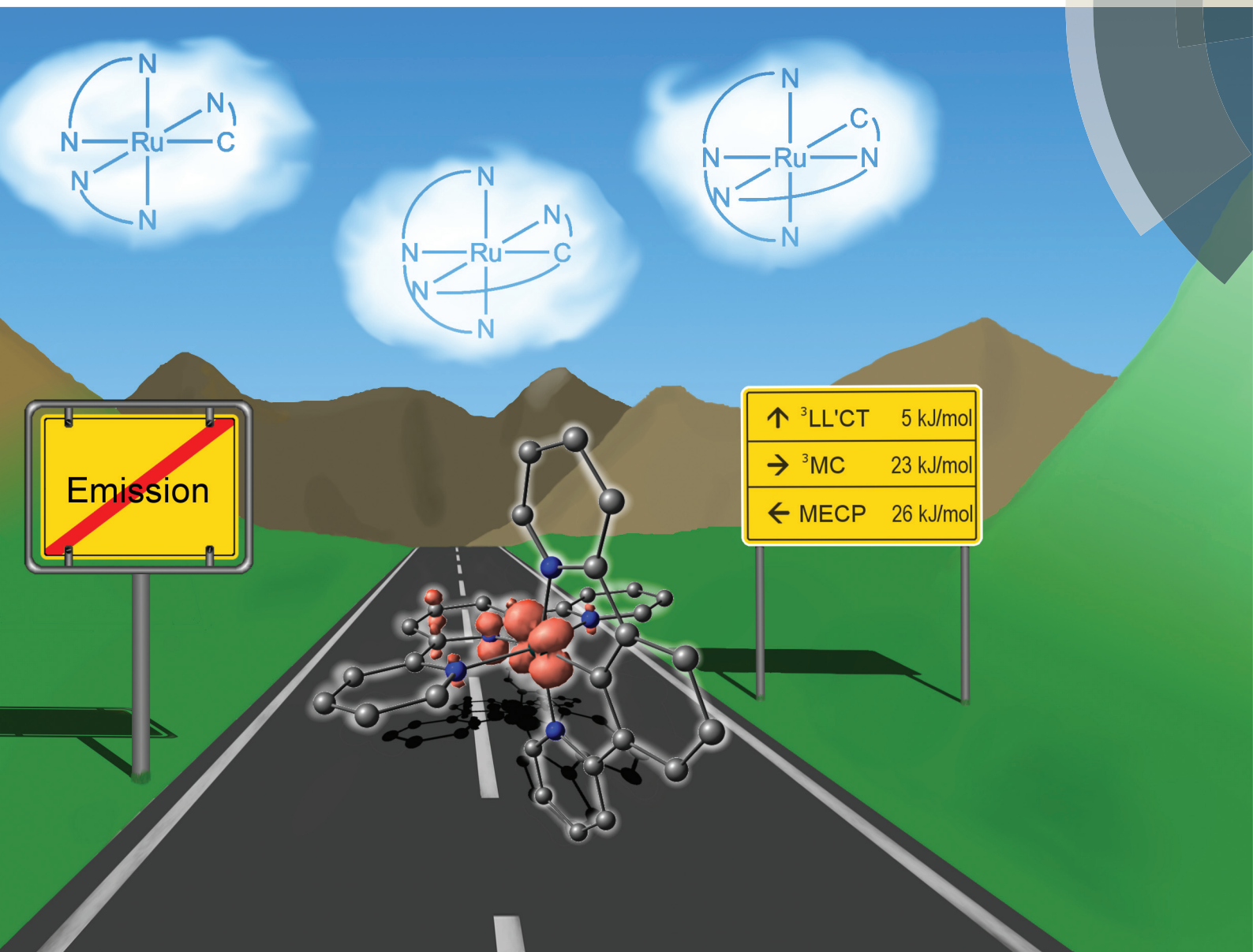


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PERSPECTIVE

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Excited state decay of cyclometalated polypyridine ruthenium complexes:
insight from theory and experiment

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13631Excited state decay of cyclometalated
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Deactivation pathways of the triplet metal-to-ligand charge transfer (³MLCT) excited state of cyclometalated polypyridine ruthenium complexes with [RuN₅C]⁺ coordination are discussed on the basis of the available experimental data and a series of density functional theory calculations. Three different complex classes are considered, namely with [Ru(N[^]N)₂(N[^]C)]⁺, [Ru(N[^]N[^]N)(N[^]C[^]N)]⁺ and [Ru(N[^]N[^]N)(N[^]N[^]C)]⁺ coordination modes. Excited state deactivation in these complex types proceeds via five distinct decay channels. Vibronic coupling of the ³MLCT state to high-energy oscillators of the singlet ground state (¹GS) allows tunneling to the ground state followed by vibrational relaxation (path A). A ligand field excited state (³MC) is thermally accessible via a ³MLCT → ³MC transition state with the ³MC state being strongly coupled to the ¹GS surface via a low-energy minimum energy crossing point (path B). Furthermore, a ³MLCT → ¹GS surface crossing point directly couples the triplet and singlet potential energy surfaces (path C). Charge transfer states either with higher singlet character or with different orbital parentage and intrinsic symmetry restrictions are thermally populated which promote non-radiative decay via tunneling to the ¹GS state (path D). Finally, the excited state can decay via phosphorescence (path E). The dominant deactivation pathways differ for the three individual complex classes. The implications of these findings for isoelectronic iridium(III) or iron(II) complexes are discussed. Ultimately, strategies for optimizing the emission efficiencies of cyclometalated polypyridine complexes of d⁶-metal ions, especially Ru^{II}, are suggested.

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Introduction

Polypyridine complexes of a wide range of transition metals have received great interest from coordination chemists and materials scientists over the last few decades due to their versatile applicability. For example, such complexes of copper(I),^{1–3} iron(II),^{4–6} osmium(II),^{7,8} iridium(III)^{9,10} and, particularly, ruthenium(II)^{11–19} were successfully applied as sensitizers in dye sensitized solar cells. Additionally, a wide range of complexes of this type have been successfully used as sensitizers in photoredox catalysis.^{20–31}

Moreover, the most fascinating and thoroughly studied property observed for a large number of polypyridine transition metal complexes is their luminescence.^{32,33} The first

polypyridine complex reported to exhibit luminescence was [Ru(bpy)₃]²⁺ (bpy = 2,2'-bipyridine).³⁴ Since then, luminescent polypyridine complexes have been described for second and third row transition metal ions with d⁶, d⁸ and d¹⁰ electron configuration,^{35–37} namely for rhenium(I),^{38–41} osmium(II),^{42–45} rhodium(III),^{46–48} iridium(III),^{41,42,49–51} palladium(II),⁵² platinum(II),^{52–57} and gold(III).^{58,59} Even a few luminescent first row transition metal polypyridine complexes are known of chromium(III),^{60–64} copper(I)^{65–71} and zinc(II).⁷²

As such luminescence was first observed for ruthenium, most of the effort understanding the underlying electronic processes evolved around this element and in particular around [Ru(bpy)₃]²⁺ as the prototype.^{73–75} Its key features are an electron-rich low-spin d⁶ metal center with (t_{2g})⁶ electron configuration in idealized O_h symmetry and strongly π-accepting chelate ligands. Upon irradiation with visible light (λ_{max} = 452 nm),⁷³ [Ru(bpy)₃]²⁺ is excited into its lowest excited singlet state which has metal-to-ligand charge transfer (MLCT) character.^{76–78} As MLCT transitions are not restricted in terms of parity selection rules, the corresponding absorption bands are typically very intense. Due to the spin-orbit coupling induced by the ruthenium atom, the excited ¹MLCT state

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undergoes very efficient intersystem crossing ($\phi_{\text{ISC}} \approx 1$) onto the triplet hypersurface populating a $^3\text{MLCT}$ state.^{79,80} At low temperatures in solid matrix, this state either evolves into the ground state without emission *via* tunnelling to the singlet energy surface and vibrational cooling or *via* phosphorescent emission of a photon (at 77 K: $\lambda_{\text{em}} = 580 \text{ nm}$,⁷⁷ $\phi_{\text{em}} = 0.38$;⁷⁷ at 298 K: $\lambda_{\text{em}} = 621 \text{ nm}$,⁸¹ $\phi_{\text{em}} = 0.095$ ⁸¹).^{77,82–84} The rate of non-radiative excited state decay is hereby governed by the so-called energy gap law.^{85–88} In a series of structurally related compounds, the rate increases with decreasing excited state energy. At room temperature however, a third deactivation pathway *via* metal centered (MC) d–d excited states ($(t_{2g})^5(e_g)^1$ electron configuration) is thermally accessible dramatically quenching the emission.^{84,89–91} The activation barrier for this thermally activated depopulation was determined to be about 45 kJ mol^{-1} for $[\text{Ru}(\text{bpy})_3]^{2+}$.^{90,91}

This general scheme for $[\text{Ru}(\text{bpy})_3]^{2+}$ is applicable to other ruthenium polypyridine complexes as well. It enables a fine-tuning of their emissive properties by manipulation of the $^3\text{MLCT}$ energies *via* introduction of functional groups or extension of the aromatic backbone of the pyridine ligands.^{75,92–96} This allowed the design of specifically tailored complexes for luminescent sensing applications^{97,98} and for optoelectronics.^{99–102}

The concept was successfully transferred to polypyridine complexes of other transition metals. For example, cyclometalated polypyridine complexes of iridium(III) proved to be exceptionally well suited for PHOLED applications as their room temperature emission is typically very intense and can be tuned throughout the visible range of the electromagnetic spectrum.^{41,103–106} Cyclometalation hereby refers to the exchange of one or multiple nitrogen atoms of the polypyridine's coordination sphere by isoelectronic carbon anions. This substitution typically yields a reduction of the overall charge of the complex moiety as well as a substantial shift of all redox processes to lower potentials.

