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Synthesis and characterization of Cu(II) paddlewheel complexes possessing fluorinated carboxylate ligands

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A B S T R A C T

The goal of this study was to establish the relationship between the ^{19}F NMR line broadening and the varying distance between the ^{19}F nucleus and copper(II) ion, with the aim of gathering data that can be used to interpret ^{19}F NMR spectra of subsequent fluorine-labeled, copper-binding proteins. Fluorinated alkyl and aryl copper(II) carboxylates were synthesized from fluorinated carboxylic acids and $Cu(OH)_2$. The copper(II) carboxylates were characterized using ^{19}F NMR, IR, and single crystal X-ray diffraction. In the alkyl carboxylate compounds, the line broadening and chemical shift lessened with increased distance between the fluorine atom and the copper ions; however, in the aryl carboxylate derivatives, increased distance was not a factor in the amount of line broadening or change in chemical shift between the acid and metal salt. The compound, bis(3-(trifluoromethyl)butyrate) copper(II) (**5**) was found to possess the optimum combination of decreased line broadening and increased chemical shift sensitivity in ^{19}F NMR. The crystal structures obtained for compounds **1**, **2**, **4**, and **6** were analogous to previous copper(II) carboxylate complexes, though it is noted that compound **6**, bis(5,5,5-trifluoropentanoate) copper(II) assumes a tetrameric structure lacking apical ligands, and thus enables the formation of an extended network of near-neighbor copper(II) ions.

1. Introduction

The use of ^{19}F NMR as a probe of protein structure and dynamics has been found in the scientific literature for quite some time, and a number of reviews have been devoted to this field of study [1–3]. There are many aspects of using fluorine-labeled protein in such studies that make it quite attractive. For example, the fluorine nucleus is similar in size to the hydrogen nucleus, and even though it possesses a considerably different dipole moment, it is expected to impart little perturbation to the structure, stability, and function of the native protein [4]. Fluorine is not found in naturally occurring proteins, so any peaks observed in a ^{19}F NMR spectrum are certain to arise from the presence of the fluorine labeled amino acids in the protein. In addition, the fluorine nucleus is extremely sensitive to its local chemical environment and to local shielding effects, thus resulting in well resolved peaks in a one-dimensional NMR spectrum [5]. This sensitivity to local chemical environment enables ^{19}F NMR to probe protein structure on an amino acid residue level, an area where circular dichroism (CD) and fluorescence spectroscopy often fail.

Though there are numerous examples of proteins that have been characterized by ^{19}F NMR studies [1,2], a small percentage of these have investigated the nature of metal binding proteins. Previous reports of ^{19}F NMR being used to probe metal binding in proteins describe the use of either a fluorinated substrate [6,7], fluorinated amino acids that are in close proximity to the metal [8,9], or cysteine ligands that have been chemically modified with fluorinated substituents [10]. However, to the best of our knowledge there are no reports of the use of a fluorinated amino acid that directly ligates metal ions.

Given the dearth of ^{19}F NMR data for metalloprotein systems, it is prudent to use small molecule model systems to develop a better understanding of how the fluorine-19 nucleus will behave in the presence of metal ions. In this report, a model system comprised of copper(II) complexes possessing fluorinated carboxylate ligands was synthesized and characterized. This system was chosen because carboxylate residues (aspartate and/or glutamate) are known to directly bind metal ions in proteins and copper(II)

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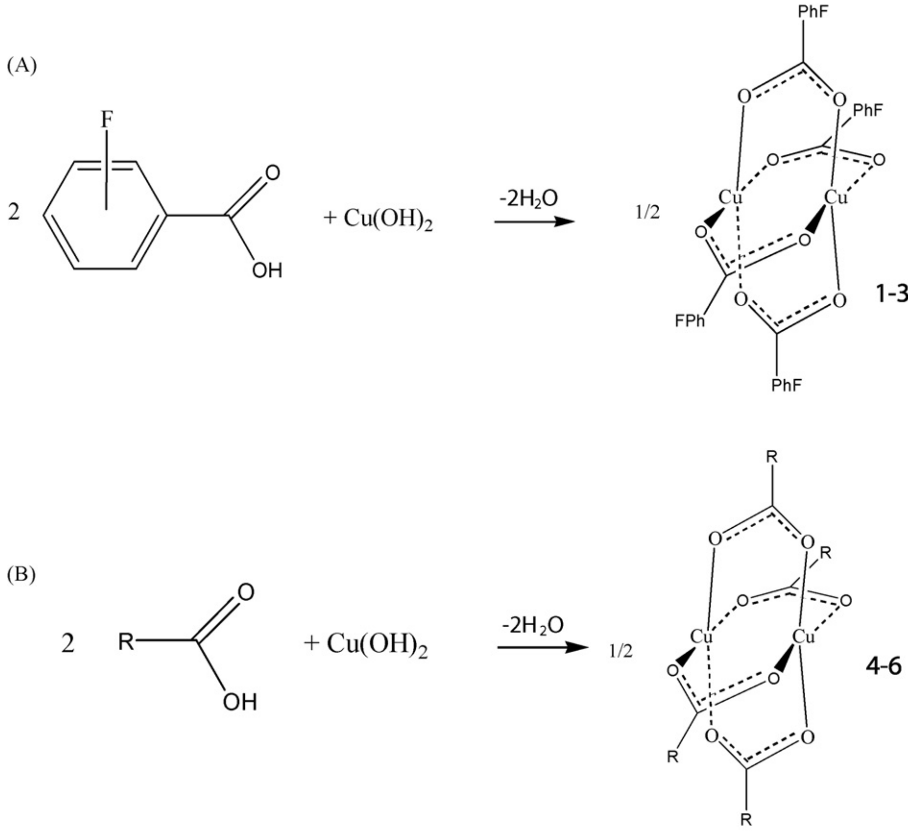

