent and the other S atom is formally a neutral bond with the iron. Surprisingly, in the anionic complex **3**, two ancillary $\text{SC}_3\text{H}_4\text{SN}^-$ ligands are N bound to the iron in the thione/amide form. Even though both complex **3** and $(\text{SC}_2\text{H}_3\text{N}_3)(\text{SC}_2\text{H}_2\text{N}_3)\text{Fe}(\text{NO})_2$ are in the $\{\text{Fe}(\text{NO})_2\}^9$ form based on the Enemark/Feltham electron count, we suggest that the influence of the non-innocent properties of NO to the iron center in terms of the oxidation state of Fe in the neutral and anionic compounds is different and may be the key factor to influence the binding mode of the $\text{SC}_3\text{H}_4\text{SN}^-$ ligands. Further studies and computational investigations of these possible linkage isomers will be explored and published in a separate article.

Electron paramagnetic resonance spectral data

The EPR spectra for complexes **2** and **3** (see SI) originate from paramagnetic $\{\text{Fe}(\text{NO})_2\}^9$ units (Enemark/Feltham electronic notation), which at 77 K display a isotropic signal at $g \sim 2.03$ in THF solution, a characteristic of DNICs, and no hyperfine coupling was observed. Only a few examples contains hyperfine coupling from nitrogen in paramagnetic $\{\text{Fe}(\text{NO})_2\}^9$. Tsai and Liaw et al. [28] published the complex $[(\text{SC}_6\text{H}_4\text{-}o\text{-NHCOPh})(\text{Imidazole})\text{Fe}(\text{NO})_2]$, whose EPR spectrum exhibited a well-resolved nine-line signal which corresponds to N -hyperfine coupling of two NOs and one imidazole of the $\{\text{Fe}(\text{NO})_2\}^9$ unit. Until now, reasons for the unresolved N -hyperfine couplings of oxidized DNICs are still unclear [29].

CV measurements

The cyclic voltammograms of complexes **2** and **3** were measured in 2 mM solution with tetrabutylammonium hexafluorophosphate as a supporting electrolyte. All

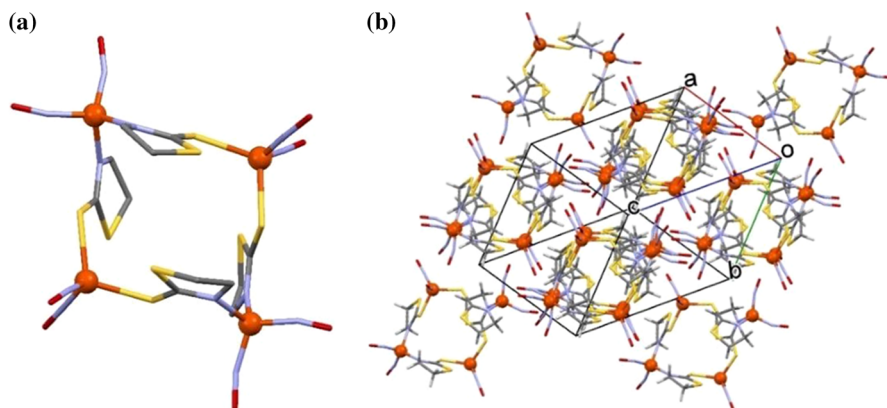


Fig. 2 **a** View of ball and stick (Fe) and capped sticks (N, O, S, C) of $[(\mu\text{-SC}_3\text{H}_4\text{SN})\text{Fe}(\text{NO})_2]$ (**2**). Red O, blue N, orange Fe, yellow S, gray C; H atoms are removed for clarity. **b** Packing diagram of complex **2**. (Color figure online)

Table 1 Selected bond distances (Å) and angle (°) for complex **2** $[(\text{Imid-iPr})\text{Fe}(\text{NO})_2]_4$ and **3b**

$\{\text{Fe}(\text{NO})_2\}^9$	2	$[(\text{Imid-iPr})\text{Fe}(\text{NO})_2]_4$ [24]	3b
Fe–NO _{avg.}	1.686(3)	1.712(1)	1.688(4)
N–O _{avg.}	1.164(5)	1.194(1)	1.175(5)
Fe–N _{Thiaz./Imid.}	2.000(2)	2.036(1)	1.997(3)
Fe...Fe (adj)	5.592, 5.617 5.671, 5.604	6.230, 6.253	–
Fe...Fe (cross)	7.132, 8.689	8.898, 8.755	–
Fe–S	2.303(1)	–	–
$\angle \text{N}_{\text{NO}}\text{–Fe–N}_{\text{NO}}$ avg.	112.8(1)	110.4(1)	108.5(2)
$\angle \text{Fe–N–O}$ avg.	165.0(3)	164.0(1)	161.1(3)
$\angle \text{S–Fe–S}$ avg.	110.8(1)	–	–
$\angle \text{N}_{\text{Thiaz./Imid.}}\text{–Fe–N}_{\text{Thiaz./Imid.}}$ avg.	–	110.7(5)	117.7(1)
Avg. deviation of Fe from Fe ₄ square plane (Å)			
	0.033	0.015	–
Dihedral angles of opposite Fe(NO) ₂ planes (°)			
	51.11, 6.72	12.52, 11.85	–

The maximum deviations from the average distances and angles are shown. Full lists of metric parameters are given in the Supplementary Information

potential values were recorded to the Ag/AgNO₃ electrode using glassy carbon working electrode and are referenced to ferrocene/ferrocenium ion (Fc/Fc⁺).

