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Alkynyl bridged cyclometalated Ir₂M₂ clusters: Impact of the heterometal in the photo- and electro-luminescent properties

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We report two unprecedented alkynyl bridging cyclometalated clusters [Ir₂M₂(ppy)₄(μ-C≡CC₆H₄-OMe₃)₄] where M is Ag (**2**) and Cu (**3**), which display distinctive luminescent properties. While **2** features a green phosphorescence/electroluminescent nature located at the ppy ligands (³LC), **3** shows an orange emission confined to the metals and alkynyl groups having a mixed ³L'C/³L'MCT/³MMCT (L' = alkynyl) nature.

Phosphorescent cyclometalated Ir^{III} complexes have aroused enormous interest due to their outstanding photo- and electro-luminescent properties, which are well suited for optoelectronic applications, such as organic light-emitting diodes (OLEDs), light-emitting electrochemical cells (LECs), sensors or biological cell imaging.¹ In particular, homoleptic and heteroleptic mononuclear Ir^{III} complexes have been extensively investigated by means of both experimental and theoretical studies to master both the color and efficiency of the emission, providing a clear understanding of the relationship between structure and photophysical properties.^{1a-d, 2} Although much less explored, Ir(C[^]N)₂ motifs have also been used as building blocks in linear or branched multinuclear 1D systems to study photoinduced energy and electron transfer processes and to form interesting homo and hetero multimetallic luminescent arrays.³

Besides the latter, owing to their rich σ- and π-bonding versatility along with the metallophilic interactions, the alkynyl ligands are known to be particularly successful to form very stable d⁸ and d¹⁰ homo and heterometallic complexes with fascinating structures and interesting photophysical

properties, including solid-state mechanochromic, thermochromic, and sensing behaviour.⁴ However, their application in optoelectronic devices has been barely explored.^{4a, 4d} Thus, it is worthwhile to investigate the photophysical properties arising from the combination of Ir(C[^]N)₂ units and coinage alkynyl motifs in the same molecule, which has not been explored yet. In these systems, the emission properties could be attributed to the Ir^{III} chromophore, the heterometal-alkynyl unit or to exhibit a unique nature derived from specific short-range interactions favoured by the alkynyl bridging ligands. In this communication, we wish to report the synthesis, the molecular and electronic structures, as well as photo- and electro-luminescent properties of two tetranuclear luminescent complexes [Ir₂M₂(ppy)₄(μ-C≡CC₆H₄OMe-3)₄] where M is Ag (**2**) or Cu (**3**), together with the diiridium precursor [Ir₂(ppy)₄(μ-C≡CC₆H₄OMe-3)₂] (**1**). Despite their similar structures, **2** and **3** display distinct optical properties, which have been interpreted with the aid of theoretical calculations based on the density-functional theory (DFT and its time-dependent approach TD-DFT).

Recently, a series of dinuclear alkynyl Ir^{III} complexes [Ir₂(ppy)₄(μ-C≡CR)₂] where R = Tol, C₆H₄OMe-4, 1-Np, Bu[†], SiMe₃ have been synthesized in our laboratory *via* reaction of [Ir₂(ppy)₄(μ-Cl)₂] with the corresponding alkynyl lithium reagent.⁵ During the investigation of possible routes to prepare this type of complexes, we discovered that the dinuclear chloride bridging precursor [Ir₂(ppy)₄(μ-Cl)₂] reacts with the polymeric silver derivative [Ag(C≡CC₆H₄OMe-3)]_n to yield the tetranuclear complex **2** as a yellow microcrystalline solid in high yield (75%). Similar to this traditional reaction, the latter and the related Cu^I copper derivative **3** are straightforward generated *via* a *quasi*-quantitative reaction of the dinuclear alkynyl bridged complex [Ir₂(ppy)₄(μ-C≡CC₆H₄OMe-3)₂] **1**, which is prepared for first time for this work, with the polymeric derivatives [M(C≡CC₆H₄OMe-3)]_n (M = Ag, Cu) with a yield of M = Ag 93%; Cu 91% (Scheme 1). The formation of luminescent alkynyl based heterometal clusters by using polymeric coinage [M(C≡CR)]_n derivatives as

