Tuning the architectures and luminescence properties of Cu(I) compounds of phenyl and carboranyl pyrazoles: the impact of 2D versus 3D aromatic moieties in the ligand backbone†

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Incorporation of one or two o-carborane moieties at the backbone of the pyrazole ring was achieved by lithiation and nucleophilic addition onto the corresponding 3,5-dimethyl-1-(2-tolueno-p-sulfonyloxyethyl)pyrazole. Two monosubstituted carboranyl pyrazoles (L2 and L3) and one disubstituted carboranyl pyrazole (L4) were synthesized and fully characterized. All new compounds, and the corresponding monosubstituted phenyl derivative (L1) behave as N-type ligands upon coordination with CuI to afford different polynuclear Cu(I) compounds 1–4. Compounds 1–4 were fully characterized and their molecular structures were determined by X-ray diffraction. It is noteworthy that whereas the pyrazolylphenyl ligand L1, without o-carborane, provides a 1D coordination polymer (1), ligands containing carborane, L2–L3, affords 0D coordination compounds 2 and 3, and disubstituted carboranyl pyrazole ligand L4 gives rise to a 3D coordination polymer. The photoluminescence behaviour of compounds 1–4 has been investigated in the solid state and by TDDFT calculations for molecular compounds 2 and 3. Complex 2 exhibits blue emission with a maximum at 483 nm and a high fluorescence quantum yield of 66.5%. According to TDDFT calculations the emission occurs from LUMO to HOMO/C0 with a maximum at 483 nm and a high fluorescence quantum yield of 66.5%. According to TDDFT calculations the emission occurs from LUMO to HOMO–1 and HOMO–2 and deexcitation could be described as cluster-centred excited state of d→s transition in origin. This result contradicts previous studies of scarce tri-coordinated rhombohedral Cu(I) clusters, where it was assumed the origin of their emissions is (X + M)ICT in nature by analogy with tetra-coordinated rhombohedral Cu(I) clusters. Complex 3 exhibits very weak emission (ΦF of 5%) in the green region with a maximum at 517 nm, which according to TDDFT is through a 3CC state. Calculations also show that, upon excitation, 3 suffers a notable distortion resulting in the total cleavage of the Cu4I4 framework. This cleavage could be the cause of the relatively large Stokes shift observed for 3. To the best of our knowledge, this is the first time that such behaviour is observed for this type of octahedral compounds. Additionally, the 1D polymer 1 exhibits weak fluorescence emission in the orange range with a maximum at 609 nm and a remarkable Stokes shift, whereas the 3D polymer 4 exhibits a similar emission to compound 2, with a moderate quantum yield (ΦF of 13.7%).

Introduction

Polynuclear copper(I) halide clusters have been widely investigated over decades due to their intriguing photophysical properties.1–10 Potential applications for these materials include light-emitting devices (OLEDs),11–13 light-emitting electrochemical cells (LECs),14 solar cells15 and luminescent sensors.16,17 The interest in this family of compounds does not only stems from their photoluminescent properties, but also from the great diversity of structural motifs of the CuXnLx (X = Cl, Br, I) skeleton.4,18 Thus, several structural motifs have been reported, ranging from 0D (coordination compounds) to 1-3D aggregates (coordination polymers).4,12,18 For instance,
Cu$_2$X$_2$ rhomboid dimer or the Cu$_4$X$_4$ cubane and stepped-cubane are among the most common 0D structural motifs, while octahedral Cu$_4$X$_4$ motifs are less common$^{19}$ (Chart 1). Regarding higher dimension aggregates, typical structural motifs include single-, double-, looped-, helical-chains, ribbons, columns, etc.$^{16,18,20}$

These different nuclear multiplicities and aggregate dimensionalities are not only intriguing per se, but are also interesting because their structural parameters greatly affect the photophysical properties of the resulting compounds. For instance, in cubane-like clusters a dual emission is observed arising from two different excited states. An halide-to-ligand charge transfer ($^3$XLCT), sometimes mixed with metal-to-ligand charge transfer, $^3$MLCT) gives rise to a high energy (HE) emission ($ca$. 450 nm) while Cu$_4$I$_4$ cluster-centred ($^3$CC) excited state yields a low energy (LE) emission ($ca$. 600 nm), which is related to the Cu-Cu distances.$^{4,21}$ In fact, this relationship between Cu-Cu distance and the LE emission gives raise to one of the most interesting properties of cubane compounds: thermochromism.$^{22}$ However, this LE emission can be quenched using rigid ligands that prevent cluster relaxation, thus “blocking” this emission,$^{23}$ or fine-tuned using different heterocyclic donors.$^{24}$ In contrast, stair-step clusters only show HE emission, due to having longer Cu-Cu distances.$^{25}$ Regarding octahedral compounds, reports including photophysical studies are much scarcer, with fewer than a dozen papers published on the subject.$^{19,23,25-31}$ This can be attributed to the fact that octahedral cores are energetically unfavourable compared to the cubane cores, as demonstrated by theoretical calculations.$^{28}$ Optical properties of these octahedral compounds have also been studied and various reports suggest that the rigidity and steric demands of the ligands seems to play a more significant role in the photophysical properties than in the cubane type clusters.$^{19}$

With regards to the ligands employed in the above mentioned polynuclear Cu(I) halides, nitrogen- (N-) and sulfur- (S-) and phosphorus- (P-)ligands containing ligands are commonly found.$^{2,5,16,31}$ Structures with N-ligands (either monodentate or multidentate) are by far more common and show intriguing luminescent properties.$^{25,33}$ Reported examples on octahedral motifs include bidentate ligands bearing small angles (e.g., P$^3$N, $^{23,25,27,28,30}$ P$^3$P, $^{26,29,31,34-37}$ C$^3$P$^8$ and N$^3$N$^{19}$), with only one example based on a monodentate N-heterocyclic carbene ligand.$^{39}$ Within the family of polynuclear Cu(I) compounds containing N-ligands, pyrazoles are significantly less studied than the overwhelming family of pyridines.$^{32}$ Furthermore, pyrazole ligands employed in such polynuclear Cu(I) compounds are deprotonated (pyrazolate ligands) or neutral pyrazolyl-pyridine/pyrimidine combinations.$^{32,40-44}$ To our knowledge, there is only one report on a neutral monodentate only-pyrazole (not having other nitrogenated substituents) based Cu(I) complex.$^{45}$ There are however some more reports on neutral poly-pyrazolyl ligands, leading to a wide variety of coordination polymers.$^{46-49}$