Due to the fact that the isoelectronic cyclometalated complexes of ruthenium(II) perform very well as sensitizers in dye sensitized solar cells, they have also received increasing interest in the last years.^{16,17,19,107–109} Additionally, cyclometalated bridging ligands enhance the electronic coupling between the redox centers in mixed-valent Ru/Ru complexes^{110–112} and Ru/organic hybrid structures.^{113–116} Despite the large variety of cyclometalated polypyridine ruthenium complexes synthesized up-to-date, however, no phosphorescence comparable to $[\text{Ru}(\text{bpy})_3]^{2+}$ has yet been achieved. Furthermore, a general explanation for the striking difference in the luminescence



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presented (*vide supra*). However, deeper interest in the photo-physical properties of cyclometalated (polypyridine)ruthenium(II) complexes did not evolve until the discovery of their excellent performance as solar cell sensitizers in 2007.¹⁶ Since then, more effort has been put into the understanding of the photophysical properties of this class of compounds.^{107,109,117–119,127,133–135}

The visible range of the absorption spectrum of $[\text{Ru}(\text{bpy})_2(\text{ppy})]^+$ -type complexes typically is dominated by two broad structured absorption bands, one appearing between 320 and 450 nm and the second between 470 and 650 nm.^{107,127,133–135} The broadness of the visible range absorption features has been attributed to the low symmetry around the metal center which breaks the degeneracy of the metal's d orbitals. Additionally, the lowest unoccupied molecular orbital (LUMO) of the ppy unit (LUMO+2) is substantially higher in energy than the bpy LUMO (Fig. 2). Hence, Berlinguette and coworkers assigned these bands to Ru \rightarrow ppy (at 400 nm) and Ru \rightarrow bpy (at 500 nm) MLCT transitions.^{3,107,127,135} Grätzel, however, suggested that all visible range absorption bands predominantly arise from Ru \rightarrow bpy MLCT transitions with varying contributions from the highest occupied molecular orbital (HOMO) of π -symmetry at the cyclometalating phenyl ring.¹⁷ Indeed, the theoretical data published by Berlinguette¹⁰⁷ show that all Ru \rightarrow ppy transitions are weak in intensity and do not contribute to the absorption spectrum which supports Grätzel's interpretation.

Additionally, the shift of the absorption bands induced by the functional groups attached to either the ppy ligand or the bpy units further underlines Grätzel's assignment of all bands as Ru \rightarrow bpy transitions.^{3,107,127,135}

For most tris(bidentate) complexes of this type, weak room temperature emission in the range between 720 and 820 nm is reported (Table 1).^{107,127–129,133,135} The emissive state is considered to be a Ru \rightarrow bpy $^3\text{MLCT}$ state.^{107,133} This is corroborated by the influence of functional groups on the emission energy. In a series of $[\text{Ru}(\text{bpy})_2(\text{ppy-R})]^+$ complexes ($[\mathbf{1e}]^+ - [\mathbf{1h}]^+$, Scheme 1) with functional groups in *meta*-position to the cyclometalating carbon atom, the emission energy decreases with increasing electron donating strength of the respective substituent as this destabilizes the metal d orbitals (Table 1).¹²⁸ Similarly, functionalization of the bpy ligands

Table 1 Emission wavelengths λ_{em} and wavenumbers $\tilde{\nu}_{\text{em}}$ as well as excited state lifetimes τ of selected tris(bidentate) cyclometalated (polypyridine)ruthenium(II) complexes at room temperature in solution

	$\lambda_{\text{em}}/\text{nm}$ ($\tilde{\nu}_{\text{em}}/\text{cm}^{-1}$)	τ/ns		$\lambda_{\text{em}}/\text{nm}$ ($\tilde{\nu}_{\text{em}}/\text{cm}^{-1}$)	τ/ns
$[\mathbf{1b}]^+_{127}$	821 (12 180)	13	$[\mathbf{1g}]^+_{128}$	781 (12 800)	—
$[\mathbf{1c}]^+_{127}$	778 (12 850)	35	$[\mathbf{1h}]^+_{128}$	776 (12 890)	—
$[\mathbf{1d}]^+_{127}$	824 (12 140)	13	$[\mathbf{2a}]^+_{129}$	787 (12 710)	9
$[\mathbf{1e}]^+_{128}$	805 (12 420)	—	$[\mathbf{2b}]^+_{129}$	761 (13 140)	27
$[\mathbf{1f}]^+_{128}$	800 (12 500)	—	$[\mathbf{2c}]^+_{129}$	779 (12 840)	14

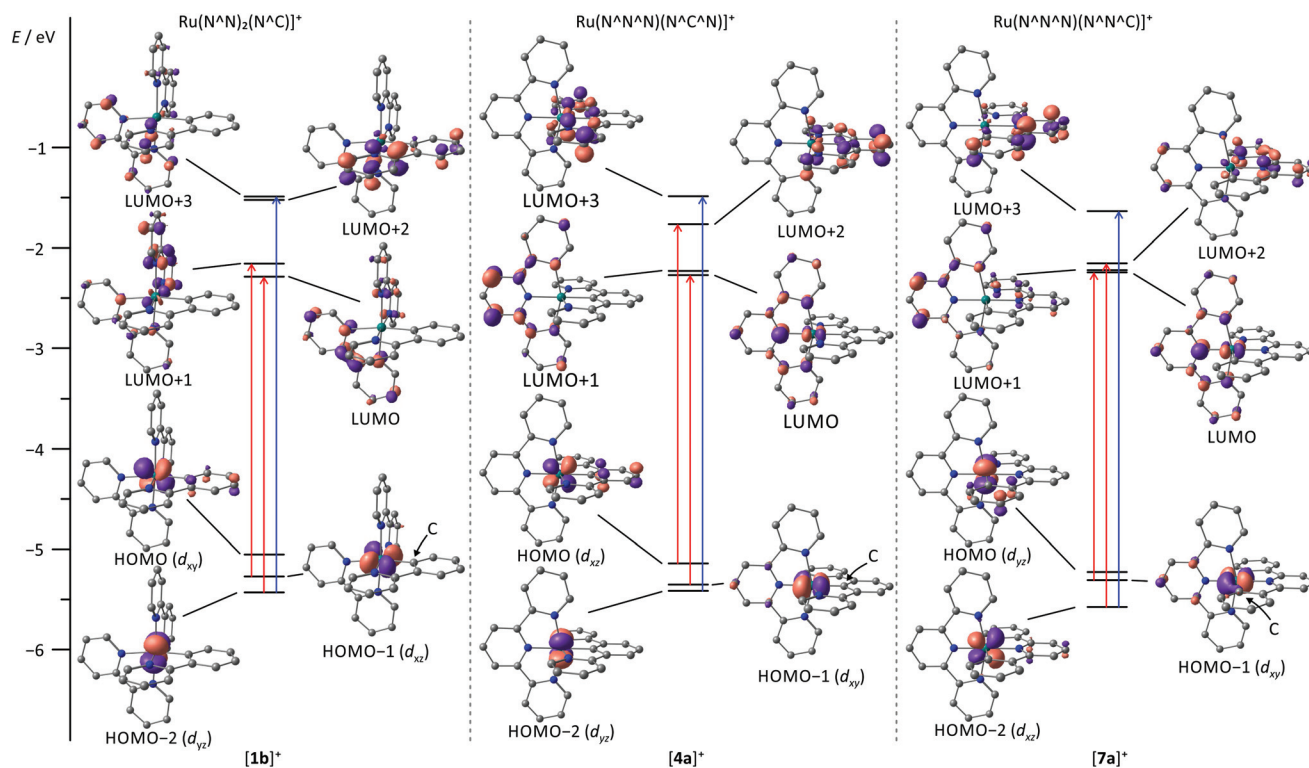


Fig. 2 MO diagram of the parent cyclometalated (polypyridine)ruthenium(II) complexes $[\mathbf{1b}]^+$, $[\mathbf{4a}]^+$ and $[\mathbf{7a}]^+$ obtained from DFT calculations (B3LYP, def2-SVP, ZORA, COSMO (acetonitrile) contour value: 0.07). H atoms are omitted for clarity. The most important orbitals involved in the dominant transitions around 500 nm and 400 nm are highlighted in red and blue, respectively.



with electron accepting substituents such as COOR groups shifts the emission bathochromically as a consequence of the lowered LUMO energy (Table 1).¹³³ However, missing low-temperature emission data (λ_{em} , ϕ , τ) currently impede a quantification of the respective effects.