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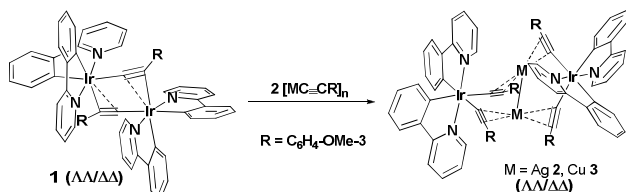
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precursors has been reported,^{4c, 4f, 6} but their employment to assemble Ir^{III} phosphorescent cyclometalated fragments Ir(C[^]N)₂ is unprecedented. Unfortunately, the attempts to obtain the analogous Ir₂Au₂ cluster both by reaction of **1** with [Au(C≡CC₆H₄OMe-3)] or by a transmetalation reaction between the Ir₂Ag₂ cluster **2** and [AuCl(SMe₂)] were



unsuccessful.

Scheme 1. Synthesis of [Ir₂M₂(ppy)₄(μ-C≡CC₆H₄OMe-3)₄] (M = Ag **2** or Cu **3**)

All **1-3** complexes were characterized by analytical and spectroscopic techniques - see electronic supporting information (ESI) for more details, Fig. S1-S15 - and their molecular structures were confirmed by X-ray crystallography. While **1** is generated only as the racemate (ΛΛ/ΔΔ), **2** and **3** feature the retention of the configuration at the Ir^{III} centres (ΛΛ/ΔΔ form) - Fig. 1, S16-S20, Tables S1-S4.

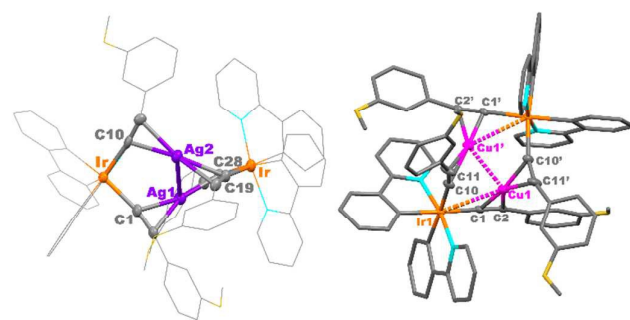


Fig. 1 Crystal structures of **2**·2CH₂Cl₂ (left) and **3** (right). Hydrogens atoms are omitted for clarity. M-M distances (Å): Ag1-Ag2 2.9985(7), Cu1-Cu1' 2.732(2), Ir...Ag 3.625 (over.), Ir-Cu1 3.154(1), Ir-Cu1' 3.529(1).

In both clusters, the two enantiomers are present in the unit cell that shows a space group triclinic *P*-1 for **2** and tetragonal *I*-4 for **3**. The forms shown in Fig. 1 are ΛΛ and ΔΔ for **2** and **3**, respectively. Both clusters are similarly constructed by two unprecedented anionic bis(alkynyl)bis(phenylpyridinyl)iridate(III), {Ir(ppy)₂(C≡CR)₂}⁻, building blocks and two Ag^I (**2**) or Cu^I (**3**) ions held together by π-C≡CM^I bonds and M^I...M^I interactions. The two bidentate bridging iridadiyne fragments [Ir](C≡C)₂ are oriented almost perpendicular each other, the dihedral angles being 84.2° for **2** and 79.30° for **3** (Fig S17). The metal centres form a rhomboidal skeleton with a *trans* annular M^I...M^I separation [2.9985(7) **2**; 2.732(2) Å **3**], shorter than the sum of Van der Waals radii (3.34 and 2.8 Å for Ag^I and Cu^I) and in the range typical for metallophilic interactions.⁷ With regard to the Ir-M^I distances, the shortest distances [3.4654(7) Å in **2** and 3.154(1) Å in **3**] are longer to those noted in other heterometallic Ir-M^I clusters^{7c} (i.e., [Ir₂M₄(C≡CR)₈(PPh₃)₂] mean 3.08 for Ag and 2.88 Å for Cu),^{6a} excluding any significant d⁶...d¹⁰ bonding interactions. The Ir^{III} centres are coordinated to two cyclometalated ppy ligands and two σ-alkynyl carbons,