As part of our on-going research on pyrazole$^{50-55}$ and carborane$^{56-63}$ based ligands for functional metal compounds, we were interested in exploring the impact of adding theicosahedral carborane clusters to the pyrazole fragment on the coordination to Cu(I) ions and the corresponding luminescence properties. Icosahedral carboranes 1,η-C$_2$B$_{10}$H$_{12}$ ($n = 2$, 7 or 12) are a class of commercially available and exceptionally stable 3D-aromatic boron-rich clusters that possess material-favourable properties such as thermal and chemical stability and high hydrophobicity.$^{64-66}$ Neutral carboranes are remarkably robust boron clusters with two carbon atoms and possess 26 electrons for 12 vertices. The delocalized electron density is not uniform through the cage, giving rise to extraordinary differences in the electronic effects of the cluster.$^{67}$ This unusual electronic structure is often highlighted by regarding carboranes as inorganic three-dimensional “aromatic” analogues of arenes.$^{68,69}$ The average size of the o-carborane (148 Å$^3$) is comparable to that of adamantane (136 Å$^3$) and is significantly larger (40%) than the phenyl ring rotation envelope (102 Å$^3$).$^{70}$ Regarding the electronic effect, o-carborane behaves as a strong electron-withdrawing group (similar to fluorinated aryl) on a substituent at one of the cluster carbons.$^{70-74}$ Thus, introduction of the carborane moiety into a ligand backbone is expected to exert a weaker metal–heteroatom interaction with respect to the related phenyl derivative.$^{58,74,75}$ In addition, and different from classical rigid flat aromatic ligands, spherical-based linkers have access to extensive conformational space by a combination of low-energy torsion of the substituents (e.g., aliphatic) and by the spherical core of the linker.$^{76}$ Thus, for example, a spherical ligand shape such as carborane could prevent the formation of intermolecular π-π stacking interactions while favouring the weak dihydrogen bond interactions.$^{77,78}$ Furthermore, a remarkable influence of the carboranes on the photophysical properties of luminescence materials has also been demonstrated.$^{79,80}$ When o-carborane is linked to an aryl donor group, an intramolecular charge transfer (ICT) process occurs from the donor moiety to the acceptor cluster, which is influenced by the C$_{cluster}$−C$_{cluster}$ (C$_{C-C}$) bond vibration,$^{81}$ usually producing a quenching of the fluorescence in solution. Moreover, these systems exhibit aggregation-induced emission (AIE) in aggregate and solid states, due to a restriction of the molecular motion, which produces an important increase of the emission quantum
yield.\textsuperscript{82–85} It is also noteworthy that the design of carborane–Cc-containing fluorophores whose fluorescence quantum yield in solution can be tailored by the cluster isomer (ortho or meta-carborane) and the substituent at the Cc atom. Some of these systems show moderate to good fluorescence emission efficiency in solution and solid state, giving rise to fluorescent materials in both states.\textsuperscript{86–91}

Herein we report the synthesis of three new pyrazolyl-carborane derivatives and their Cu(i) compounds. We also report a new Cu(i) derivative of a commercially available N-substituted phenyl pyrazole ligand (L1) that was taken for comparison between 2D and 3D aromatic groups (Scheme 1). We present the synthesis, structural characterization, and photophysical properties in solid state for all compounds. Additionally, photophysical properties for the molecular coordination compounds have been analysed by TDDFT calculations.

Results and discussion

Synthesis and characterization

Three new N-substituted carboranyl pyrazole ligands, derived from o-carborane, L2–L4 (Scheme 1), were prepared by the reaction of lithiated o-carborane with the corresponding 3,5-dimethyl-1-(2-toluene-p-sulfonyloxyethyl)pyrazole at low temperature (see ESI† for details). All carboranyl pyrazole ligands were fully characterized by standard spectroscopic and analytical techniques (ESI,† Fig. S1–S16) and the structure of L3 has been solved by single crystal X-ray diffraction (SCXRD; Fig. S17, ESI†). Reactions of the phenyl pyrazole ligand L1 or the carboranyl pyrazole ligands (L2–L4) with anhydrous CuI in dry acetonitrile under nitrogen provided crystalline compounds 1–4 in good yields (Scheme 1). FTIR-ATR spectra showed the characteristic signals in the region from 1556 to 650 cm\(^{-1}\) that belong to vibrations of the pyrazole ring (Pz) and of the N-substituted pyrazole derivatives.\textsuperscript{92,93} Carborane based compounds 2–4 show the characteristic broad B–H stretching bands from the carborane (in the range 2572–2563 cm\(^{-1}\); Fig. S18–S21, ESI†). Crystal structures of these Cu(I) compounds were determined by SCXRD (vide infra), and their simulated

![Scheme 1](image_url) Representation of pyrazole ligands L1–L4 and their Cu(I) compounds 1–4.