To the best of our knowledge, no quantum yields have been determined neither at room temperature nor at 77 K for any of the reported tris(bidentate) cyclometalated complexes due to their very weakly emissive character and the associated instrumental limitations.^{127,128} Castellano and coworkers estimated the phosphorescence quantum yields to be $\phi < 0.005$,¹²⁷ while Housecroft and coworkers reported yields below 0.01 for compounds $[\mathbf{1e}]^+ - [\mathbf{1h}]^+$.¹²⁸ However, Berlinguette¹²⁹ and Castellano¹²⁷ provided lifetime data of the emissive excited states for two series of complexes $[\mathbf{2a}]^+ - [\mathbf{2c}]^+$ and $[\mathbf{1b}]^+ - [\mathbf{1d}]^+$, respectively (Scheme 1, Table 1). The lifetimes are in the nanosecond range for all complexes and correlate nicely with the emission energy: the excited state lifetimes become smaller with decreasing emission energy. In (polypyridine)ruthenium(II) complexes, the emissive $^3\text{MLCT}$ state typically is depopulated to some extent *via* a ^3MC state (path B, *vide supra*).^{84,89–91} However, cyclometalation substantially increases the ^3MC energy, as pointed out by Dixon¹³⁶ and van Koten,¹³⁷ efficiently retarding emission quenching *via* this pathway.¹¹⁸ In fact, we were able to localize the respective $^3\text{MLCT}$ and ^3MC states of $[\mathbf{1b}]^+$ *via* DFT calculations (Fig. 3). The ^3MC state (Mulliken spin population at Ru: 1.87) is located 66 kJ mol⁻¹ above the $^3\text{MLCT}$ level while for $[\text{Ru}(\text{bpy})_3]^{2+}$, the $^3\text{MLCT} - ^3\text{MC}$ energy gap was calculated to be -7.7 kJ mol⁻¹ in favour of the ^3MC state.^{138–140} Remarkably, the nitrogen donor atom N1 of the cyclometalating ligand as well as the *trans* nitrogen atom N4 are essentially decoordinates in the ^3MC state of $[\mathbf{1b}]^+$ with Ru–N distances of 2.48 and 2.39 Å, respectively (Fig. 4). This tetragonal distortion along the N1–Ru–N4 axis underlines the strongly dissociative character of the ^3MC state similar to that described for biscyclometalated tris(bidentate) iridium complexes^{141–143} and for $[\text{Ru}(\text{bpy})_3]^{2+}$.^{138–140} It resembles the Jahn–Teller mode of d⁷ low-spin Co^{II} complexes due to the (e_g)¹ electron configuration.^{144,145}

The transition state between the ^3MC and $^3\text{MLCT}$ state was localized on the potential surface with an energy of 69 kJ mol⁻¹ above the $^3\text{MLCT}$ state (Fig. 3). Hence, in contrast to the isoelectronic complex $[\text{Ru}(\text{bpy})_3]^{2+}$, the ^3MC state of $[\mathbf{1b}]^+$ is thermally inaccessible. The comparably low quantum yields of $[\mathbf{1b}]^+$ are attributed to an increased thermal relaxation into the ground state. Non-emissive excited state decay occurs *via* vibronic coupling to high-energy oscillators (path A) or *via* a thermally activated surface crossing to the ground state potential surface (path C).⁸⁶ The latter requires a low-energy surface crossing point. We attempted to localize such a minimum energy crossing point (MECP) between the $^3\text{MLCT}$ and ^1GS potential surfaces. However, the lowest $^3\text{MLCT} \rightarrow ^1\text{GS}$ MECP we could find was localized at 120 kJ mol⁻¹ above the $^3\text{MLCT}$ level. An analogous $^3\text{MC} \rightarrow ^1\text{GS}$ MECP on the other hand is localized at 72 kJ mol⁻¹ merely 6 kJ mol⁻¹ above the ^3MC state (path B, Fig. 3). However, since all of these states are thermally

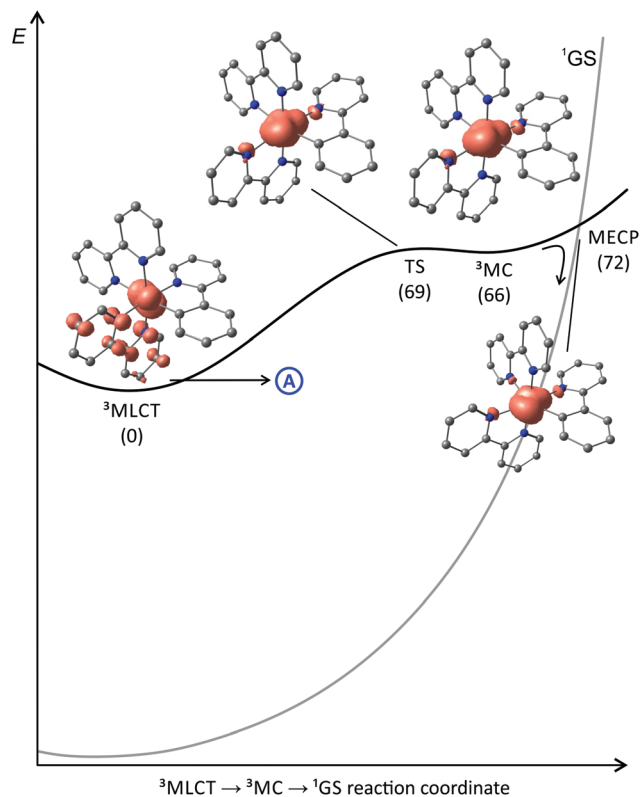


Fig. 3 Schematic representation of the energy landscape of $[\mathbf{1b}]^+$ including spin density contour plots (contour value: 0.01) of the $^3\text{MLCT}$ and the ^3MC states as well as the $^3\text{MLCT} \rightarrow ^3\text{MC}$ transition state and the $^3\text{MC} \rightarrow ^1\text{GS}$ minimum energy surface crossing point. H atoms are omitted for clarity. Energies (kJ mol⁻¹) are given in parentheses relative to the $^3\text{MLCT}$ state ($E = 0$ kJ mol⁻¹). The shape of the singlet potential energy surface is estimated from the DFT-calculated triplet–singlet energy differences at the various excited state geometries.

inaccessible at room temperature or below, surface crossing to the singlet ground state is irrelevant for the excited state deactivation of $[\mathbf{1b}]^+$. As a consequence, emission quenching in $[\mathbf{1b}]^+$ appears to occur exclusively *via* tunnelling into high-energy oscillators of the ground state (path A). According to the energy gap law, the vibronic coupling of the $^3\text{MLCT}$ state and ^1GS becomes stronger, the smaller the $^3\text{MLCT} - ^1\text{GS}$ energy gap is.^{86–88} Secondly, a more pronounced distortion of the $^3\text{MLCT}$ excited state compared to the ground state geometry increases the non-radiative decay rate as it results in a higher Franck–Condon overlap of the vibronic wavefunctions of the ground and excited state.^{86–88,127,146,147} Indeed, inspection of the DFT-optimized geometries of the $^3\text{MLCT}$ and ^1GS states reveals a sizable distortion of the former (Fig. 4) allowing for an efficient radiationless deactivation. This distortion is mainly localized at the bpy ligand *trans* to Ru–C. The Ru–N2 and Ru–N3 bonds are significantly elongated as a consequence of the formal oxidation of ruthenium to +III in the $^3\text{MLCT}$ state and the *trans* influence of the cyclometalating phenyl ring. However, while the Ru–N2 and Ru–N3 bonds are elongated, the formal negative charge on the second bpy ligand



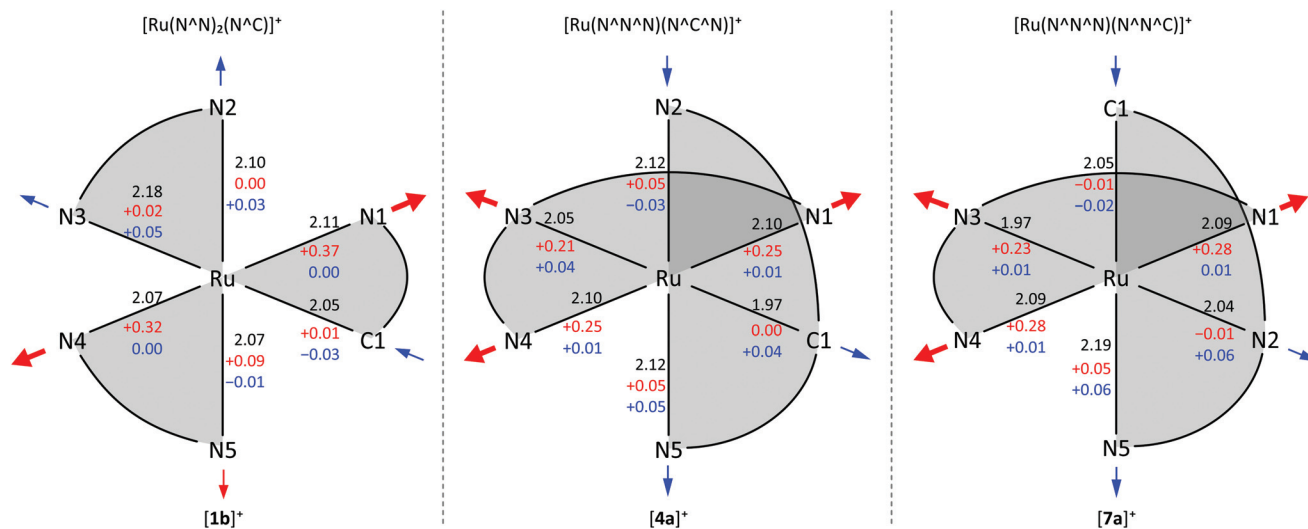


Fig. 4 Schematic representation of the 1GS geometries of $[1b]^+$, $[4a]^+$ and $[7a]^+$ including Ru–X bond lengths in Å (black). The bond length changes in Å in the 3MC (red) and 3MLCT states (blue) are given with respect to the 1GS state. Arrows indicate major molecular distortions of the respective states.

compensates the repulsion yielding essentially unaltered Ru–N4 and Ru–N5 bond lengths.