adopting typical C,C-*cis* and N,N-*trans* configurations, whereas the Ag^I (**2**) or Cu^I (**3**) ions are dicoordinated bonded to two staggered ethynide units mutually *trans* of each Ir^{III} block. The Cu-C_αC_β distances [1.991(10)-2.102(10) Å] in **3** are shorter than those Ag-C_αC_β [2.287(6)-2.305(6) Å] in **2**, a feature that is in accordance with the lower ν(C≡C) stretching vibration found in **3** (1952 cm⁻¹) in relation to **2** (1990, 1964 cm⁻¹). This indicates, in line with previous observations,^{4c, 4f} that the η²-alkyne interaction is stronger in the Cu^I than in the Ag^I complex. In **3**, one C₆H₄OMe-3 ring is disordered over two positions (occupancy 0.75/0.25), although it does not affect the essential parameters of the structure. The structural data given refer to the majority component of the disorder. For **2**, the crystal structure reveals the formation of a zigzag chain stabilized by weak O(OMe)·H(ppy) interactions and offset face-to-face π-π stacking between ppy moieties (Fig. S18), whereas in **3** each cluster is involved in two bad directed π...π contacts reinforced with CH(ppy)···(C≡C) interactions, which leads to a more compact network (Fig. S20).

The electrochemical properties were examined by cyclic voltammetry (Fig. S21) and the data are shown in Table S5. **1** displays in THF a single irreversible 2 e⁻ oxidation at 0.65 V, whereas in CH₂Cl₂ it shows two oxidation waves (*i*_{pa}/*i*_{pc} < 1) with peak potentials (*E*_{pa}) at 0.57 and 0.81 V, formally ascribed to two sequential Ir^{III}/Ir^{IV} processes. The separation of the Ir^{III}/Ir^{IV} waves (Δ*E*_{pa} 240 mV) suggests electronic interaction between the iridium centres, as in previously related doubly bridged arylacetylide diiridium complexes.⁵ The tetranuclear clusters display in THF one (0.94 V for **2**) or two (0.82 and 0.98 V **3**) irreversible oxidations, which are anodically shifted compared to **1**, indicating that the highest-occupied molecular orbitals (HOMOs) are substantially stabilized in relation to that of **1**. At a first glance, this result could be ascribed to the lower π-donor ability of the alkynyl ligand upon a η²-bonding interaction with the acidic Ag^I and Cu^I ions, rendering the Ir^{III} metal centres oxidation more difficult in the clusters. Since the η²-alkyne-M bonding interaction is stronger for Cu^I in relation to Ag^I, **3** should exhibit a higher oxidation potential than **2**, however, this is opposite to what we noted. The irreversibility nature of the oxidation processes suggests a relatively high contribution of the ligands in the HOMOs, as confirmed by calculations. Here, DFT calculations and atomic orbital composition analyses on the optimized S₀ geometries revealed that their frontier orbitals are quite different (Tables S7-S9, Fig. S28, S29). In detail, the HOMO of **2** is localized in one of the Ir^{III} fragments (Ir^{III} 40%; ppy 40%; C≡CR 17%), with small contribution of one Ag^I(5sp) (2%). However, **3** shows a delocalized HOMO between both Ir^{III} fragments with a higher contribution of the alkynyl groups (36%) and a lower contribution of ppy units (22%) and Ir^{III} (34%) than **2**. The 0.1 eV energy difference between both HOMOs (-6.82 eV **2**, -6.72 eV **3**) is in line with the experimental trend. Thus, the easier oxidation of **3** can be understood by the remarkable contribution of the donor C≡CR groups, which increases the energy of the HOMO. In both derivatives, the lowest-energy unoccupied orbitals (LUMO to LUMO +3) are mainly located on the π* orbitals of the ppy units (92-94% **2**, 96% **3**), being the

main difference that in **2** the ppy units contributing to each orbital are associated to the same Ir^{III} complex, while in **3** are distributed over all four ppy ligands.