### Table 1 Crystal and structure refinement data for L3 and compounds 1–4

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<thead>
<tr>
<th>Compound</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<td>Empirical formula</td>
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<td>C(<em>{13})H(</em>{16})CuIN(_{2})</td>
<td>C(<em>{18})H(</em>{44})B(<em>{20})Cu(</em>{2})N(_{4})</td>
<td>C(<em>{20})H(</em>{48})B(<em>{20})Cu(</em>{2})N(_{4})</td>
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<td>Triclinic</td>
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<td>P(_{1})</td>
<td>P(_{1})</td>
<td>P(<em>{2})(</em>{1})/c</td>
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<td>1911.64(2)</td>
<td>1924.94(2)</td>
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<td>2381 (0.0937)</td>
<td>8766 (0.0594)</td>
<td>6686 (0.0917)</td>
<td>13.904 (0.1346)</td>
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<td>Final R indices</td>
<td>R(<em>{1}) = 0.0703, R(</em>{2}) = 0.0451, wR(_{2}) = 0.0774</td>
<td>R(<em>{1}) = 0.0408, wR(</em>{2}) = 0.0774</td>
<td>R(<em>{1}) = 0.0541, wR(</em>{2}) = 0.1341</td>
<td>R(<em>{1}) = 0.0509, wR(</em>{2}) = 0.1006</td>
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PXRD patterns were compared with their experimental ones, confirming their phase purity (Fig. S22–S24, ESI†). As shown in Scheme 1, compounds 1 and 4 are insoluble coordination polymers, while compounds 2 and 3 are molecular coordination compounds and therefore soluble in most organic solvents. All spectroscopic and analytical data is consistent with the solid-state structures determined by single crystal X-ray diffraction methods (vide infra and Fig. S25–S32, ESI†)

Crystal structures

Suitable crystals for SCXRD were obtained for all compounds (Table 1). Coordination polymers 1 and 4 crystallized in the monoclinic P2_1/c space group, while molecular compounds 2 and 3 crystallized in the triclinic P1 space group (Fig. 1–3).

[CuL1]_2(Cu(I) compounds formed from carborane based pyrazole ligands L2 and L3 provide molecular compounds 2 and 3, respectively (Scheme 1). This contrast with the non carborane 2D aromatic ligand L1, which formed the coordination polymer 1. Single crystal analysis of 2 revealed a dinuclear complex with the chemical composition [CuL2]_2. Fig. 2a shows a rhombohedric shaped CuI_2 core featuring very short Cu···Cu distances. There are two independent molecules in the unit cell with slightly different Cu···Cu distances, 2.4728(8) and 2.5158(9) Å. Each trigonal-planar Cu atom of 2 is bonded to the carboranyl pyrazole ligands through the pyrazole N atom. Selected bond lengths and angles are listed in Table S1 (ESI†). The geometric parameters for this complex agree with the values found in other Cu(i)-iodine structures. The CuI_2 unit lies on an inversion center that is located in the middle of the motif. Consequently, the carboranyl pyrazole ligands lie on opposite sides of the plane containing the CuI_2 units. Within each molecule, the pyrazole rings' planes are nearly perpendicular to that of the CuI_2 plane (84.5°). The 3D structure of 2 is formed by self-assembly of molecules by intermolecular C–H···N interactions (H···N 2.717 Å, C–H···N 145.4°; see dotted blue lines in Fig. 2b) between the carborane C–H atoms and a one of the pyrazole nitrogen atoms (Fig. 2b).

The structure of 3 consists of a tetranuclear complex containing a CuI_4 cluster and four molecules of ligand (Fig. 2c). Compound 3 represents a novel example of the rare octahedral clusters (Chart 1). The four Cu(i) atoms are arranged in a rectangular array with two significantly different Cu···Cu distances [2.5917(8) and 2.9289(7) Å]. The L3 and iodide ligands

![Fig. 1](image1.png)

Crystal structure of 1: (a) view of the coordination environment of the Cu(i) centers. (b) Fragment of the 1D network of 1 showing the π–π interactions. (c) View of the 3D structure. H atoms have been omitted for clarity in (a) and (b). Intermolecular contacts are shown as dotted blue lines. Color codes: H pale grey; C grey; N blue; I violet; Cu yellow.

![Fig. 2](image2.png)

Molecular structures of 2 (a) and 3 (c) and two perspective views of the packing of four molecules (b) and (d). H atoms have been omitted for clarity. Intermolecular contacts are shown as dotted blue lines. Color codes: B orange; C grey; N blue; I violet; Cu yellow.
bridge each edge of the Cu₄ plane to form a Cu₄(L₃)₄ core. The Cu₄ plane is further μ₄-capped by two iodine atoms providing a distorted octahedral (Fig. 2c). The Cu–I bond lengths in μ₂-bridging Cu–I lengths vary from 2.6985 to 3.1044 Å, which are significantly longer than the ones bridging the edges of the Cu₄ plane (2.5662 and 2.6475 Å). The carboranyl pyrazole ligands coordinate to the four Cu(II) atoms through the ligand’s pyrazole N atom (Fig. 2c). Cu–N distances vary from 1.983(4) to 1.990(4) Å. Selected bond lengths and angles are listed in Table S2 (ESI†). The geometric parameters have been compared with other reported examples. There are only fifteen entries in the CSD95 for eleven such type of octahedral cluster compounds and all of them bear two bidentate (neutral P=N) or anionic N–N(11) ligands. Thus, complex 3 represents the first example of such a family having monosubstituted neutral N-donor ligands. The 3D structure in this case is formed by self-assembly of molecules by weak intermolecular C–H···I (H···I 3.019 Å, C–H···I 161.7°) and C–H···B (H···B 2.448 Å, C–H···B 130.5°, B–H···B 110.4°) contacts (Fig. 2d and Fig. S33, ESI†).