Scheme 1. A (**1** = 2-fluoro, **2** = 3-fluoro, **3** = 4-fluoro), B (**4**: R = CH_2CF_3, **5**: R = $CH_2CH(CH_3)CF_3$, **6**: R = $CH_2CH_2CH_2CF_3$).

coordination sites are found in a variety of biological enzymes. Copper binding is also believed to play a part in the pathogenesis of Cruetzfeldt–Jacob disease [11]. In addition to playing an important physiological role, copper carboxylate complexes have been investigated for a variety of other applications, including catalytic chemical bond activation [12], the preparation of metal oxide materials [13], the supra-molecular assembly of metal ions [14], and studying the fundamental nature of metal–metal interactions [15].

Due to the paramagnetic nature of copper(II), NMR spectra of complexes possessing Cu(II) often exhibit extensive line broadening. As a result, ^{19}F NMR studies on paramagnetic copper coordination compounds are quite limited. Based on studies completed with the H-BPMP (2,6-bis[(bis(2-pyridyl-methyl)amino)methyl]4-methylphenol) based ligand [16] and perfluorocarboxylate ligands [17], as the fluorine atom is further removed from the bound Cu(II) ion, the change in chemical shift should be less and the peaks should become less broadened. The effect of the paramagnetic copper is also thought to be lessened if the fluorine nucleus is on a substituent with more rotational freedom and if there is no π conjugation on the ligand between the copper and fluorine atoms [16,17].

The primary aim of this work was to compare the effect of paramagnetic copper on fluorine nuclei located on tri-fluoro alkyl and mono-fluoro aryl carboxylates, and to determine the copper–fluorine distance that provides the optimum combination of decreased line broadening and increased chemical shift sensitivity in ^{19}F NMR. To this end, a series of fluorinated carboxylic acids were reacted with copper(II) hydroxide (see Scheme 1). The composition of compounds **1**–**6** was verified by elemental analysis and a qualitative comparison of the ^{19}F NMR spectra carried out. The synthesis of this set of compounds also provided an opportunity to determine how subtle changes in the carboxylate ligand affected the solid state structural properties of the dimeric copper(II) paddlewheel complexes **1**, **2**, **4**, and **6**.

2. Results and discussion

2.1. Synthesis

Compounds **1**–**6** were synthesized by the straightforward reaction of the parent carboxylic acids with copper(II) hydroxide in alcohol solvents. Upon reaction, the dark green reaction mixtures turned blue/blue-green and all of the subsequent solid carboxylate complexes, except for compound **3**, were recrystallized in good yields. After being used in the X-ray crystallographic studies, the crystals were dried *in vacuo* and used for all subsequent analyses.

2.1.1. IR

Compounds **1**–**6** exhibited a weakening of the C=O bond, due to the π delocalization of the carboxylate moiety that occurred upon deprotonation of the free acid. The fluorobenzoate copper complexes (**1**–**3**) underwent a similar decrease in the C=O absorption (127–131 cm^{-1}), whereas the C=O stretch in the alkyl chain analogues (**4**–**6**) was found to be dependent on the length of the carbon chain [decrease in C=O stretch: **4** (93 cm^{-1}); **5** (119 cm^{-1}); **6** (143 cm^{-1}); see Table 1). The fact that the placement of the fluorine on the phenyl ring had little effect on the IR properties of compounds **1**–**3** is likely due to the π system's ability to similarly transmit the electronic effects of the fluorine nucleus from any position on the ring. This is in agreement with work done by Boiadjiev and Lightner, in which it was found that moving the fluorine to different locations on the phenyl ring had much less effect on the pK_a of the benzoic acid than did changing the distance

Table 1
C=O stretch of compounds **1-6** and parent carboxylic acids (cm^{-1}).

Compound	Parent acid absorbtion	Copper(II) complex peak absorbtion
1	1694	1565
2	1687	1556
3	1682	1555
4	1733	1640
5	1713	1594
6	1731	1588

Table 2
Chemicals shifts (ppm) and peak widths (Hz) for compounds **1-6**.

Compound	Acid peak (ppm)	Complex peak (ppm)	Change (ppm)	Complex peak width (Hz)
1	−111.6	−111.8	−0.2	160
2	−114.5	−111.4	+3.1	500
3	−108.1	−110.9	−2.8	175
4	−64.7	−52.1	12.6	600
5	−74.7	−72.7	2.0	75
6	−67.3	−67.6	−0.3	35

between the carboxylic acid and the fluorine nucleus in the alkyl chain derivatives [18].