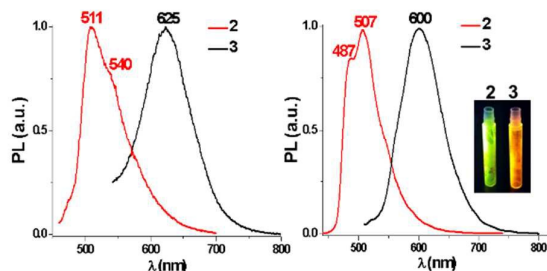


Fig. 2 Normalized emission spectra of **2** and **3** in THF (10^{-4} M) (left) and in PMMA (10%) (right) at 298 K

The photophysical properties of **2** and **3** were investigated and compared to that of **1**. Representative emission spectra are shown in Fig. 2. The UV-vis absorption spectra of **2** and **3** are similar and closely comparable to that of the precursor **1** (Fig. S22) with only slight blue shifts in the low energy region [395 nm (**2**), 392 nm (**3**), and 406 nm (**1**)]. Previous studies on $[\text{Ir}_2(\text{ppy})_4(\mu\text{-C}\equiv\text{C}\text{To})_2]^5$ and TD-DFT analyses now conducted on optimized structures of **2** and **3** were used to interpret these spectra (Table S10, Fig. S27). In particular, the high-energy absorptions ($\lambda < 290$ nm) are ascribed to typical $\pi\text{-}\pi^*$ ligand centred transitions at the ppy and alkyne moieties. The calculated transitions by TD-DFT agree reasonably well with the experimental data, although the low energy bands at 395 nm (**2**) and 392 nm (**3**) are not properly computed. The lowest energy band of **2** are composed of four transitions (314-325 nm) from HOMO, HOMO-1, and HOMO-6, which are mainly contributed by the Ir^{III} and ppy units (40-84% ppy, 5-41% Ir^{III} and 12-17% alkyne fragment), to the LUMO to LUMO+3, which are mainly distributed on the ppy units. Therefore, this band is assigned as a mixture of $^1\text{ILCT}$ and $^1\text{MLCT}$ with some $^1\text{L}^1\text{LCT}$ (alkyne to ppy) character. The first singlet-singlet transition in **3** is computed slightly blue shifted at 321 nm, in line with the experimental values. The lowest energy band is composed by four transitions (315-321 nm) from HOMO (Ir^{III} 34%; ppy 22%; C \equiv CR 36%; Cu^I 8%) and HOMO-1 (Ir^{III} 40%; ppy 28%; C \equiv CR 24%; Cu^I 8%) to LUMO to LUMO+3, which are distributed over all four π^* orbitals (ppy 96%). This band is attributed as Ir^{III}/Cu^I/C \equiv CR/ppy \rightarrow ppy transitions, having mixed $^1\text{MLCT}$ and $^1\text{L}^1\text{LCT}$ character.

Both clusters are moderate phosphorescent emitters in rigid and fluid media with lifetimes in the microsecond regime, whereas **1** is only weakly emissive in fluid and glassy solution - Table S6. In detail, **1** shows a slightly structured band - ca. 525 nm - both at 298 and 77 K (Fig. S23), which is ascribed to a mixture of $^3\text{MLCT}/^3\text{L}^1\text{LCT}$ (L = ppy; L' = C \equiv CR) according to the previous theoretical calculations.⁵ Similarly, **2** emits in the green region at 298 K (480-515 nm, Fig. 2 and S24). In glassy solution, the emission becomes well-structured and is significantly blue shifted in relation to **1** (475 **2** vs. 520 nm **1**), indicating that the emission in the cluster contains more ^3LC character.