[Cu₄(L₄)₄]₄ (4). Single crystal analysis of 4 reveals this compound as a 3D coordination polymer (Fig. 3). Each carboranyl bis-pyrazole ligand coordinates to two different Cu₄ clusters, namely, a rhombohedral shaped [Cu₁₄]₂ cluster and a stepped cubane [Cu₄]₄ cluster. The rhombohedral shaped Cu₁₄ core is similar to that present in complex 2 and features a quite short Cu···Cu distance of 2.588(1) Å. Each trigonal-planar Cu(i) atom in this Cu₁₄ core is bonded to two different carboranyl bis-pyrazole ligands through the pyrazole N atom. The stepped cubane [Cu₄]₄ cluster can be seen as the deformation of the normal cubane-like [Cu₄]₄ cluster by the cleavage of two trans-Cu–I bonds located in the same face of the cubane and bending the free rhombohedra to fulfill the chair conformation. The Cu₃···Cu₄ distance is 2.637(1) Å, which is quite short implying strong metal···metal bonding interactions. Each stepped cubane core is bonded to four different carboranyl bis-pyrazole ligands through the pyrazole N atom. Selected bond lengths and angles are listed in Table S3 (ESI†). Although these two types of Cu₁₄ clusters have been reported,⁴⁹⁸ compound 4 represents the first example where both types are combined in a coordination polymer. The carboranyl pyrazole ligand L₄ adopts two different conformations that alternate along the 3D structure (Fig. S34, ESI†).

It is noteworthy that whilst the pyrazolylphenyl ligand (L₁, Scheme 1) provides a Cu(i) coordination polymer, the corresponding ligands with carborane in place of phenyl (L₂–L₃, Scheme 1) provide 0D metal compounds (Scheme 1 and Fig. 1, 2). The π–π interactions observed between the pyrazole and phenyl rings of L₁ in compound 1 indicate that most probably such interactions occur in solution and during the reaction with CuI to provide the observed single chain coordination polymer 1. Such π–π interactions are not possible when the phenyl ring is replaced by the carborane fragments and this obviously prevents the formation of coordination polymers. The latter can only be obtained by employing the disubstituted carboranyl pyrazole ligand L₄ (Scheme 1 and Fig. 3).

**Luminescence properties in the solid state**

Compounds 1–4 are white crystalline solids under ambient light. The absorption spectra of 1–4 were measured in solid-state at room temperature (Fig. S35, ESI†). Polymer 1 shows three absorption bands at high energies (224, 269, 290 nm) and a shoulder at lower energy (369 nm). Complex 2 exhibits a maximum of absorption at 363 nm. The tetranuclear complex 3 shows three absorption regions, the first one at high energy in the range from 200 nm to 320 nm with a maximum at 306 nm, a second region in the range 320–410 nm and a third one at lower energy from 410 tailing to 600 nm. Polymer 4 exhibits a very broad absorption band composed of two different regions, the high energy region from 210 nm to 320 nm with two maxima at 257 and 289 nm and a low energy region from 320 nm tailing to 600 nm. This broad absorption band of 4 seems to correspond to the combined absorption spectra for 2 and 3 (Fig. S35, ESI†). Absorption bands at higher energies have been associated with pyrazole ligand-centred π → π* transitions and they correlate nicely with the UV-vis spectra of the free ligands (Fig. S16, ESI†). On the other hand, lower energy absorptions have been attributed to (X+M)LCT transfers.⁹⁸ In order to further investigate the UV-vis spectra, theoretical calculations were performed for discrete coordination compounds 2 and 3 (vide infra).

The normalised solid-state excitation and emission spectra for the four compounds are shown in Fig. 4. The emissive excited states observed in Cu(i)-halide compounds are known to originate from a variety of sources, such as halide-to-ligand charge transfer (XLC[T]),¹⁰⁹ metal-to-ligand charge transfer (MLCT),¹¹⁰ intra-ligand charge transfer (ILCT)¹²⁰ and, for Cu(i)-cluster compounds, a cluster-centred excited state of d–s character (CC).⁹⁹ As such, their photophysical properties bear a strong intrinsic relationship with their structural features.

The crystalline solid of polymer 1 exhibits dual emission in the blue (460 nm, HE) and orange (609 nm, LE) regions of the visible spectra upon excitation at 283 nm, with low absolute quantum yield (Φₑ) of 4% (Table 2). The emission spectrum of 1 is broad and unstructured, which according to the literature on Cu(i) compounds is typical of charge-transfer (CT) emissions.¹⁰¹

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**Fig. 3** Fragment of the 3D structure of 4 showing rhombohedral [Cu₁₄]₂ (green) and stepped cubane [Cu₄]₄ (red) clusters. H atoms have been omitted for clarity. Color codes: B orange; C grey; N blue; I violet; Cu yellow.
Contrary to Cu(i)-iodide rhomboid dimers or tetrarners, photophysical studies of single-stranded Cu(i)-iodide polymers are scarce. The first one was reported by Cariati et al. in 2002,3 and since, only few others have been reported.48,49,102,103 As the Cu–Cu bond length is the primary factor governing CC excited states in Cu(i) clusters,4 their long distances in Cu–Cu bond length is the primary factor governing CC excited pblue-to-yellow region (450–520 nm) of the visible spectrum 1 290 283 460, 609, 3.8 306 318 517 4.9 349 336 467 13.7

Table 2 Photophysical data for compounds 1–4

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<tr>
<th>Compound</th>
<th>UV-vis maximum (nm)</th>
<th>Excitation (λmax nm)</th>
<th>Emission (λmax nm)</th>
<th>ΦE (%)</th>
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<td>1</td>
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<td>283</td>
<td>460, 609</td>
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<td>336</td>
<td>467</td>
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</table>

Fig. 4 Excitation (dashed lines) and emission (solid lines) spectra for compounds 1–4 in the solid state at 298 K.

We therefore decided to perform TDDFT calculations in order to verify or refute this hypothesis (vide infra). To the best of our knowledge, ours is the first report of photophysical studies of N-donor tri-coordinated Cu(i) rhomboid dimer compounds supported by TDDFT calculations.