In summary, the high energy of the 3MC state is very favourable for efficient emitters because it eliminates one pathway for excited state deactivation and concomitantly prevents photodecomposition reactions, that typically occur from the dissociative 3MC state.^{90,148} However, in order to increase phosphorescence quantum yields of cyclometalated (polypyridine)ruthenium, radiationless deactivation *via* vibronic coupling has to be suppressed. This can be approached in two ways: the distortion of the 3MLCT state compared to the 1GS has to be reduced and the emission energy has to be blue-shifted as far as possible. Chou and coworkers provided a beautiful example successfully implementing both approaches.¹³⁰ Clever molecular design yielded systems with Ru \rightarrow ppy MLCT states as lowest triplet excited states. This is straight-forwardly accomplished by making the cyclometalating ppy⁻ ligand the strongest π -acceptor in the complex. Chou and coworkers achieved this with carbon monoxide and phosphanes which are rather poor π -acceptors towards Ru^{II} in biscyclometalated complexes of the type Ru(bq)₂(CO)(PPh₂Me) 3 (bqH = benzo-[h]quinoline, Scheme 1).¹³⁰ As the LUMO of bq⁻ is much higher in energy than that of bpy (Fig. 2), the emission from the corresponding Ru \rightarrow bq 3MLCT state is blue-shifted substantially to 575 nm with a quantum yield of $\phi = 0.24$. Additionally, as the excited state involves a cyclometalating ligand, its distortion compared to the ground state geometry should be less pronounced as in complex $[1b]^+$. Similar observations were made for the isoelectronic osmium complexes.¹⁴⁹

These findings suggest that with careful choice of suitable, very weakly π -accepting polypyridine ligands, cyclometalated (polypyridine)ruthenium complexes with similar emission behaviour arising from high-energy Ru \rightarrow ppy 3MLCT states are

accessible. Another way of improving the emission behaviour of cyclometalated (polypyridine)ruthenium complexes could be by introducing tridentate chelate ligands as this potentially suppresses excited state distortions while maintaining the high energies of parasitic 3MC states. This should yield nested states with poorer Franck–Condon overlap (weakly coupling limit) which reduces tunnelling processes into high-energy singlet states (path A). We will discuss the possibilities and consequences of bis(tridentate) coordination spheres on the phosphorescence properties of cyclometalated ruthenium complexes in the next section.

Bis(tridentate) ruthenium complexes

Considering cyclometalated bis(tridentate) complexes, a distinction between $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ and $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{N}^{\wedge}\text{C})]^+$ coordination environments is reasonable. The next two sections will highlight similarities between the two classes of bis(tridentate) complexes as well as important differences and compare these findings to those concerning tris(bidentate) complexes (*vide supra*).

The $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ coordination sphere

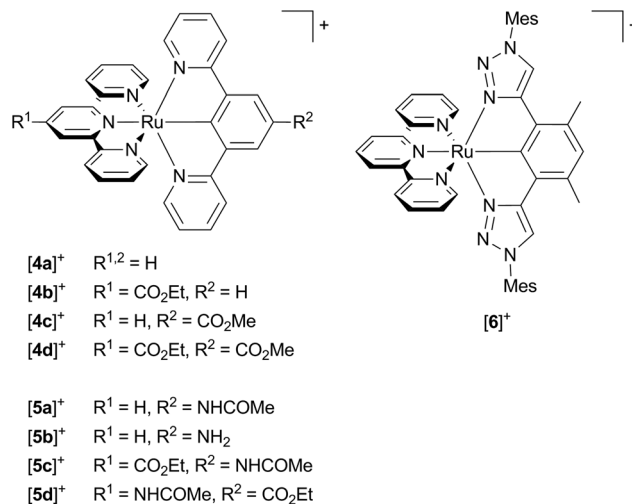
Similar to tris(bidentate) complexes, the visible range of the absorption spectrum of bis(tridentate) complexes with central cyclometalation is dominated by intense and broad absorption bands that have been assigned to MLCT transitions. Again, two bands are observed, one in the range of 350–450 nm and a second between 470 and 650 nm. Van Koten^{137,150} and Berlinguette¹⁰⁷ assigned the high energy MLCT band to Ru \rightarrow dpb transitions and the low-energy band to Ru \rightarrow tpy excitations based on relative orbital energies of the lowest π^* -orbitals of the respective ligands (Fig. 2). Schubert and coworkers^{117,151} on the other hand assigned the low-energy band to mixed MLCT and ligand-to-ligand charge transfer (LL/CT) transitions



arising from a HOMO–LUMO transition while the blue absorption band was attributed to mixed MLCT/LL/CT and MC transitions. We examined several $[\text{Ru}(\text{dpb-R}^1)(\text{tpy-R}^2)]^+$ complexes and demonstrated experimentally (resonance Raman spectroscopy) and theoretically that the low energy absorption arises from both $\text{Ru} \rightarrow \text{tpy}$ and $\text{Ru} \rightarrow \text{dpb}$ excitations (Fig. 2).^{118,152} Excitation into the tpy-centered LUMO is only possible from the HOMO–1, while the dpb-centered LUMO+2 can be reached from the HOMO as evidenced from time-dependent DFT calculations. Both excitations occur at very similar energy and contribute comparably to the absorption band at 500 nm. The higher energy absorption features result from MLCT transitions targeting the higher π^* orbitals of the tpy ligand. In fact, a LL/CT transition as suggested by Schubert¹¹⁷ is symmetry-forbidden as it involves two mutually perpendicular π orbitals. This symmetry argument will become important for the emission properties as well.

Weak emission is observed under ambient conditions for most bis(tridentate) complexes with central cyclometalation in the range between 700 and 800 nm while the parent $[\text{Ru}(\text{tpy})_2]^{2+}$ complex is virtually non-emissive at room temperature.^{107,109,118,119,137,151} Van Koten¹³⁷ and we^{118,119} determined extremely low quantum yields in the range of 10^{-5} for complexes of type $[\text{Ru}(\text{dpb-R}^1)(\text{tpy-R}^2)]^+$. In contrast to the tris(bidentate) series, however, no excited state lifetimes were reported so far (Table 2). Our attempts to obtain lifetimes suggested that they are in the picosecond range.¹¹⁹

Van Koten¹³⁷ studied complexes of the type $[\text{Ru}(\text{dpb-R}^1)(\text{tpy-R}^2)]^+$ bearing carboxy-substituents on either or both ligands (Scheme 2, $[\mathbf{4a}]^+–[\mathbf{4d}]^+$). The effect of the functional groups on the respective emission energy (Table 2) points to a ³MLCT emissive state. In fact, a COOR substituent at the tpy ligand ($[\mathbf{4b}]^+$) leads to complexes that are non-emissive at room temperature due to its stabilizing influence on the tpy-centered LUMO. Since the phosphorescence quantum yields decrease with increasing emission wavelength following the energy gap law, van Koten suggested vibrational relaxation as main source of emission quenching.¹³⁷ We extended this study by also introducing electron-donating substituents such as NH_2 and NHCOMe to the dpb ligand (Scheme 2, $[\mathbf{5a}]^+–[\mathbf{5c}]^+$) and the tpy ligand ($[\mathbf{5d}]^+$).^{118,119} Using theoretical methods we showed, that the emissive state is in fact a ³MLCT state. The two singly



Scheme 2 Literature-known $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ complexes relevant to this work ($[\mathbf{4a}]^+,^{107,137}$ $[\mathbf{4b}]^+–[\mathbf{4d}]^+,^{137}$ $[\mathbf{5a}]^+$ and $[\mathbf{5b}]^+,^{119}$ $[\mathbf{5c}]^+$ and $[\mathbf{5d}]^+,^{118}$ $[\mathbf{6}]^+,^{117}$).

occupied orbitals (SOMOs) in this state correspond to the d_{xy} (HOMO–1) and the tpy LUMO, respectively (Fig. 2). No dpb ligand participation was observed. However, we localized a second charge transfer state with LL/CT character (dpb \rightarrow tpy, HOMO \rightarrow LUMO orbital parentage) on the triplet potential energy surface. The mutually perpendicular SOMOs make this state spectroscopically undetectable and non-emissive (dark state). As third type of triplet states, the ³MC states were found (Fig. 5 and Table 3). While the ³LL/CT state is essentially undistorted compared to the ground state with only a small displacement of ruthenium towards C1 and a concomitant elongation of the Ru–N3 bond, the ³MLCT state exhibits substantial distortions within the tpy ligand. It is inclined with respect to the plane perpendicular to the dpb ligand by 12° (Fig. 5). At the same time the Ru–C and Ru–N5 bonds are slightly elongated while the Ru–N2 bond shortens (Fig. 4). In the ³MC state on the other hand, the peripheral pyridine rings of the tpy ligand are tilted away from the metal center forming dihedral angles of about 11° with the central pyridine ring, respectively. Furthermore, the all Ru–N_{tpy} bonds Ru–N1, Ru–N3 and Ru–N4 are substantially elongated (Fig. 4) underlining the dissociative character of the ³MC state.