Surprisingly, there is very little IR data for structurally analogous compounds available in the literature. Data are available for two derivatives of a copper(II) dimer possessing the trifluoroacetate (TFA) ligand [$Cu_2(TFA)_4$]. The complex possessing terminal THF solvent ligands exhibited a C=O absorbance of 1684 cm^{-1}, whereas its isopropoxyethanol congener displayed a C=O stretch at 1706 cm^{-1} [13]. These are both higher than the C=O stretch found in **4**, and follow the trend of higher energy carbonyl absorption being associated with shorter fluorinated alkyl chains. It appears that as the fluorine atom is farther removed from the carboxylate moiety, the C=O stretch is weakened, presumably due to the fact that the carboxylate anion is not stabilized as much by the electron-withdrawing effects of the more remote fluorine nuclei. By the fifth carbon, there appears to be little effect on the IR absorption of the C=O. The non-fluorinated cousin of compound **4**, $Cu_2(CH_3CH_2COO)_4$, was reported to exhibit a C=O stretching frequency of 1628 cm^{-1}, slightly lower than that reported for compound **4** [23]. Again, this seems to indicate that the presence of fluorine on the ligand helps stabilize the anion. The IR absorptions of compound **5** and anhydrous copper(II) hexanoate [19] are nearly identical, presumably due to the limited electron withdrawing ability of the fluorine nucleus at this distance. No previous IR data could be found for either fluorinated or non-fluorinated benzoate copper complexes in the dinuclear paddlewheel configuration.

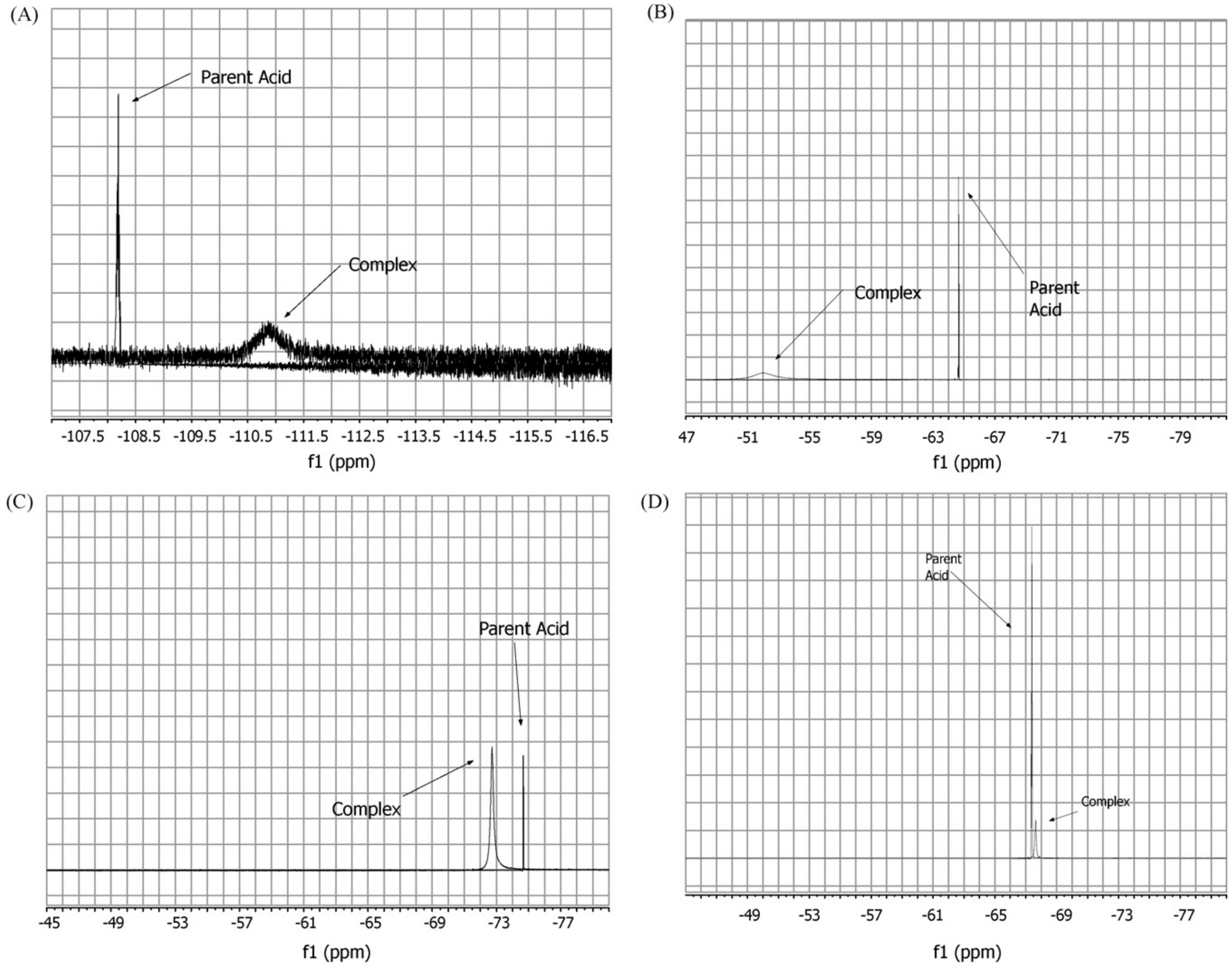

Fig. 1. ^{19}F NMR spectra of A: compound **3**; B: compound **4**; C: compound **5**; D: compound **6** (the spectra of the complexes are overlayed with the spectra of the parent carboxylic acids).