The crystalline solid of complex 3 shows a very broad emission band with a maximum at 517 nm upon excitation at 318 nm at room temperature with an absolute ΦE of around 5% (Fig. 4 and Table 2). The latter is significantly lower than those reported for a number of homologous compounds.26,28 For some reported octahedral Cu4 compounds, dual emission has been observed, that is a LE emission (550–600 nm) dominating at room temperature and a HE emission (400–500 nm) dominating at lower temperatures.23,28,31 By analogy with the better studied Cu4I4L8 (x = 2–4) cubane clusters, these have been attributed to 3CC transitions and 3XLCT transitions respectively.15,26,29 However, recent studies have shown that other octahedral clusters display single LE or HE emission bands which are largely temperature independent,116,117 a phenomenon known as rigidichromism, while others display only a single emission in the region of 500–560 nm, halfway between LE and HE emission.28,10 Complex 3 seems to fall under this behaviour, as no dual emission is observed. This disparity in the results of photophysical studies for octahedral clusters show that a universally accepted process for rationalizing its photoluminescent behaviour has yet to been achieved. Therefore, we have performed the TD-DFT calculations for 3 (vide infra).

The crystalline solid of multinuclear coordination polymer 4 exhibits blue emission with a maximum at 467 nm upon excitation at 336 nm and an absolute quantum yield of 13.7% (Fig. 4 and Table 2). It is noteworthy that both the emission and excitation spectra of 4 are similar to those of complex 2 (Cu2I2 units). In one of the few Cu(i) compounds containing different...
metal clusters, it was observed that its photoluminescent behaviour was a combination of that of its constituent parts.\(^{44}\) Thus, assuming a similar behaviour for 4, it seems that the emission originating in the Cu\(_{2}\)I\(_{2}\) unit dominates over that originating in the open cubane Cu\(_{4}\)I\(_{4}\) unit. This fact is also consistent with the high \(\Phi_F\) observed for 2, compared to the low \(\Phi_F\) observed for the tetranuclear cluster in 3. Thus, we assume the emission for both 4 and 2 originate in the dimeric units. On this basis, the TDDFT calculations performed for 2 also help shed some light on the photophysical results obtained for 4 (vide infra).

In order to analyze and fully understand the photophysical properties of the molecular systems, time-dependent density functional theory (TDDFT) calculations (see Computational details section) were performed using Gaussian16 program,\(^{118}\) with the B3LYP functional\(^{119,120}\) using the Def2TZV basis set.\(^{121}\) Complex 2, containing a rhombohedral shape Cu\(_{2}\)I\(_{2}\) core, has absorption and excitation peaks at 363 and 340 nm, respectively (Table 2). The calculated TDDFT values at B3LYP level show the first non-zero extinction coefficient (second excitation) at 321 and 335 nm, respectively for the optimized and experimental structures. The orbitals involved in such processes are represented in the top of Fig. 5. The excitation is from the HOMO to the LUMO, respectively, and 2.516 Å in the experimental structure. On the other hand, the structure is considerably distorted, especially the central Cu\(_{4}\)I\(_{4}\) framework.

One of the Cu\(_{2}\)I\(_{2}\) units adopts a similar structure to that of the open cubane Cu\(_{4}\)I\(_{4}\) unit. This fact is also consistent with the high \(\Phi_F\) observed for 2, compared to the low \(\Phi_F\) observed for the tetranuclear cluster in 3. Thus, we assume the emission for both 4 and 2 originate in the dimeric units. On this basis, the TDDFT calculations performed for 2 also help shed some light on the photophysical results obtained for 4 (vide infra).

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triplet state of complex 2 with a short Cu–Cu distance (2.363 Å) and with terminal iodide ligands (see Fig. 5 and 7). The second CuI₂ moiety has the bridging iodide ligands and a relatively long Cu···Cu distance (2.655 Å). The calculation of the vertical excitations using TDDFT of the singlet ground state for such triplet optimized structure gives triplet deexcitation transitions at 538 and 531 nm in good agreement with the experimental emission band at 517 nm. The analysis of the orbitals involved indicates a deexcitation from the LUMO orbital (Fig. 7) mainly localized in the CuI₂ moiety with short Cu···Cu distance to orbitals delocalized in the whole Cu₄I₄ framework (HOMO and HOMO−1, Fig. 7). Thus, as for 2, the deexcitation process can be described as a 3CC process.

Conclusions

In summary, we have synthesized and fully characterized two monosubstituted carboranyl pyrazole ligands (L₂ and L₃) and one disubstituted carboranyl pyrazole ligand (L₄) by lithiation and nucleophilic addition onto the corresponding 3,5-dimethyl-1-(2-toluene-p-sulfonyloxethyl)pyrazole. All new ligands, and the corresponding monosubstituted phenyl derivative (L₁) behave as N-type ligands upon coordination with CuI to afford a series of polymeric ([Cu(L₁)I]ₙ (1) and [Cu₄(L₄)I₄]ₙ (4)) or molecular ([Cu(L₂)I]₂ (2) and [Cu(L₃)I]₂ (3)) Cu(I) structures. Whereas 1, having a phenyl-based pyrazole, forms a coordination polymer, 2 and 3, both possessing a carboranyl-based pyrazole ligand, form molecular compounds. Lastly, the use of bidentate L₄, results in the formation of another coordination polymer 4. 3 represents a novel example of the rare octahedral clusters, and the first one bearing a neutral monodentate ligand. 4 represents the first example where both dimeric and stepped cubane clusters are combined in a single coordination polymer.

Absorption and emission properties of 1–4 have been studied in the solid state. Their emission covers a remarkable range of the visible spectrum, from the blue to the orange (460–609 nm). Noticeably, complex 2 exhibits an outstanding fluorescence efficiency of 66.5%, which is higher than that
observed for reported analogues without the carborane units. TDDFT calculations performed for 2 and 3 allowed us to gain insight in the origin of their emission. For 2, they confirm that the emission origin is a cluster-centred excited state of d-s transition. This result is remarkable, as, to date, the origin of the emission in similar dimers has been assumed to be (X + M)|LCT in nature. Regarding compound 3, TDDFT calculations indicate that the emission is through a 3CC state. Calculations also show that, upon excitation, 3 suffers a notable distortion resulting in the total cleavage of the Cu₄I₄ framework. To the best of our knowledge, this is the first time that such behaviour is observed for this type of octahedral compounds. These results depart from the classical assumption that octahedral Cu₄I₄ clusters behave as cubane clusters, highlighting that more effort is required to rationalise their emission.