The calculated relative energies of the triplet states (Fig. 5) of $[\mathbf{5a}]^+–[\mathbf{5d}]^+$ as well as the transition states connecting them are summarized in Table 3. The emissive ³MLCT state is flanked by two thermally accessible quenching states, namely the ³LL/CT and ³MC states. The lowering of the relative ³MC energy from 66 kJ mol^{-1} in $[\mathbf{1b}]^+$ to 10–30 kJ mol^{-1} in these bis(tridentate) complexes is attributed to the smaller N–Ru–N bite angles and the weaker overlap of the nitrogen lone pairs with the e_g metal orbitals which results in a smaller ligand field splitting. The distortion of the ³MC state allows for tunnelling to the ¹GS and for a surface crossing point (MECP) that is just 9 kJ mol^{-1} above the ³MC level providing an accessible

Table 2 Emission wavelengths λ_{em} and wavenumbers $\tilde{\nu}_{em}$ as well as quantum yields ϕ of selected $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ complexes at room temperature

	λ_{em}/nm ($\tilde{\nu}_{em}/\text{cm}^{-1}$)	ϕ
$[\mathbf{4a}]^+^{137}$	781 (12 800)	9.4×10^{-6}
$[\mathbf{4b}]^+^{137}$	—	—
$[\mathbf{4c}]^+^{137}$	743 (13 460)	1.5×10^{-5}
$[\mathbf{4d}]^+^{137}$	789 (12 670)	4×10^{-7}
$[\mathbf{5a}]^+^{119}$	800 (12 500)	8×10^{-6}
$[\mathbf{5b}]^+^{119}$	780 (12 820)	$<2 \times 10^{-6}$
$[\mathbf{5c}]^+^{118}$	—	—
$[\mathbf{5d}]^+^{118}$	751 (13 320)	1.4×10^{-5}
$[\mathbf{6}]^+^{117}$	751 (13 320)	6.1×10^{-5}



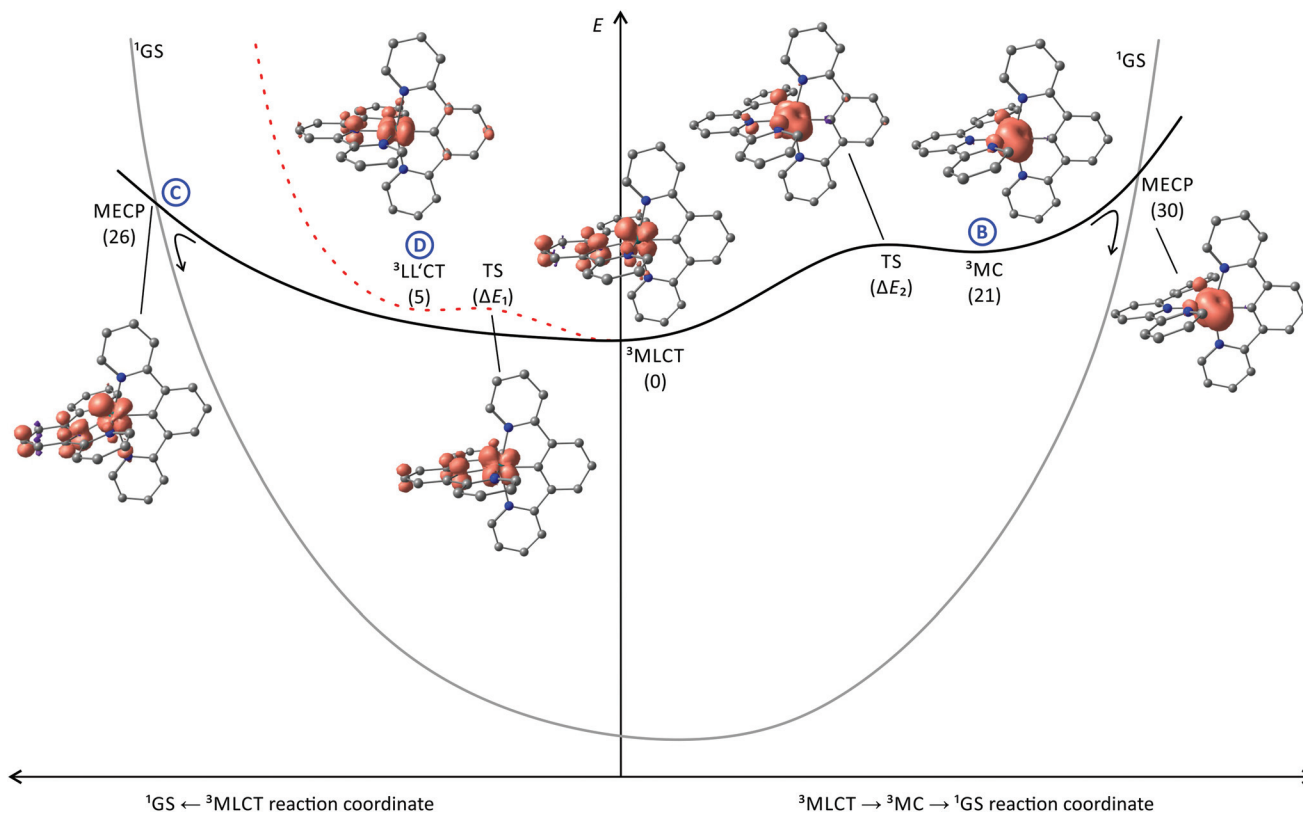


Fig. 5 Schematic representation of the energy landscape of $[\text{Ru}(\text{dpb})(\text{tpy})]^+$ type of complexes including spin density contour plots (contour value: 0.01) of the $^3\text{LL}'\text{CT}$, $^3\text{MLCT}$ and ^3MC states of $[\mathbf{4a}]^+$, the $^3\text{MLCT} \rightarrow ^3\text{MC}$ and $^3\text{MLCT} \rightarrow ^3\text{LL}'\text{CT}$ transition states as well as the minimum energy points for the $^3\text{MLCT} \rightarrow ^1\text{GS}$ and the $^3\text{MC} \rightarrow ^1\text{GS}$ surface crossing. H atoms are omitted for clarity. Energies (kJ mol^{-1}) of the respective states are given in parentheses relative to the $^3\text{MLCT}$ state ($E = 0 \text{ kJ mol}^{-1}$). The shape of the singlet potential energy surface is estimated from the DFT-calculated triplet–singlet energy differences at the various excited state geometries.

Table 3 DFT-calculated Gibbs free enthalpies (in kJ mol^{-1}) of the $^3\text{LL}'\text{CT}$ and ^3MC states as well as the $^3\text{MLCT} \rightarrow ^3\text{LL}'\text{CT}$ (ΔE_1) and $^3\text{MLCT} \rightarrow ^3\text{MC}$ (ΔE_2) transition states of complexes $[\mathbf{4a}]^+$, $[\mathbf{4c}]^+$, $[\mathbf{5a}]^+$, $[\mathbf{5b}]^+$, $[\mathbf{5d}]^+$ and $[\mathbf{6}]^+$ relative to the respective $^3\text{MLCT}$ state energy. Experimentally determined activation barriers are given in parentheses

	$E(^3\text{LL}'\text{CT})$	ΔE_1	$E(^3\text{MC})$	ΔE_2
$[\mathbf{4a}]^+$	5	5	21	23
$[\mathbf{4c}]^+$	-3	4 (2)	13	21 (22)
$[\mathbf{5a}]^+$	8	8 (6)	13	22 (23)
$[\mathbf{5c}]^+$	-10	—	31	—
$[\mathbf{5d}]^+$	—	—	9	(11)
$[\mathbf{6}]^+$	—	— (4)	—	— (22)

non-emissive deactivation channel for the $^3\text{MLCT}$ state (path B, Fig. 5).

Interestingly, a direct $^3\text{MLCT} \rightarrow ^1\text{GS}$ MECP was found for $[\mathbf{4a}]^+$ as well at a moderate energy (26 kJ mol^{-1} above the $^3\text{MLCT}$ state). It is qualitatively similarly distorted as the $^3\text{MLCT}$ state but the degree of the distortion is larger. Thus, the geometry of this crossing point can be regarded as a high-amplitude distortional vibration along the $^1\text{GS} \rightarrow ^3\text{MLCT}$ vibrational mode ($^3\text{MLCT} \rightarrow ^1\text{GS}$ reaction coordinate, Fig. 5).

Hence, the $^3\text{MLCT}$ distortion of $[\mathbf{4a}]^+$ opens up this low-energy deactivation channel (path C), that is absent for $[\mathbf{1b}]^+$. However, experimental evidence for such a quenching channel is difficult to obtain as its activation barrier is similar to that of the ^3MC deactivation channel and hence a similar temperature-dependent emission behaviour is expected.

The $^3\text{LL}'\text{CT}$ state is connected to the $^3\text{MLCT}$ state *via* a transition state with a very low activation barrier (Table 3). As the $^3\text{LL}'\text{CT}$ state is barely distorted compared to the ^1GS geometry (*vide supra*) it is considered a nested state. Indeed, attempts to localize a $^3\text{LL}'\text{CT} \rightarrow ^1\text{GS}$ MECP, that would provide a non-emissive decay channel, failed. Because emission from the $^3\text{LL}'\text{CT}$ state is symmetry-forbidden, its only decay pathway proceeds *via* tunnelling into the vibrationally excited singlet state followed by thermal relaxation (path D, Fig. 5).

Hence both, the $^3\text{LL}'\text{CT}$ and ^3MC states (and potentially also the $^3\text{MLCT} \rightarrow ^1\text{GS}$ MECP) are responsible for the efficient phosphorescence quenching at room temperature. This DFT-based interpretation was evidenced experimentally by recording the temperature dependence of the quantum yield. The respective $\ln(\phi)$ vs. T^{-1} data of $[\mathbf{4c}]^+$ and $[\mathbf{5a}]^+$ were reproduced using a fit function accounting for two thermally activated de-



activation pathways. The activation barriers obtained from the fit are in excellent agreement with the computed transition state energies (Table 3).