The photoluminescence quantum yield of **2** in solution is triple than that of **1** ($\phi = 1.8$ **2** vs. 0.6% **1**) and remarkably

enhanced in the solid state ($\phi = 7\%$). Doped in a poly(methyl methacrylate) (PMMA) film, **2** displays similar green emission (Fig. 2), rising a $\phi = 23\%$ at low concentration (10% wt.). Upon increasing the complex concentration, the peak maxima shifts slightly to the red and the ϕ progressively decreases (Fig. S26), due to the well-known self-quenching process.⁵

In stark contrast to **2**, the emission of **3** is placed in the orange region (620-600 nm, Fig. 2 and S25). The remarkable red shift and unstructured shape of the band is unequivocally a result of the involvement of the Cu- π -alkynyl in the emitting excited state. The ϕ value is similar to that of **2** in solution ($\phi = 1.8\%$), but is appreciably greater in the solid state ($\phi = 18\%$). In doped PMMA films, the influence of the concentration is opposite to that observed in **1**, enhancing with increasing the doping concentration (Fig. S26), pointing to a different emissive state.

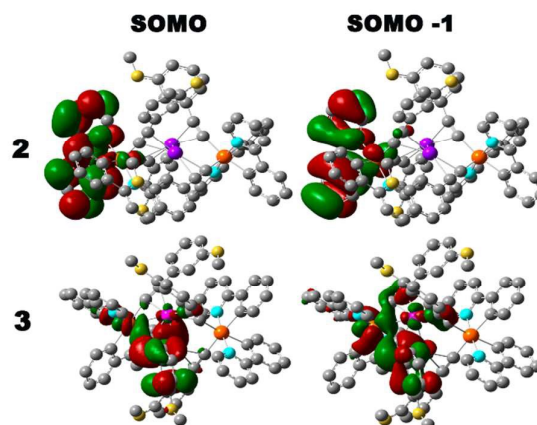


Fig. 3 Molecular orbital topology for the computed T_1 states of **2** and **3**.

To get further understanding of the distinctive emission properties of both clusters, the geometries of the lowest T_1 states were optimized in gas phase (Tables S7, S8). Negligible structural changes were observed in the computed T_1 state for **2** in relation to the ground state (S_0) geometry, which is in agreement with the small Stokes shift found in the emission. The SOMO and SOMO-1 are primarily located on one of the phenylpyridinate groups with small contribution of the Ir^{III} and the alkyne ligands (Fig. 3 and Table S11) and, consequently, the emissive state of this cluster has mainly ^3LC nature with minor $^3\text{MLCT}$ character. The calculated emission energy (ESI \ddagger) is estimated at 495 nm, in agreement with the values obtained in the solid-state (515 nm) and PMMA (487 and 507 nm). To our surprise, a remarkable structural distortion was found in the T_1 of **3** compared to that of S_0 . As shown in Fig. S30, upon photoexcitation, the ligation of one of the C \equiv C-R units change from $\mu\text{-}\eta^1(\text{Ir}^{\text{III}}):\eta^2(\text{Cu}^{\text{I}})$ to $\mu_3\text{-}\eta^1,\eta^1,\eta^1(\text{Ir}^{\text{III}},\text{Cu}^{\text{I}},\text{Cu}^{\text{I}})$, which is also reflected in the notable bent at the C_α atom (Ir^{III}C10^oC11^o 143.11 $^\circ$ in T_1 vs: 162.14 $^\circ$ in S_0). As a consequence, the Cu^I \cdots Cu^I separation (Δ 0.172 \AA) and the Cu^I \cdots Ir^{III} distances to one of the "Ir(C \equiv CC₆H₄OMe-3)₂" fragments decrease considerably (Ir^{III} \cdots Cu^I 2.725 \AA in T_1 vs Ir^{III} \cdots Cu^I 2.928 in S_0). For **3**, the SOMO is primarily confined on the alkyne group (Fig. 3), which bridges the three metals (IrCu₂) and bears contribution of both Cu^I atoms having Cu^I-Cu^I bonding (C \equiv CR/Ir^{III}/Cu^I 73/4/13%) character. The SOMO-1 is extended over both alkynyls through

the Ir^{III}(d) and has higher metallic contribution ($C \equiv CR/Ir^{III}/Cu^I$ 53/24/13%). Therefore, the emission has ³L'C alkynyl nature and alkynyl to metal charge transfer character (³L'MCT) with a higher contribution of the metal centres (³MMCT) than in **2**. The computed value at 625 nm is almost identical to the obtained experimentally in the solid-state (615 nm).