We demonstrate that it is possible to tune the molecular structure and luminescent properties of these Cu(i) compounds by changing a phenyl ring (2D) by a carborane cluster (3D), which also allows introducing substituents at the cage. Herein, we report new understanding on some significant luminescence aspects for a rare type of Cu(i) complex for the first time and explore the relationship between the structural features and their luminescent behaviour, a knowledge that is key in the rational design of photoluminescent materials.

**Experimental section**

**Materials and methods**

All synthetic procedures were performed under dinitrogen atmosphere using standard Schlenk techniques unless otherwise noted. Tetrahydrofuran (THF) was purchased from Carlo Erba Reagents S.A. and distilled from Na/benzophenone prior to use. Commercial grade acetonitrile (CH₃CN) was purchased from ROMIL-SpS and used as received. Commercial grade methanol (MeOH) was purchased from Merck and dried using 3 Å activated molecular sieves. All synthetic procedures were performed under dinitrogen atmosphere. 

**Synthesis of carboranyl pyrazole ligands L₂ and L₄.** n-BuLi (4.70 mL, 1.50 M in hexane, 7.05 mmol) was added dropwise to a solution of o-carborane (0.456 g, 3.16 mmol) in dry THF (20 mL) under a nitrogen atmosphere at 0 °C (ice/water bath). The solution was stirred for 45 minutes at 0 °C and 45 minutes at r.t. resulting in a pale-yellow suspension. Next, a solution of 3,5-dimethyl-1-(2-toluene-methanol (MeOH) was purchased from ROMIL-SpS and used as received. Commercial grade acetonitrile (CH₃CN) was purchased from Erba Reagents S.A. and distilled from Na/benzophenone prior to use. Commercial grade methanol (MeOH) was purchased from Merck and dried using 3 Å activated molecular sieves. All synthetic procedures were performed under dinitrogen atmosphere.


**Synthesis of carboranyl pyrazole ligand L₃.** A solution of 4.71 mL, 1.50 M in hexane, 4.05 mmol), 1-methyl-2-picolinic acid (274.32 g, 2.00 mmol), and 3,5-dimethyl-1-(2-toluene-methanol (MeOH) was purchased from ROMIL-SpS and used as received. Commercial grade acetonitrile (CH₃CN) was purchased from Erba Reagents S.A. and distilled from Na/benzophenone prior to use. Commercial grade methanol (MeOH) was purchased from Merck and dried using 3 Å activated molecular sieves. All synthetic procedures were performed under dinitrogen atmosphere.

Yield: 33% (0.622 g). Elem. anal. calc. for C₉H₂₂B₁₀N₂ (266.39): C 40.58, H 8.32, N 14.01. Found: C 40.49, H 8.23, N 13.85. M.p.: 172–176 °C. ATR-FTIR (wavenumber, cm⁻¹): 2982–2917 (w) [v(C–H)₃], 2561 (s) [v(B–H)], 2551 (s) [v(B–H)], 1555 (s) [v(C–C–C–N)ₙ], 1489 (w), 1466 (m), 1442 (m), 1425 (s) [v(C–C)/v(C–N)ₙ], 1377 (w), 1372 (m), 1321 (m), 1282 (w), 1218 (w), 1139 (w), 1071 (m), 1024 (s) [v(C–H)ₙ], 988 (w), 937 (w), 903 (w), 835 (w), 789 (vs) [v(C–H)ₙ], 719 (vs) [v(C–H)ₙ], 673 (w), 656 (w), 640 (w), 566 (w), 540 (w), 1H NMR (CD₃CN, 400.0 MHz): δ = 5.84 (s, 1H, CH(Pz)), 4.43 (br, 1H, Ccarb–H) 4.06 (m, 2H, NpCH₂CH₂Ccarb), 2.75 (m, 2H, NpCH₂CH₂Ccarb), 2.19 (s, 3H, CH₂–Pz), 2.10 (s, 3H, Pz–CH₃). ¹³B NMR (CD₃CN, 128.6 MHz): δ = −2.75 (br d, J₁BH = 155.0, 15B), −5.67 (br d, J₁BH = 155.0, 15B), −9.66 (br d, J₁BH = 149.5, 2B), −10.2 to −13.6, overlapping signals (6B). ¹¹B¹¹H NMR (CD₃CN, 128.6 MHz): δ = −2.88 (br s, 1B), −5.75 (br s, 1B), −9.65 (s, 2B), −11.15 to −13.0, overlapping signals (6B). ¹³C¹¹H NMR (CD₃CN, 100.6 MHz): δ = 147.6, 145.5 (Pz–C), 108.1 (Pz–CH₃), 73.0 (Ccarb–CH₂R), 63.7 (Ccarb–H), 47.3 (Ccarb–CH₂CH₂N₄), 36.5 (Ccarb–CH₂CH₂N₄), 11.8, 11.2 (CH₃(Pz)). UV-vis: (CH₃CN, 6.5 × 10⁻⁵ M) λmax (ε (M⁻¹ cm⁻¹)) = 201 nm (6380).

**Synthesis of carboranyl pyrazole ligand L₃.** A similar procedure as that described above was followed: n-BuLi (2.70 mL, 1.50 M in hexane, 4.05 mmol), 1-methyl-o-carborane (0.834 g, 3.270 mmol) in dry THF (20 mL) and 3,5-dimethyl-1-(2-toluene-p-sulfonyloxyethyl)pyrazole (1.002 g, 3.74 mmol) in dry THF (20 mL). After quenching the reaction by using a saturated aqueous solution of NH₄Cl (10 mL), the aqueous phase was extracted using Et₂O (3 × 20 mL) and the organic layers were washed with cold hexane (2 mL) and dried under vacuum.