Schubert and coworkers¹¹⁷ published very similar results on structurally related complexes such as $[\text{Ru}(\text{dtp})(\text{tpy})]^+$ ($\text{dtbH} = 1,3\text{-di-(1,2,3-triazol-4-yl)benzene}$, Scheme 2, $[\mathbf{6}]^+$). Two Arrhenius-like activation parameters were required to properly reproduce the temperature-dependent lifetime data yielding very similar activation energies compared to our findings for $[\mathbf{4c}]^+$ and $[\mathbf{5a}]^+$. In contrast to our assignments, however, they attributed the two deactivation channels of $[\mathbf{6}]^+$ to an irreversible ${}^3\text{MLCT} \rightarrow {}^3\text{MC}$ surface crossing and an internal conversion to a higher-lying MLCT state of increased singlet character. The latter is a common feature of non-cyclometalated (polypyridine)ruthenium(II) complexes.^{77,83,91,153} In the light of our results and the electronic similarity of the studied structures, it seems plausible that the second deactivation channel in $[\mathbf{6}]^+$ actually is *via* a state of ${}^3\text{LL}'\text{CT}$ nature as well. In fact, their DFT-optimization of a triplet state of $[\mathbf{6}]^+$ afforded a ${}^3\text{CT}$ state with orthogonal SOMOs.¹¹⁷ Even if the cyclometalating ligand does not contribute significantly to the spin density of this state, its emissive relaxation is symmetry-forbidden.

To summarize, the combination of orthogonal ligands with strongly differing electronic properties, one being an excellent π -acceptor and the second a strong π -donor typically yields a low-lying ${}^3\text{CT}$ state. Even though this state is not directly populated after optical excitation into a ${}^1\text{MLCT}$ state and subsequent intersystem crossing onto the triplet manifold it serves as a further low-barrier channel for radiationless deactivation of the emissive ${}^3\text{MLCT}$ state (path **D**) besides the ${}^3\text{MC}$ state (path **B**). Recent reports underline that these results are transferable to structurally similar complexes of other transition metals with orthogonal tridentate ligands. In fact, Williams and coworkers suggested that a ${}^3\text{LL}'\text{CT}$ state plays a key role in the excited state deactivation of isostructural and iso-electronic $[\text{Ir}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^{2+}$ complexes.¹⁵⁴ A beautiful theoretical study on the excited state deactivation pathways in biscyclometalated gold(III) complexes of the general formula $[\text{Au}(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})(\text{acetylide})]$ revealed a ${}^3\text{LL}'\text{CT}$ state which efficiently contributed to the radiationless deactivation of the emissive state.^{56,57,155} Its substantial distortion compared to the ground state increased the rate of non-radiative decay.

In order to optimize the emissive properties of bis(tridentate) cyclometalated ruthenium complexes, circumventing the low-energy non-emissive ${}^3\text{LL}'\text{CT}$ state is a key objective, for example by removing the axial symmetry. This can be achieved using a $\text{N}^{\wedge}\text{N}^{\wedge}\text{C}$ coordination mode on the cyclometalating ligand which will be discussed in the next section (*vide infra*). However, the kinetic parameters extracted by Schubert and coworkers¹¹⁷ from the temperature-dependent lifetime data suggest, that at room temperature the ${}^3\text{LL}'\text{CT}$ state (path **D**) with an activation barrier ΔE_2 of just 4.2 kJ mol⁻¹ is only responsible for the quenching of about 25% of the excited molecules of $[\mathbf{6}]^+$ and structurally similar complexes. At the same time, the ${}^3\text{MC}$ state with a considerably higher barrier ΔE_1 of 21.9 kJ mol⁻¹ is responsible for about 75% of the

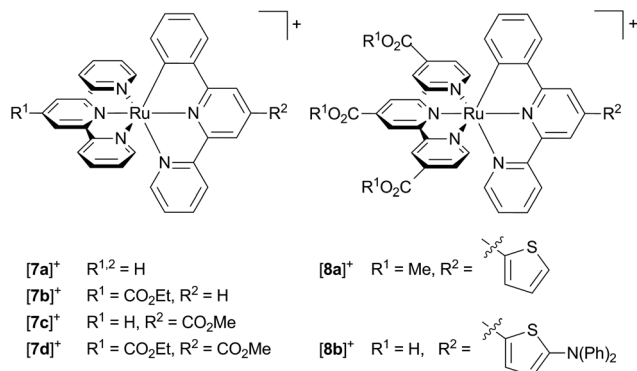
excited state deactivation (path **B** and potentially path **C**), while direct radiationless decay into the ground state only contributes 0.1% (path **A**). Hence, even avoiding the ${}^3\text{LL}'\text{CT}$ state by clever molecular design will not *per se* yield strong emitters. The strong electronic coupling of the ${}^3\text{MLCT}$ and ${}^3\text{MC}$ states [k_0 (${}^3\text{MLCT} \rightarrow {}^3\text{MC}$) = $10^{11}\text{--}10^{13}$ s⁻¹; k_0 (${}^3\text{MLCT} \rightarrow {}^3\text{LL}'\text{CT}$) $\approx 10^8$ s⁻¹]¹¹⁷ renders the former the dominant deactivating state despite the substantially higher activation barrier. The appreciably weaker coupling of the ${}^3\text{MLCT}$ and ${}^3\text{LL}'\text{CT}$ states can be traced back to the two states still being electronically nearly orthogonal (*vide supra*). Concluding, despite the occurrence of a ${}^3\text{LL}'\text{CT}$ state in this kind of bis(tridentate) complexes the important states to manipulate for improving emission efficiencies remain the ${}^3\text{MC}$ and ${}^3\text{MLCT}$ states. Some well-thought-out examples have been provided in the recent literature employing ligand bite angle manipulation^{94,95,156,157} and push-pull concepts^{93,157,158} to increase the ${}^3\text{MLCT}$ - ${}^3\text{MC}$ gap in bis(tridentate) ruthenium complexes which in principle are applicable to cyclometalated complexes as well. However, these conceptual approaches are beyond the scope of this perspective. Recently, Dixon and coworkers¹⁵⁹⁻¹⁶¹ suggested on a computational basis, that two cyclometalating sites in *cis*-position could be beneficial to increase the ligand field splitting of iron(II) complexes and provide a tool for controlling the relative ${}^3\text{MLCT}$ and ${}^3\text{MC}$ energies. This concept should be transferable to cyclometalated ruthenium complexes as well (*cf.* 3) although it is likely accompanied with synthetic challenges.^{105,130,162,163} An alternative approach could again involve attaching very weakly π -accepting ligands *trans* to a $\text{N}^{\wedge}\text{C}^{\wedge}\text{N}$ ligand to yield potentially highly luminescent $\text{Ru} \rightarrow \text{N}^{\wedge}\text{C}^{\wedge}\text{N}$ ${}^3\text{MLCT}$ states.

The $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{N}^{\wedge}\text{C})]^+$ coordination sphere

The absorption spectrum of $[\text{Ru}(\text{tpy})(\text{pbpy})]^+$ type complexes resembles that of $[\text{Ru}(\text{bpy})_2(\text{ppy})]^+$ with two absorption bands, one around 400 nm, and a second around 500–600 nm. Again, the low-energy band is composed of MLCT transitions both involving the tpy and the cyclometalating ligand. However, the π^* orbital of the coordinating phenyl ring (LUMO+3) is not involved in any of the low-energy transitions, as its energy is substantially higher than the frontier orbitals (Fig. 2).¹⁰⁷ Due to the near-degeneracy of the three lowest unoccupied orbitals (LUMO–LUMO+2), the absorption band at 500 nm is markedly sharper than that of $[\text{Ru}(\text{dpb})(\text{tpy})]^+$ and $[\text{Ru}(\text{bpy})_2(\text{ppy})]^+$ complexes. The feature around 400 nm is dominated by an intense $\text{Ru} \rightarrow \text{phenyl}$ (LUMO+3) transition (Fig. 2).¹⁰⁷

Unfortunately, accounts on emission properties of these $[\text{Ru}(\text{tpy})(\text{pbpy})]^+$ complexes are very limited.^{107,134,137,164} A few examples are summarized in Scheme 3 and Table 4. In the series $[\mathbf{7a}]^+ \text{--} [\mathbf{7d}]^+$ with carboxy substituents at either or both ligands, the quantum yields and trends in the emission energies are similar to those of the isomeric $[\text{Ru}(\text{tpy})(\text{dpb})]^+$ complexes $[\mathbf{4a}]^+ \text{--} [\mathbf{4d}]^+$. Again, carboxy-substitution at the tpy ligand lowers the LUMO energy sufficiently to yield non-emissive ($[\mathbf{7b}]^+$) or essentially non-emissive ($[\mathbf{7d}]^+$) complexes at room temperature due to the energy gap law.¹³⁷ However, carboxy-substitution at the pbpy ligand ($[\mathbf{7c}]^+$) does not blueshift the





Scheme 3 Literature-known [Ru(N[^]N[^]N[^])(N[^]N[^]C)]⁺ complexes relevant to this work ([7a]⁺–[7d]⁺,^{107,137} [8a]⁺,¹³⁴ [8b]⁺¹⁶⁴).