2.1.2. ^{19}F NMR

When analyzed using fluorine-19 NMR, all six compounds showed some degree of line broadening along with a change in chemical shift compared to the parent acid. Compounds **1**–**3** showed no discernable pattern relating chemical shift sensitivity or line broadening to the distance between the fluorine nucleus and the copper ion. The change in chemical shifts between the free acid and benzoate salts were −0.2, +3.1, and −2.8 ppm for **1**, **2**, and **3**, respectively. Complex **2** yielded the greatest peak width at half-height (500 Hz), whereas compounds **1** (160 Hz) and **3** (175 Hz) displayed similar line broadening and were much narrower than **2** (Table 2). For the alkyl analogues, the ^{19}F NMR resonance for compound **4**, as expected, underwent the largest chemical shift compared to the free acid (12.6 ppm). The resonance for compound **5** shifted 2.0 ppm, whereas compound **6** exhibited very little change in chemical shift (Table 2). The three-carbon propionate salt (**4**) displayed a considerable amount of line broadening (600 Hz) compared to the five-carbon methylbutyrate (**5**, 75 Hz) and pentanoate (**6**, 35 Hz) salts (Fig. 1). As previously reported, the lack of π conjugation between the copper(II) ion, along with a larger distance between the copper metal center and fluorine nucleus results in less line broadening in the ^{19}F NMR spectrum [16,17].

Though no studies have looked at the effect of metals on the ^{19}F NMR spectra of fluorinated benzoates, Boiadijiev and Lightner, found that the ^{19}F NMR chemical shift of *ortho*- and *para*-fluorobenzoic acid are much more sensitive to deprotonation of the carboxylate than the *meta*-isomer, with the *para*-isomer being the most sensitive [18]. For our compounds, the *meta*-isomer (**2**) is the most sensitive to the presence of the copper atom, with a significantly larger change in chemical shift than the *ortho*-isomer (**1**) (Table 2). Previous ^{19}F NMR studies have been carried out on the perfluorinated analogues of compounds **4** and **6**, as well as a perfluorobutyrate copper complex that is similar to compound **5** [17]. However, given that these studies were done under significantly different experimental conditions, a conclusive comparison is not possible. It is noted though that our data seem to indicate that the use of the tri-fluoro carboxylate ligands in **4**–**6** may impart less line broadening and a greater range of chemical shift sensitivity. As mentioned above, fluorine-19 NMR studies have been previously carried out on the parent carboxylic acids from compounds **1**–**5** [18]. The shift of the ^{19}F resonances were monitored as a function of pH. Based on these data, it is apparent the chemical shift change upon forming the copper(II) complex is greater than the change observed during the simple deprotonation of the acid in both the alkyl and aryl derivatives.

The effect of the copper(II) ion dissipates rapidly as the alkyl chain is lengthened. After adding a fifth carbon in the alkyl carboxylate, there is no significant effect on the chemical shift of fluorine. Therefore, the most useful compound for detecting the presence of copper ions seems to be **5**. Though it undergoes some increase in line broadening, it is much less than that observed for compound **4** (as well as compounds **1**–**3**), and it exhibits a more detectable change in chemical shift not seen in compound **6**.

2.1.3. Crystal structures

The crystal structures obtained for **1**, **2**, **3** [20], **4**, and **6** indicate that the compounds exist in the dinuclear paddlewheel configuration that is common among copper(II) carboxylates. In general, these compounds consist of two copper(II) metal centers bridged by four carboxylate ligands. The distorted octahedral geometry is completed by a Cu–Cu interaction, and by solvent ligands bound at the axial position (**1**–**4**) or by carboxylate oxygens from an adjoining copper dimer (**6**).

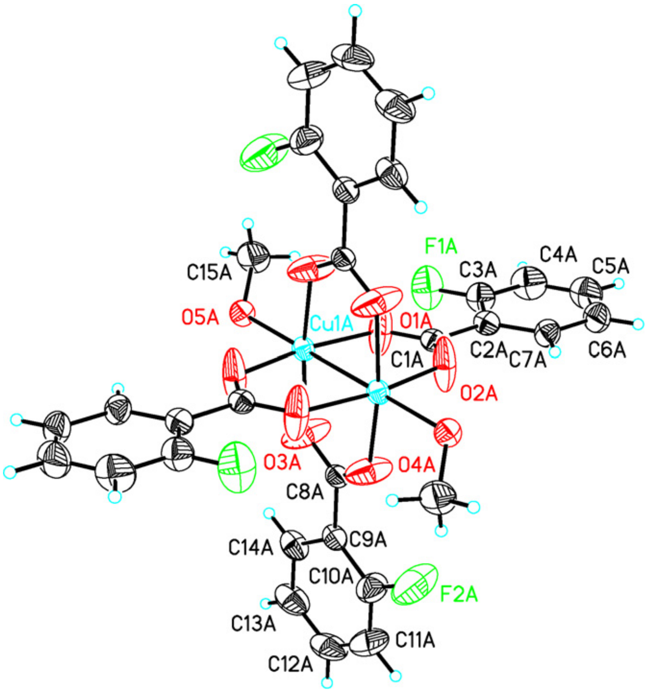

Fig. 2. Crystal structure of **1** showing paddlewheel configuration with solvent coordination[1].