The desired products were purified by preparative TLC (L₂, eluent = ethyl acetate/chloroform 1:4; Rf = 0.76; L₄, eluent = ethyl acetate/hexane 9:1, Rf = 0.68). The products were extracted from the corresponding silica portions with CHCl₃ and obtained as white powders on solvent evaporation. The products were washed with cold hexane (2 mL) and dried under vacuum.
dried over anhydrous MgSO₄. L₃ was purified by preparative TLC (eluent = ethyl acetate/hexane 2:3, Rₛ = 0.47). The product was extracted from the remaining silica portions with THF and obtained as white powders on solvent evaporation. Crystals suitable for SCXRD were obtained via slow evaporation of the latter THF solutions.


M.p.: 138–142 °C. ATR-FTIR (wave number, cm⁻¹): 3134–3061 (w) [v(C–H)ₐr], 2978–2858 (w) [v(C–H)ₐr], 2571 (s) [v(B–H)], 1554 (s) [v(C–C/N)ₐr], 1482 (w), 1463 (m), 1452 (s) [δ(C–C)/δ(C–N)ₐr], 1421 (s), 1388 (s), 1372 (w), 1317 (w), 1299 (w), 1278 (m), 1218 (w), 1177 (w), 1161 (w), 1129 (w), 1088 (w), δ(C–H)ₐr: 1024 (s), 977 (w), 946 (w), 921 (w), 779 [δ(C–H)ₐr], 726 (s) [δ(C–H)ₐr], 666 (m), 648 (m), 550 (m). ¹H NMR (CD₃CN, 400.0 MHz): δ = 5.78 (s, 1H, C[H(Pz)]), 4.07 (m, 2H, N₃P(CH₂CH₂)₃), 2.72 (m, 2H, N₃P(CH₂CH₂)₃), 2.10 (s, 3H, CH₃(Carb)), and 2.08 (s, 6H, CH₂(Carb)). ¹³C{¹H} NMR (CD₃CN, 128.6 MHz): δ = 4.42 (br d, J = 157.3 Hz, 1B), −6.08 (br d, J = 151.1 Hz, 1B), −8.28 to −11.40, overlapping signals (8B). ¹¹B{¹H} NMR (CD₃CN, 128.6 MHz): δ = −5.11 (s, 1B). ATR-FTIR (wavenumber, cm⁻¹): 3126–3030 (w) [v(C–H)ₐr], 2978–2855 (w) [v(C–H)ₐr], 1550 (s) [v(C–C/N)ₐr], 1496 (m), 1488 (m), 1462 (m), 1453 (s) [δ(C–C)/δ(C–N)ₐr], 1421 (w), 1388 (m), 1371 (w), 1357 (m), 1310 (m), 1253 (m), 1152 (w), 1075 (w), 1048 (w), 1031 (w), 904 (w), 800 (s), 746 (s) [δ(C–H)ₐr], 696 (s) [δ(C–H)ₐr] and 687 (s) [δ(C–H)ₐr]. UV-vis: (solid state) λ_max = 290 nm. Fluorescence (solid state): λ_ex = 283 nm, λ_em = 609 nm.

Synthesis of Cu(L2)I₂ (2). A solution of anhydrous CuI (0.019 g, 0.098 mmol) and L₂ (0.020 g, 0.098 mmol) in dry CH₃CN (20 mL) was stirred at r.t. until all CuI was dissolved. After that period, the solvent was evaporated under vacuum, resulting in pure 1 as a white powder. Suitable crystals for SCXRD were obtained via slow evaporation of the solvent.

1. Yield: 60.1% (0.023 g) elem. anal. calc. for C₁₃H₁₄IN₂Cu (390.72): C 39.96, H 4.13, N 7.17. ATR-FTIR (wave number, cm⁻¹): 3216–3030 (w) [v(C–H)ₐr], 2978–2855 (w) [v(C–H)ₐr], 1550 (s) [v(C–C/N)ₐr], 1496 (m), 1488 (m), 1462 (m), 1453 (s) [δ(C–C)/δ(C–N)ₐr], 1421 (w), 1388 (m), 1371 (w), 1357 (m), 1310 (m), 1253 (m), 1152 (w), 1075 (w), 1048 (w), 1031 (w), 904 (w), 800 (s), 746 (s) [δ(C–H)ₐr], 696 (s) [δ(C–H)ₐr] and 687 (s) [δ(C–H)ₐr]. UV-vis: (solid state) λ_max = 290 nm. Fluorescence (solid state): λ_ex = 283 nm, λ_em = 609 nm.

Synthesis of Cu(L3)I₄ (3). A solution of anhydrous Cu (0.037 g, 0.188 mmol) and L₃ (0.051 g, 0.188 mmol) in dry CH₃CN (20 mL) was stirred for 1 h at r.t. under nitrogen. After that period, the solvent was evaporated under nitrogen, resulting in a white powder.

Suitable crystals for SCXRD were obtained via recrystallization of a solution of the white powder in dry CH₃CN.