Table 4 Emission wavelengths λ_{em} and wavenumbers $\tilde{\nu}_{em}$ as well as quantum yields ϕ of selected [Ru(N[^]N[^]N[^])(N[^]N[^]C)]⁺ complexes at room temperature in solution

	λ_{em}/nm ($\tilde{\nu}_{em}/cm^{-1}$)	ϕ
[7a] ⁺ ¹³⁷	797 (12 550)	5.1×10^{-6}
[7b] ⁺ ¹³⁷	—	—
[7c] ⁺ ¹³⁷	780 (12 820)	1.3×10^{-5}
[7d] ⁺ ¹³⁷	807 (12 390)	4×10^{-7}
[8a] ⁺ ¹³⁴	810 (12 350)	—
[8b] ⁺ ¹⁶⁴	549 (18 210)	0.27

emission energy compared to the unsubstituted complex [7a]⁺ (270 cm⁻¹) as much as in the case of the [Ru(dpb)(tpy)]⁺ complexes [4c]⁺ and [4a]⁺ (660 cm⁻¹).¹³⁷ This was traced back to a change of the orbital parentage of the emissive ³MLCT state. Instead of being a Ru → tpy state as in [7a]⁺, emission of [7c]⁺ arises from a Ru → (pbpy-COOR) ³MLCT state. This is accompanied by an altered energy ordering of the lowest unoccupied orbitals and reflects their energetic similarity (Fig. 2). This example highlights that in [Ru(N[^]N[^]N[^])(N[^]N[^]C)]⁺ type complexes Ru → N[^]N[^]C ³MLCT states are obtained by tuning the respective frontier orbital energies of the ligands. However, the cyclometalating phenyl ring does not contribute as π -accepting moiety and the excited electron is entirely localized on the bipyridine fragment of the pbpy ligand. Consequently, the phosphorescence efficiency is not affected significantly (Table 4).

Interestingly, Berlinguette and coworkers reported on a series of [Ru(tpy)(pbpy)]⁺ based complexes with diarylamine groups appended *via* a thiophene linker such as [8b]⁺. These are highly emissive (quantum yields in the range of 0.1–0.3) in some cases, but emit at much higher energy than typically observed for these complexes.¹⁶⁴ In fact, the analogous thiophene substituted complex [8a]⁺ without the diarylamine functionality lacks the strong emission.¹³⁴ However, Berlinguette showed that the emissive behaviour of [8b]⁺ actually arises from a singlet intraligand charge transfer state (¹ILCT) involving the diarylamine unit as electron donor and the polypyridine moiety as electron acceptor.^{165,166} An identical emission

energy was observed for the free ligand with even higher fluorescence quantum yields ($\phi = 0.91$, $\tau = 3.4$ ns) explaining the untypically high emission energy and quantum yield of [8b]⁺.^{164–166}

To get a better understanding of the states involved in the excited state deactivation of [Ru(tpy)(pbpy)]⁺ complexes, we studied the triplet potential energy surface of [7a]⁺ using DFT calculations. Inspecting the ³MLCT state geometry and spin density of [7a]⁺ reveals a striking similarity to [4a]⁺ (Fig. 4, 5 and 6). In fact, a similar distortion of the tpy ligand with an offset central pyridine ring is found in both cases (*vide supra*). Additionally, the bond length changes of the ³MLCT states compared to the respective ¹GS geometries of [4a]⁺ and [7a]⁺ are very similar (Fig. 4). Given the similar quantum yields of the isoelectronic classes of complexes [Ru(dpb)(tpy)]⁺ and [Ru(tpy)(pbpy)]⁺ this suggests excited state deactivation channels with similar barriers are dominant in both cases. However, the ³MC state (path B) is found to be 60 kJ mol⁻¹ (³MLCT → ³MC transition state at 62 kJ mol⁻¹) higher in energy than the ³MLCT state and thus it is thermally inaccessible at room temperature. As a consequence, its contribution to the excited state deactivation of [7a]⁺ is negligible. The marked increase of the ³MC–³MLCT energy gap by about 30 kJ mol⁻¹ by exchanging N[^]C[^]N by N[^]N[^]C chelate ligands in bis(tridentate) complexes (Fig. 6) was also found for the isoelectronic iron(II) complexes by Dixon and coworkers.¹⁶¹ They argued that the cyclometalating ligand does not only act as a strong σ -donor but also as a π -donor. In the iron(II) complex [Fe(dpb)(tpy)]⁺ the π -donor strength is the dominant influence yielding a net reduction of the effective ligand field strength and hence a stabilization of the ³MC state compared to the non-cyclometalated complex [Fe(tpy)₂]²⁺. In [Fe(tpy)(pbpy)]⁺ on the other hand, the π -overlap between the peripheral cyclometalating phenyl ring and the metal d orbitals is not as pronounced. As a consequence of the σ -overlap an increased ligand field splitting and a higher ³MC energy compared to [Fe(dpb)(tpy)]⁺ are calculated. At the same time, the ³MLCT energies of [Fe(tpy)(pbpy)]⁺ and [Fe(dpb)(tpy)]⁺ are essentially identical yielding an overall higher ³MLCT–³MC energy gap by about 30 kJ mol⁻¹ for [Fe(tpy)(pbpy)]⁺. As for ruthenium, the d orbitals are more diffuse than for iron, the destabilization of the t_{2g} orbitals *via* π -donor interactions is much less pronounced yielding ³MC states well above the ³MLCT level in all cyclometalating complexes, but the same principles apply explaining the trends we observe for the isoelectronic ruthenium complexes.¹⁶¹

In principle, a ³LL/CT state similar to that described for [Ru(dpb)(tpy)]⁺ complexes (*vide supra*) is also conceivable for complexes of the [Ru(N[^]N[^]N[^])(N[^]N[^]C)]⁺ class. However, an analogous symmetry restriction as discussed above for the former does not apply in this case due to the lowered molecular symmetry. Although we tried to localize such a ³LL/CT state it remained elusive. Whether such a state actually contributes to the excited state deactivation of [Ru(N[^]N[^]N[^])(N[^]N[^]C)]⁺ complexes has to be evaluated based on experimental emission data at variable temperatures. This exceeds the scope of this article.



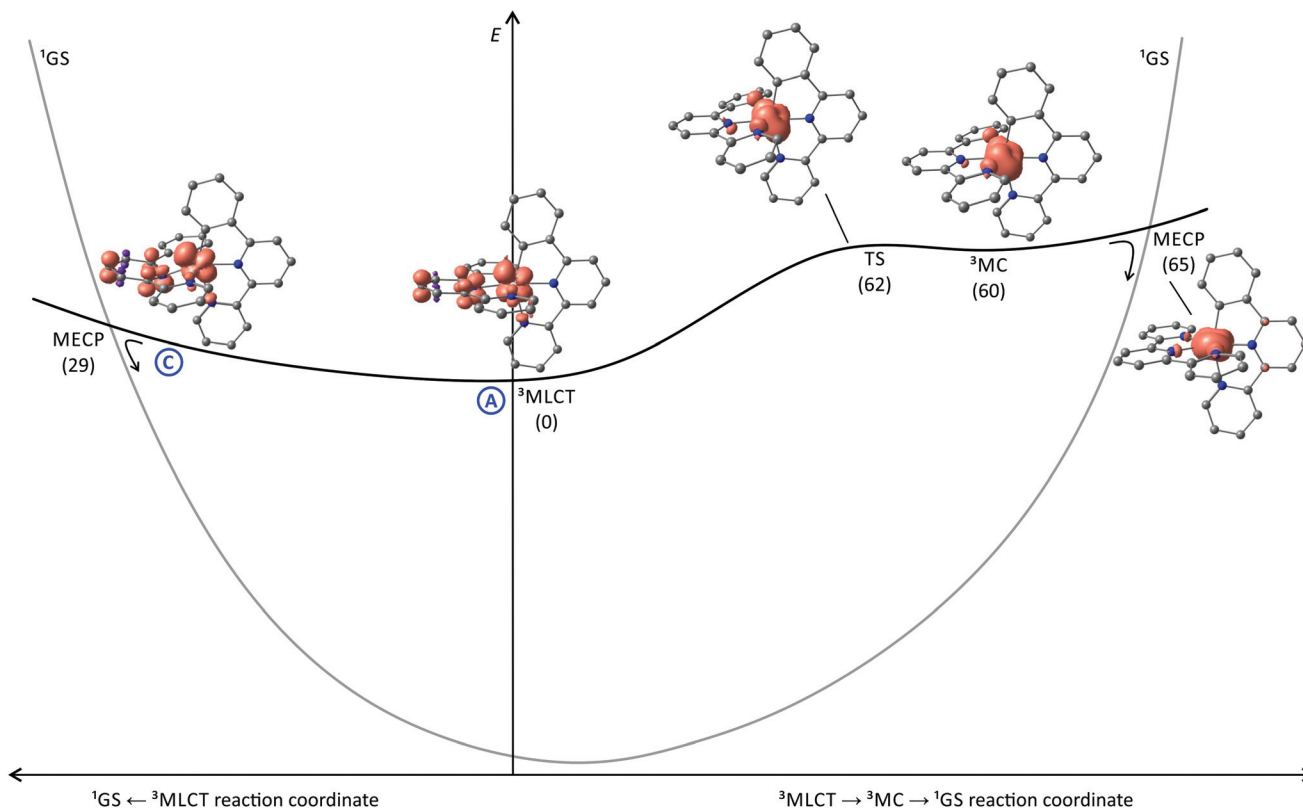


Fig. 6 Schematic representation of the energy landscape of $[\text{Ru}(\text{tpy})(\text{pbpy})]^+$ type of complexes including spin density contour plots (contour value: 0.01) of the $^3\text{MLCT}$ and ^3MC states of $[\text{7a}]^+$, the $^3\text{MLCT} \rightarrow ^3\text{MC}$ transition state as well as the minimum energy points for the $^3\text{MLCT} \rightarrow ^1\text{GS}$ and the $^3\text{MC} \rightarrow ^1\text{GS}$ surface crossing. H atoms are omitted for clarity. Energies (kJ mol^{-1}) of the respective states are given in parentheses relative to the $^3\text{MLCT}$ state ($E = 0 \text{ kJ mol}^{-1}$). The shape of the singlet potential energy surface is estimated from the DFT-calculated triplet–singlet energy differences at the various excited state geometries.