Compounds **1, 2,** and **3** are isostructural (a derivative of compound **3**, possessing ethanol ligands in the axial position, has been previously characterized by X-ray crystallography [20]). The Cu–Cu distances of 2.5882(13), 2.614(2), and 2.5843(8) Å, respectively, are in general agreement with the previously reported 2,6-difluorobenzoate analogue [Cu–Cu distance: 2.6139(2) Å ($Cu_2(C_6H_4F_2)_4(H_2O)_2$)][21]. The Cu–$O_{carboxy}$ distances for **1**–**3**, ranging from 1.926(7)–1.966(8) Å, are in agreement with the 2,6-difluorobenzoate copper(II) structure (average Cu–$O_{carboxy}$ = 1.9655(7) Å)[21], and as expected, are found to be shorter than the Cu–O_{solv} distances (**1**: 2.126(3) Å; **2**: average = 2.142(7) Å; **3**: 2.141(2) Å [25]). Kariprdes and White report that the copper(II) 2,6-difluorobenzoate species ($Cu_2(C_6H_4F_2)_4(H_2O)_2$) [22] has a C–F···H–$O_{water}$ distance of 2.962 Å, which they describe as the shortest known organic hydrogen bond of its kind. Lim et al. found the same compound showed a C–F···H–O_{water} distance of 2.928 Å [21]. Compound **1** shows a C–F···H–O_{MeOH} interatomic distance of 2.955 Å, intermediate of these two previous distances. In addition to this particular interaction, other hydrogen bonds can be found in compounds **1** and **2**. Unbound methanol molecules reside in the spaces between the paddle wheels and are held in place by hydrogen bonds with the fluorine and carboxylate oxygens. The hydrogen bonds cause some distortion in the paddlewheel, though neither **1** nor **2** have O_{carobx}–Cu–O_{carbox} angles that vary more than 8° from a right angle (Fig. 2 and Tables 3 and 4).

The crystal structures of **4** and **6** also exist in the standard dinuclear paddlewheel configuration. Compound **4** possesses axial water ligands, whereas compound **6** has no terminal ligands, and therefore forms a tetramer where carboxylate oxygens of neighboring dimers ($O_{carboxy'}$) complete the copper coordination sphere. As found for all analogous paddlewheel complexes, the Cu–$O_{carboxy}$ distances for **4** and **6** (1.9534(1)–1.999(3) Å) are shorter than the Cu–O_{H20} (**4**: 2.1088(1)–2.1440(11) Å) and Cu–$O_{carboxy'}$ (**6**: 2.201(3)–2.205(3) Å) distances. Two previously published struc-

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[1] The ^{19}F NMR spectra of compounds **1** and **2** are shown in supplemental information.

Table 3
Selected bond lengths (Å) and angles (°) for **1**.

Cu(1)–O(2)#1	1.949(4)
Cu(1)–O(4)#1	1.950(4)
Cu(1)–O(1)	1.956(3)
Cu(1)–O(3)	1.964(4)
Cu(1)–O(5)	2.126(3)
Cu(1)–Cu(1)#1	2.5882(13)
O(2)–Cu(1)#1	1.949(4)
O(4)–Cu(1)#1	1.950(4)
Cu(1)–Cu(1)#1	2.5882(13)
O(2)#1–Cu(1)–O(4)#1	89.9(3)
O(4)#1–Cu(1)–O(1)	89.6(2)
O(2)#1–Cu(1)–O(3)	89.9(3)
O(1)–Cu(1)–O(3)	88.0(2)
O(5)–Cu(1)–Cu(1)#1	177.78(11)

Table 4
Selected bond lengths (Å) and angles (°) for **3**[20].

Cu–Cu	2.584
Cu–O$_{carboxy}$	1.956
	1.955
	1.952
	1.951
Cu–O$_{EtOH}$	2.140
O$_{EtOH}$–Cu–Cu	177.89
O$_{carboxy}$–Cu–O$_{EtOH}$	96.08
	95.03
O$_{carboxy}$–Cu–O$_{carboxy}$	89.63
	90.89
	89.39
	87.90

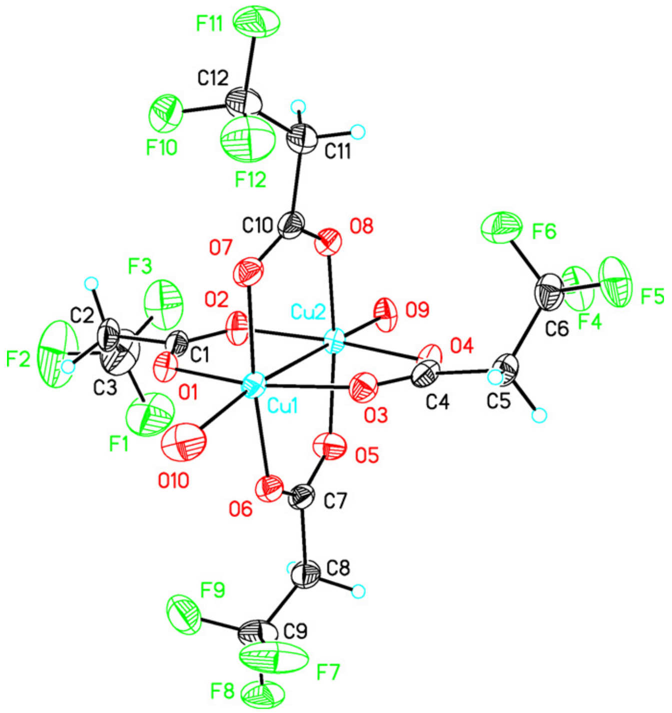

Fig. 3. Crystal structure of **4** showing paddlewheel configuration with solvent oxygens coordinating in the apical position (hydrogens from the coordinating water molecules are not shown).

tures of the non-fluorinated propionate complex, [Cu$_2$(CH$_3$CH$_2$OO)$_4$], are structurally analogous to compound **4** [23,24]. However, the Cu–Cu distance seen in **4** (2.614(2) Å) is slightly longer than that of its non-fluorinated analogues (2.5826(12) and 2.578(4) Å). This can be attributed to the fact that as the electron withdrawing ability of the carboxylate ligand increases, the Cu–Cu interatomic distance also increases [13,25]. There are no previously reported structural congeners for compound **6**; however, comparison to compound **4** indicates that the Cu–Cu distance for **6** (2.580 Å) is slightly shorter. This also follows the trend where complexes with more electron withdrawing ligands possess longer Cu–Cu distances [13,25] (Figs. 3 and 4 and Tables 5 and 6).