Yield: 58.5% (0.052 g) elem. anal. calc. for C₁₃H₂₆B₁₄N₄I₄Cu₄ (1883.48): C 25.51; H 5.14; N 5.95. Found: C 25.51; H 4.98; N 5.85. ATR-FTIR (wave number, cm⁻¹): 2984–2917 (w) [v(C–H)ₐr], 2563 (s) [v(B–H)], 1556 (s) [v(C–C/N)ₐr], 1467 (w), 1445 (s), 1418 (s) [δ(C–C/N)ₐr], 1376 (m), 1324 (m), 1280 (m), 1041 (m), 1023 (m), 779 (s) [δ(C–H)ₐr], 729 (s) [δ(C–H)ₐr], 676 (w), 663 (w), 647 (w) and 633 (w). ¹H NMR (CD₃CN, 400.0 MHz): δ = −4.46 (br d, J = 157.3 Hz, 1B), −6.05 (br d, J = 151.1 Hz, 1B), −8.05 to −11.8, overlapping signals (8B). ¹³C{¹H} NMR (CD₃CN, 128.6 MHz): δ = 4.19 (s, 2H). ATR-FTIR (wavenumber, cm⁻¹): 3126–3030 (w) [v(C–H)ₐr], 2978–2855 (w) [v(C–H)ₐr], 1550 (s) [v(C–C/N)ₐr], 1496 (m), 1488 (m), 1462 (m), 1453 (s) [δ(C–C)/δ(C–N)ₐr], 1421 (w), 1388 (m), 1371 (w), 1357 (m), 1310 (m), 1253 (m), 1152 (w), 1075 (w), 1048 (w), 1031 (w), 904 (w), 800 (s), 746 (s) [δ(C–H)ₐr], 696 (s) [δ(C–H)ₐr] and 687 (s) [δ(C–H)ₐr]. UV-vis: (solid state) λ_max = 306 nm. Fluorescence (solid state): λ_ex = 318 nm, λ_em = 517 nm.

Synthesis of [Cu(L4)I₄(CH₃CN)]₄ (4). A solution of anhydrous Cu (0.100 g, 0.525 mmol) and L₄ (0.082 g, 0.210 mmol) in dry CH₃CN (20 mL) was stirred for 3 h at r.t. Then, the resulting solution was filtered, concentrated up to 5 mL and left standing overnight in the fridge, which provided a white precipitate. The precipitate was filtered, washed with cold Et₂O and dried under vacuum.

Yield: 42.1% (0.068 g) elem. anal. calc. for C₁₃H₂₆B₁₄N₄I₄Cu₄ (1538.92): C 25.85; H 4.27; N 7.98. Found: C 25.67; H 4.19; N 7.86. ATR-FTIR (wave number, cm⁻¹): 3126 (w) [v(C–H)ₐr], 2990–2918 (w) [v(C–H)ₐr], 2572 (vs)
spectrometer using deuterated acetonitrile (CD$_3$ CN) at 25
NMR spectra were recorded on a NMR-FT Bruker 400 MHz

For each step. For an external standard for $^{11}$B and $^{11}$B{ $^1$H} NMR. Chemical shifts are reported in ppm and coupling constants in Hertz. Multi-

Chemical shifts are reported in ppm and referenced to the

UV-vis: (solid

state) $\lambda_{	ext{em}} = 467$ nm.

Powder X-ray diffraction patterns (PXRD) for 1–3 were measured using a Siemens D5000 apparatus [with 40 kW and 45 mA using Cu K$_\alpha$ radiation with $\lambda = 1.5406\ \text{Å}$]. Patterns were recorded from $2\theta = 5^\circ$ to $40^\circ$ with a step scan of 0.02° counting for 1 s at each step. For 4, PXRD pattern was measured using a Malvern PANanalytical Xpert PRO Material Powder Diffractometer (with 45 kW and 40 mA using Cu K$_\alpha$ radiation with $\lambda = 1.5406\ \text{Å}$). The pattern was recorded in transmission mode from $2\theta = 2.5^\circ$ to $40^\circ$ with a step scan of 0.03° counting for 200 s at each step.

The electronic spectra in CH$_3$ CN (1.45–5.0 M) were run on a JASCO V-780 UV-visible/NIR spectrophotometer using deuterated acetonitrile (CD$_3$ CN) at 25 °C.

Crystallographic data

Crystallographic data of L$_3$ and compounds 1–4 is gathered in Table 1. Suitable crystals for X-ray elucidation were obtained via recrystallization of the products in THF (L$_3$) or dry CH$_3$CN (1–4).

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Kirkpatrick–Baez focusing mirrors with a selected wavelength of 0.72932 Å. An MD2M-Maatel diffractometer with a Dectris Pilatus 6M detector was employed. The sample was kept at 100 K with an Oxford Cryosystems 700 series Cryostream. Crystallographic data for 2 and 4 were collected with a Bruker D8 Venture diffractometer with graphite monochromated MoK$_\alpha$ radiation ($\lambda = 0.71073\ \text{Å}$).

The structure for L$_3$ was solved with the ShelXT 2014/5 (Sheldrick, 2014) structure solution program using the direct phasing methods solution method and by using Olex2 as the graphical interface. The model was refined with version 2016/6 of ShelXL using Least Squares minimisation. The data for 1–4 were processed with APEX3 suite (Bruker APEX3, APEX3 V2019.i; Bruker-AXS: Madison, WI, USA, 2019). The structures were solved by Intrinsic Phasing using the ShelXT program, which revealed the position of all non-hydrogen atoms. These atoms were refined on F$^2$ by a full-matrix least-squares procedure using anisotropic displacement parameter. All hydrogen atoms were located in difference Fourier maps and included as fixed contributions riding on the attached atoms with isotropic thermal displacement parameters 1.2 or 1.5 times those of the respective atom. The OLEX2 software was used as a graphical interface.

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Computational details

To analyse the electronic structure and the nature of the excited states, time-dependent DFT calculations were performed by using the implementation of such approach in Gaussian16 program. After some test, B3LYP functional was selected because it provided a better agreement with the experimental data than other common exchange–correlation functional. An all electron Def2TZV basis set was employed in the calculations. The calculations were performed for the discrete molecules 2 and 3. To compare with the experimental absorption data, the calculations were carried out using both the experimental and also the optimized structures. The TDDFT calculations were employed only for the discrete molecules because for periodic structures would be mandatory to employ discrete models that usually lead to non-realistic results. The deexcitations energies are calculated by optimizing the structure of the excited triplet state and using such optimized geometry to perform a singlet calculation. Such procedure is employed because TDDFT calculations must be performed in the singlet ground state to extract the vertical excitation energies.
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References

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