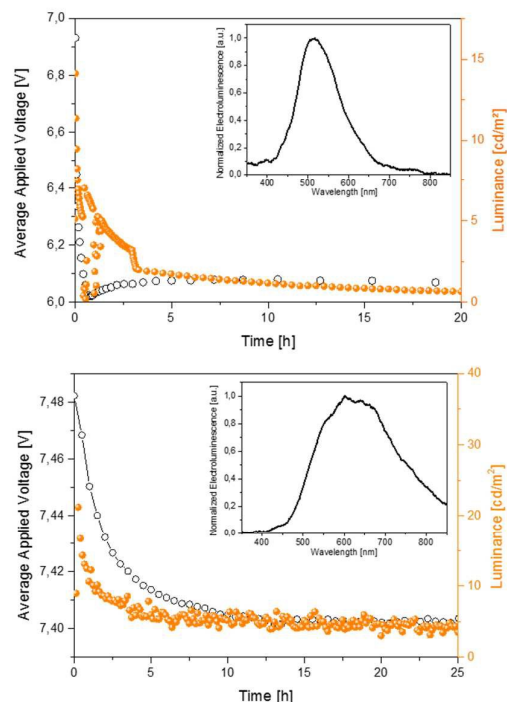


Fig. 4. Luminance and applied voltage vs. time of devices **2** (top) and **3** (bottom) driven with a pulsed-current of 2.5 mA. Inset graphs show the EL spectrum of the devices.

Finally, the electroluminescence features of **2** and **3** were investigated in single-layer lighting devices. Owing to the simple device preparation and optimization compared to OLEDs, we decided to follow a recent approach based on the design of host-guest LECs (see ESI for more details and references) with an active layer that consists of electroactive host matrix doped with mobile anions in the form of ionic liquids with the emitter. As shown in Fig. 4, the electroluminescent features of both clusters are similar to those noted in the photoluminescence studies, suggesting that the same T₁ state is involved under both photo- and electro-excitation conditions. In detail, devices with **2** are green emitting with maximum at 518 nm with x/y colour coordinates of 0.29/0.44, while devices with **3** shows a broad orange emission centred at 625 nm and x/y colour coordinates 0.47/0.46. Importantly, the emission of the matrix is not observed at the high-energy region (390–450 nm), suggesting an efficient energy transfer process from the matrix to the emitters. Regarding the device performance, although the brightness is moderate low, the efficiency of approximately 0.5 cd/A and the stability of several hours are encouraging with respect to the future design of this novel family of emitters in concert with the device optimization.

In summary, two luminescent Ir₂M₂ (M = Ag, Cu) clusters featuring iridium-bis(cyclometalated) fragments and C≡CC₆H₄OMe-3 connecting the metal centers are reported for the first time. In addition, their distinct photo- and electro-luminescent behavior provides an interesting example of the role of the of alkynyl groups in modulating metallophillic bonding in the excited state. This new family of clusters provides new opportunities to achieve color tuning with potential in the field of optoelectronics and further work is currently in progress to study the formation, structures and properties of other Ir-M clusters, as well as the device optimization.

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Alkynyl bridged cyclometalated Ir₂M₂ clusters: Impact of the heterometal in the photo- and electro-luminescent properties

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M. Teresa Moreno,^a Sergio Sánchez,^b Michael D. Weber,^c Rubén D. Costa^{c,*}

The unprecedented alkynyl bridged cyclometalated clusters [Ir₂M₂(ppy)₄(μ-C≡CC₆H₄-OMe₃)₄] (M = Ag, Cu), which display distinctive photo- and electro-luminescent behavior, represent an example of the role of the C≡CR groups in modulating metallophillic bonding in the excited state.