The fact that compound **6** lacks terminal axial ligands and exists as a tetramer makes it unique among the structures reported here. A similar copper tetramer was previously prepared using a hexanoate ligand system, though it is noted this complex possessed terminal urea ligands [26]. The hexanoate complex is comparable to **6**, with a Cu–Cu distance of 2.5791(5) Å, Cu–O$_{carboxy}$ distances ranging from 1.94 to 1.96 Å and Cu–O$_{carboxy'}$ distances of 2.01 Å (compound **6**: Cu–Cu, 2.580 Å; Cu–O$_{carboxy}$, 1.932(3)–1.999(3) Å; Cu–O$_{carboxy'}$, 2.201(3)–2.205(3) Å). Upon looking at the extended crystal network of compound **6**, it was found that the tetrameric units polymerized via bridging carboxylate oxygens (O$_{caroboxy'}$), analogous to the formation of the tetramer. This gives rise to a chain of Cu···Cu–Cu···Cu interactions, which alternate between 2.57919(5) and 3.210 Å. These distances are in agreement with previously reported polymeric structures with carboxylate ligands including methylbutyrate (Cu–Cu: 2.5893 Å [27], Cu···Cu 3.268 Å), hexanoate (Cu–Cu: 2.579 Å, Cu···Cu 3.236 Å) [24], heptanoate (Cu–Cu: 2.578 Å, Cu···Cu 3.232 Å) [28], octanoate

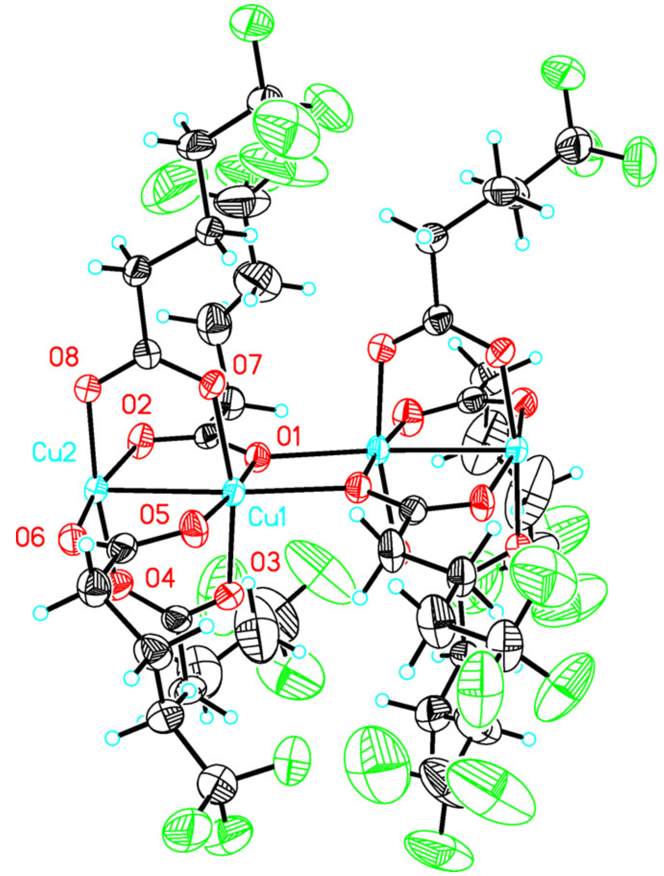

Fig. 4. Crystal structure of **6** showing dobule paddlewheel configuration with no solvent coordination.

Table 5
Selected bond lengths (Å) and angles (°) for **4**.

Cu(1)–O(7)	1.9716	Cu(3)–O(11)	1.9619(11)	Cu(4)–Cu(4)#2	2.6349(13)
Cu(1)–O(6)	1.9735	Cu(3)–O(13)	1.9680(12)	O(7)–Cu(1)–O(6)	170.93(6)
Cu(1)–O(3)	1.9808(10)	Cu(3)–O(14)	1.9717(11)	O(7)–Cu(1)–O(3)	87.0
Cu(1)–O(1)	1.9991	Cu(3)–O(12)	1.9780(10)	O(6)–Cu(1)–O(3)	91.3
Cu(1)–O(10)	2.1182	Cu(3)–O(15)	2.1440(11)	O(7)–Cu(1)–O(1)	89.1
Cu(1)–Cu(2)	2.6500(9)	Cu(3)–Cu(3)#1	2.6315(12)	O(6)–Cu(1)–O(1)	90.0
Cu(2)–O(2)	1.9534	Cu(4)–O(17)	1.9630	O(2)–Cu(2)–O(8)	92.8
Cu(2)–O(4)	1.9655	Cu(4)–O(19)	1.9708	O(13)–Cu(3)–O(12)	90.4
Cu(2)–O(8)	1.9676	Cu(4)–O(18)	1.9726	O(14)–Cu(3)–O(12)	168.80(7)
Cu(2)–O(5)	1.9711(12)	Cu(4)–O(16)	1.9832	O(12)–Cu(3)–Cu(3)#1	83.55(4)
Cu(2)–O(9)	2.1338(11)	Cu(4)–O(20)	2.1088	O(15)–Cu(3)–Cu(3)#1	177.31(5)

Table 6
Selected bond lengths (Å) and angles (°) for **6**.