For the tetranuclear complex **2**, three reductive events are observed at -1.25 , -1.56 and -1.67 V. The reductive events at -1.25 and -1.56 V are associate with the oxidative events at -0.92 and -1.33 V, respectively. Similar to $[(\text{Imid-}$

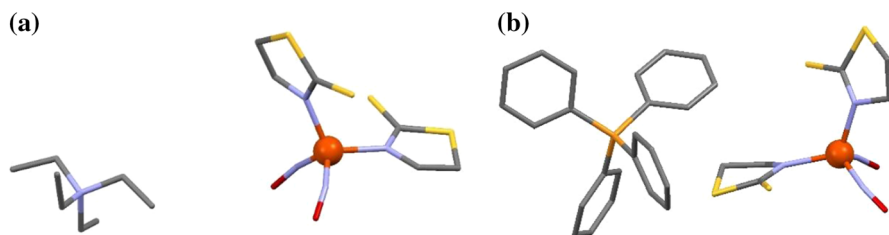


Fig. 3 Ball and capped sticks representation of the X-ray single crystal structure of complex [cation][(SC₃H₄SN)₂Fe(NO)₂] (cation = Et₄N⁺ (**3a**) and Ph₄P⁺ (**3b**)). Red O, blue N, orange Fe, yellow S, gray C, sienna P; H atoms are removed for clarity. (Color figure online)

iPr)Fe(NO)₂]₄ [24, 30], three reductive events are shown at -1.29 , -1.67 , and -1.98 V. Again, the -1.29 and -1.67 V associated to oxidative events -1.09 and -1.41 V, respectively, Fig. 4. The pattern of these multiple redox couples are consistent with the previously reported tetrametallic CV data (Fig. 4a). The CV scan of compound **3**, measured on THF solution, displays an irreversible electrochemical response within the THF solvent window with E_{pc} at -1.66 V and E_{pa} at -1.35 and -0.96 V. These complicated events suggest somewhat that complex **3** is unstable when the redox reaction occurred.

	E_{pc}^d (V)	E_{pa}^d (V)
2 ^{b,e}	-1.25	-0.92
	-1.56	-1.33
	-1.67	
[(Imid-iPr)Fe(NO) ₂] ₄ ^{a,c}	-1.29	-1.09
	-1.67	-1.41
	-1.98	
3 ^{b,e}	-1.66	-1.35
		-0.96

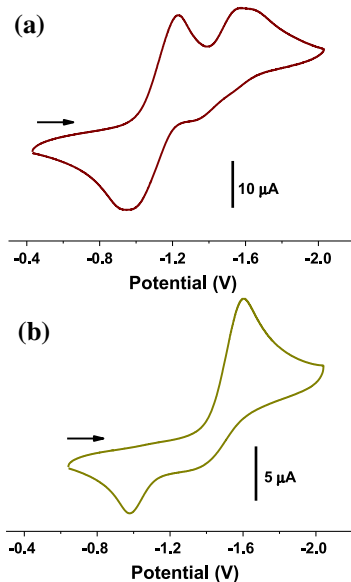


Fig. 4 Redox potential values for complex **2**, [(Imid-iPr)Fe(NO)₂]₄ and **3**. **a** In CH₂Cl₂ solution. **b** In THF solution. **c** Redox potentials from Ref. [30]. **d** All the experiments were measured by using a glassy carbon working electrode and Pt counter electrode. Redox potentials referenced to Fc/Fc⁺ at 100 mV/s scan rate. **e** This work

Conclusions

A new tetrameric complex **2** forms a molecular diamond shape; each edge was comprised of a 2-mercaptothiazoline ligand bridging to the $\{\text{Fe}(\text{NO})_2\}$ units; to our knowledge, only a few tetranuclear DNIC have been reported prior to this study. However, many heterocyclic analogs of 2-mercaptothiazoline ligand have been adopted to synthesize DNICs, but all the structures were characterized in the dinuclear [19–23], a variation of Roussin's red esters (RRE), or a mononuclear S-bound DNIC [23]. In this paper, we report DNICs with 2-mercaptothiazoline ligand in the tetranuclear and mononuclear N-bound forms, but whether 2-mercaptothiazoline could serve as an inhibitor to the cancer cell or how NO releases from DNICs may be the following challenge to be explored.

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