Cu(1)–O(5)	1.932(3)	O(5)–Cu(1)–O(3)	90.07(14)
Cu(1)–O(3)	1.974(3)	O(5)–Cu(1)–O(7)	90.72(14)
Cu(1)–O(7)	1.980(3)	O(3)–Cu(1)–O(7)	165.69(13)
Cu(1)–O(1)	1.999(3)	O(5)–Cu(1)–O(1)	172.22(13)
Cu(1)–O(8)#1	2.201(3)	O(3)–Cu(1)–O(1)	88.83(14)
Cu(1)–Cu(2)	2.5802(8)	O(7)–Cu(1)–O(1)	88.46(13)
Cu(2)–O(4)	1.937(3)	O(1)–Cu(1)–O(8)#1	80.04(12)
Cu(2)–O(6)	1.961(3)	O(5)–Cu(1)–Cu(2)	87.19(9)
Cu(2)–O(8)	1.982(3)	O(3)–Cu(1)–Cu(2)	82.50(9)
Cu(2)–O(2)	1.984(3)	O(7)–Cu(1)–Cu(2)	83.26(9)
Cu(2)–O(1)#2	2.205(3)	O(1)–Cu(1)–Cu(2)	85.03(9)
O(1)–Cu(2)#1	2.205(3)	O(8)#1–Cu(1)–Cu(2)	165.00(9)
O(8)–Cu(1)#2	2.201(3)		

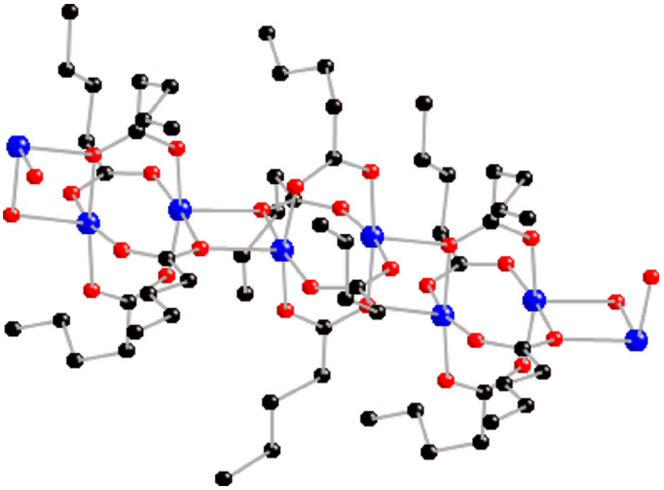

Fig. 5. Macro-molecular structure of **6** showing direct coordination between Cu and O of adjacent paddlewheels (copper atoms shown in blue; oxygen shown in red; carbon shown in black; hydrogen and fluorine are omitted for clarity). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(Cu–Cu: 2.575 Å, Cu···Cu 3.269 Å) [29], and decanoate (Cu–Cu: 2.624 Å, Cu···Cu 3.365 Å) [30]. Though other polymeric copper(II) carboxylates have been reported [14,15,24,27–30], compound **6** appears to be the first such structure possessing a fluorinated carboxylate ligand and subsequent close C–F···H–C interactions between individual polymer chains (C–F···H–C interactions of 2.448, 2.823, and 3.044 Å; Fig. 5).

3. Conclusion

The synthesis and characterization of the series of mono-fluorobenzoate and tri-fluoroalkyl carboxylate copper(II) complexes, **1**–**6**, reveals that the 3-(trifluoromethyl)butyrate species [$Cu_2(CH_3(CF_3)CHCH_2COO)_4$; **5**] provides the optimal combination of reduced line broadening and chemical shift sensitivity in ^{19}F NMR studies. This result suggests that this compound represents a potential structural model for developing fluorinated probes that could be used in ^{19}F NMR studies of copper(II) binding proteins. The lower degree of line broadening in **5** reduces the uncertainly in assigning the chemical shift to a peak, thus providing a potential structural target for fluorinated labels that could be used for studying conformational changes in proteins. In addition, results from X-ray crystallography experiments indicate that the use of tri-fluoroalkyl carboxylate ligands allow for the straightforward tuning of metal–metal interatomic distances in transition metal carboxylate paddlewheel complexes. Given the fact that compound **6** affords an extended network of copper(II)–copper(II) interactions, the tri-fluoropentanoate ligand may provide an opportunity to develop analogous supramolecular networks with other metals.

4. Experimental

4.1. General procedures

2-, 3-, and 4-fluorobenzoic acids and were purchased from Sigma–Aldrich; 3,3,3-trifluoropropionic acid, 3-(trifluoromethyl)-butyric acid, and 5,5,5-trifluoropentanoic acid were purchased from Oakwood Products, Inc.; $Cu(OH)_2$ was purchased from Alfa Aesar. All reagents were used without further purification.

IR data was obtained on a PerkinElmer FT-IR Paragon 500 using a KBr pellet. The ^{19}F NMR spectra were obtained on a Varian Innova 400 spectrometer at 376 MHz. All samples were dissolved in a 1250:1 CD_3OD:C_6F_6 solution. Data are reported as chemical shifts (δ ppm) relative to C_6F_6. Peak width at half-height was estimated using Mestre-C (v. 4.9.9.0) [31].

For X-ray crystallography, suitable crystals of **1**, **2**, **4**, and **6** were coated with Paratone N oil, suspended in a small fiber loop and placed in a cooled nitrogen gas stream at 173 K on a Bruker D8 APEX II CCD sealed tube diffractometer with graphite monochromated Cu Kα (1.54178 Å) radiation. Data were measured using a series of combinations of phi and omega scans with 10 s frame exposures and 0.5° frame widths. Data collection, indexing and initial cell refinements were all carried out using APEX II software [32]. Frame integration and final cell refinements were done using SAINT software [33]. The structure was solved using Direct methods and difference Fourier techniques (SHELXTL, V6.12) [34]. Hydrogen atoms were placed their expected chemical positions using the HFIX command and were included in the final cycles of least squares with isotropic U_{ij}'s related to the atom's ridden upon. All non-hydrogen atoms were refined anisotropically. Scattering factors and anomalous dispersion corrections are taken from the *International Tables for X-ray Crystallography* [35]. Structure solution, refinement, graphics and generation of publication materials were performed by using SHELXTL, V6.12 software.

4.1.1. General procedure for synthesis of copper(II) aryl carboxylate salts

The fluorinated acid (**1**: 504 mg, 3.6 mmol; **2**: 559 mg, 4.0 mmol; **3**: 490 mg, 3.5 mmol) was dissolved in methanol, and to it was added $MgSO_4$ and excess $Cu(OH)_2$ (**1**: 515 mg, 5.2 mmol; **2**: 527 mg, 5.4 mmol; **3**: 488 mg, 5.0 mmol). The solutions were stirred for 20 min, upon which a blue or blue/green color was noticeable. The solid, consisting of $MgSO_4$ and excess $Cu(OH)_2$, was filtered off and the solvent reduced *in vacuo*. Crystals of compounds **1**–**3** were then grown at low temperature (between 5 and −20 °C), isolated, and used for all subsequent analyses.

4.1.2. General procedure for synthesis of copper(II) alkyl carboxylate salts

The fluorinated acid (**4**: 695 mg, 4.4 mmol; **5**: 515 mg, 4.0 mmol; **6**: 526 mg, 3.3 mmol) was reacted with ≤0.5 equivalents of $Cu(OH)_2$ (**4**: 159 mg, 1.6 mmol; **5**: 193 mg, 1.9 mmol; **6**: 156 mg, 1.5 mmol). The starting materials were dissolved separately in ethanol, and after the solutions were combined, the reaction mixture was refluxed for 3 h. As the reflux progressed, the solutions turned blue or blue/green. The solvent was then removed by rotary evaporation to yield the solid product, which was dried under vacuum and moderate heate (approximately 0.5 Torr, 50 °C). Crystals were obtained by slow evaporation from methanol, isolated, and used for all subsequent analyses.

4.1.3. Data for compounds **1**–**6**[2]

*4.1.3.1. bis(2-fluorobenzoate) copper(II) (***1***).* 76.5% yield (by recrystallization at 5 °C); blue-green needles; IR (KBr) (cm^{-1}): 1615 (aromatic C–C), 1565 (C=O), 1406 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 111.8 (s); elemental analysis, calculated for $CuC_{14}H_8O_4F_2$: C: 49.18, H: 2.36; found: C: 48.75, H: 2.31.

*4.1.3.2. bis(3-fluorobenzoate) copper(II) (***2***).* 54.2% yield (by recrystallization at −20 °C); blue-green prisms; IR (KBr) (cm^{-1}): 1595 (aromatic C–C), 1556 (C=O), 1415 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 111.4 (s); elemental analysis, calculated for $CuC_{14}H_8O_4F_2{\cdot}0.5H_2O$: C: 47.92, H: 2.59; found: C 47.83: H: 2.30.

*4.1.3.3. bis(4-fluorobenzoate) copper(II) (***3***).* 5% yield (by recrystallization at 0 °C); small blue-green crystals, rapidly degraded to a light blue solid when exposed to air; IR (KBr) (cm^{-1}): 1607 (aromatic C–C), 1555 (C=O), 1421 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 110.9 (s); elemental analysis, calculated for $CuC_{14}H_8O_4F_2$: C: 49.2, H: 2.3; found: C:47.2, H: 2.3.

*4.1.3.4. bis(3,3,3-tri-fluoropropionate) copper(II) (***4***).* 88.7% yield; green-blue powder; IR (KBr) (cm^{-1}): 1640 (C=O), 1466 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 52.1 (s); elemental analysis, calculated for $CuC_6H_4O_4F_6$: C: 22.67, H: 1.27; found: C 22.68, H: 1.20.

*4.1.3.5. bis(3-(tri-fluoromethyl)butyrate) copper(II) (***5***).* 52.2% yield; blue powder; IR (KBr) (cm^{-1}): 1594 (C=O), 1431 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 72.7 (s); elemental analysis, calculated for $CuC_{10}H_{10}O_4F_6$: C: 32.29, H: 2.71; found: C: 31.98, H: 3.16.

*4.1.3.6. bis(5,5,5-tri-fluoropentanoate) copper(II) (***6***).* 34.7% yield; blue powder; IR (KBr) (cm^{-1}): 1588 (C=O), 1424 (C–F); ^{19}F NMR (376 MHz, CD_3OD w/C_6F_6) δ (ppm): 67.6 (s); elemental analysis, calculated for $CuC_{10}H_{12}O_4F_6$: C: 32.12, H: 3.24; found: C: 32.36, H: 3.22.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jfluchem.2008.10.001.

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[2] Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre (CCDC) as supplementary publication nos. 703384 (compound **1**), 703385 (compound **2**), 703386 (compound **4**), and 703383 (compound **6**). Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk). The ORTEP diagram, and table of bond angles and distances for compound **2** are given in supplemental information. The crystal data refinement parameters and cif files for compounds **1**, **2**, **4**, and **6** are also provided in supplemental information.