Since the $^3\text{MLCT}$ state of $[\text{7a}]^+$ is electronically very similar to the $^3\text{MLCT}$ state of the tris(bidentate) complex $[\text{1b}]^+$, an argumentation based on emission quenching *via* vibronic coupling to the ground state (path **A**) is insufficient to account for the substantially lower emission quantum yields of the former (10^{-6} – 10^{-5} as compared to 10^{-4} – 10^{-3}). Additionally, deactivation channels *via* low-lying ^3MC (path **B**) or $^3\text{LL}'\text{CT}$ states (path **D**) as found for $[\text{Ru}(\text{dpb})(\text{tpy})]^+$ complexes do not contribute to the efficient non-emissive excited state decay of $[\text{Ru}(\text{tpy})(\text{pbpy})]^+$ complexes. A surface crossing point between the $^3\text{MLCT}$ and ^1GS potential energy surfaces (path **C**), however, similar to that found for $[\text{4a}]^+$ (Fig. 5), would provide a concise explanation for the marked difference between the tris(bidentate) and bis(tridentate) complexes. Indeed, we localized a thermally accessible $^3\text{MLCT} \rightarrow ^1\text{GS}$ surface crossing point that is only 29 kJ mol^{-1} higher in energy than the $^3\text{MLCT}$ state (Fig. 6). Remarkably, the geometry and energy of this crossing point is similar to that of the $^3\text{MLCT} \rightarrow ^1\text{GS}$ MECP of $[\text{4a}]^+$. Again, the distortion of the $^3\text{MLCT}$ state provides an excited state deactivation pathway for polypyridine ruthenium complexes. This finding has some predictive value as well. The ^3MC state is thermally inaccessible at temperatures below 298 K in $[\text{7a}]^+$ and does not contribute to the excited state decay. Hence, the temperature dependence of the emission of

$[\text{7a}]^+$ can provide information on the contribution of a minimum energy surface crossing point in proximity to the relaxed $^3\text{MLCT}$ geometry to the emission quenching. An increasing emission intensity upon cooling would support this hypothesis. Additionally, as the dissociative anti-bonding ^3MC state is out of reach at room temperature, no photosubstitution reactions should occur for $[\text{7a}]^+$ in contrast to $[\text{Ru}(\text{bpy})_3]^{2+}$ which is very prone to such reactivity.⁹⁰ We will devote future work into elucidating these predictions.

In conclusion, it does not suffice to reduce the molecular symmetry and circumvent the parasitic $^3\text{LL}'\text{CT}$ state to increase phosphorescence quantum yields in bis(tridentate) cyclometalated complexes. Bis(tridentate) $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{N}^{\wedge}\text{C})]^+$ complexes with peripheral cyclometalation suffer from the same distortion and low energy of the $^3\text{MLCT}$ state as the analogous tris(bidentate) complexes. As the relative ^3MC state energy of $[\text{Ru}(\text{tpy})(\text{pbpy})]^+$ complexes is substantially higher than for comparable $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ complexes, its contribution to the excited state decay can be neglected (path **B**). Hence, similar strategies are applicable for increasing the luminescence quantum yields as suggested before for tris(bidentate) complexes. These should focus on reducing the excited state distortion yielding a nested emissive state and shutting down the deactivation *via* direct $^3\text{MLCT} \rightarrow ^1\text{GS}$ surface crossing



(path C). This might be achieved by shifting the LUMO to higher energies and making the π^* orbital of the cyclometalating moiety the acceptor site of the lowest $^3\text{MLCT}$ state. At the same time, a lower excited state distortion would shift the energy of the $^3\text{MLCT} \rightarrow ^1\text{GS}$ MECP to higher energies as well. This could potentially be accomplished by a combination of a very weakly π -accepting spectator ligand with a cyclometalating ligand that also contains a weakly π -accepting site such as an N-heterocyclic carbene.^{167,168}

Experimental section

Density functional theory calculations

DFT calculations were carried out using the ORCA program package (version 3.0.2).¹⁶⁹ Tight convergence criteria were chosen for all calculations (Keywords TightSCF and TightOpt). All calculations were performed using the hybrid functional B3LYP¹⁷⁰ and employ the RIJCOSX approximation.^{171,172} Relativistic effects were calculated at the zeroth order regular approximation (ZORA) level. The ZORA keyword automatically invokes relativistically adjusted basis sets.¹⁷³ To account for solvent effects, a conductor-like screening model (COSMO) modelling acetonitrile was used in all calculations.¹⁷⁴ Geometry, transition state and minimum energy crossing point optimizations were performed using Ahlrichs' split-valence double- ζ basis set def2-SV(P) which comprises polarization functions for all non-hydrogen atoms.^{175,176} Optimized geometries were confirmed to be minima or first-order saddle points by subsequent frequency analysis ($n_{\text{imag}} = 0$ or 1, respectively). Surface crossing geometries were subjected to SurfCrossNum-Freq calculations to confirm that they are minima in the 3N-7 dimensional subspace excluding the surface crossing reaction coordinate. Computed free Gibbs enthalpies were used to compare the relative energies of all structures. Explicit counterions and/or solvent molecules were not taken into account in any case.

The $^3\text{MLCT}$ and $^3\text{LL}'\text{CT}$ states were localized by triplet geometry optimizations from the optimized ^1GS geometry. ^3MC states were found by elongating two opposite Ru-N bonds to 2.40 Å and subsequent geometry optimizations. Transition state optimizations were started from geometries obtained by averaging all coordinates of the starting and final state geometries using the exact Hessian matrix of the initial geometry. MECP geometries were obtained by starting at the respective optimized triplet state geometry ($^3\text{MLCT}$ geometry for $^3\text{MLCT}-^1\text{GS}$ MECP, ^3MC geometry for $^3\text{MC}-^1\text{GS}$ MECP).

Conclusions

Cyclometalated polypyridineruthenium(II) complexes with N_5C coordination sphere typically exhibit very weak room temperature emission in the near infrared range (700–800 nm) of the electromagnetic spectrum. The reasons for the weak emission are various and depend on the chelate coordination sphere

around the metal center. In tris(bidentate) $[\text{Ru}(\text{N}^{\wedge}\text{N})_2(\text{N}^{\wedge}\text{C})]^+$ complexes, the ^3MC state (path B) that is typically a major channel for excited state decay in polypyridineruthenium(II) complexes,^{84,89,90} does not contribute as it is thermally inaccessible ($\Delta E(^3\text{MLCT} \rightarrow ^3\text{MC}) = 60\text{--}70 \text{ kJ mol}^{-1}$) at room temperature. Furthermore, no low energy $^3\text{MLCT} \rightarrow ^1\text{GS}$ surface crossing point was found (path C) which suggests that tunnelling into high-energy vibrationally excited singlet states is the main channel of excited state deactivation (path A).

In contrast, the emission quenching of $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{C}^{\wedge}\text{N})]^+$ complexes is dominated by two thermally accessible triplet states, that flank the emissive $^3\text{MLCT}$ state, namely the ^3MC state (path B, $\Delta E(^3\text{MLCT} \rightarrow ^3\text{MC}) = 10\text{--}30 \text{ kJ mol}^{-1}$) and a $^3\text{LL}'\text{CT}$ state (path D, $\Delta E(^3\text{MLCT} \rightarrow ^3\text{LL}'\text{CT}) < 10 \text{ kJ mol}^{-1}$).^{117–119} The $^3\text{LL}'\text{CT}$ state is a peculiarity of C_2 -symmetric cyclometalated complexes and provides a second, unprecedented non-emissive deactivation channel. Additionally, a $^3\text{MLCT} \rightarrow ^1\text{GS}$ surface crossing point provides another decay channel (path C) whose contribution yet needs to be quantified. These three channels B, C and D are responsible for almost 100% of the emission quenching. Although significantly faster than the emission process itself, direct non-emissive decay *via* $^3\text{MLCT} \rightarrow ^1\text{GS}$ tunnelling (path A) only plays a subordinate role simply because excited state decay *via* paths B, C and D is so efficient. This is reflected by the very low excited state lifetimes below the nanosecond range.

In $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{N}^{\wedge}\text{C})]^+$ complexes, the ^3MC states are thermally inaccessible ($\Delta E(^3\text{MLCT} \rightarrow ^3\text{MC}) \approx 60 \text{ kJ mol}^{-1}$) and no quenching $^3\text{LL}'\text{CT}$ states are relevant. However, the triplet and singlet potential surfaces intersect close to the relaxed $^3\text{MLCT}$ state providing an efficient deactivation channel (path C) with an activation barrier of only about 30 kJ mol^{-1} . This explains the similarly low emission quantum yields of bis(tridentate) complexes with central and peripheral cyclometalating site despite the markedly different triplet states relevant to the two systems. However, the amount of emission quenching *via* tunneling (path A) in $[\text{Ru}(\text{N}^{\wedge}\text{N}^{\wedge}\text{N})(\text{N}^{\wedge}\text{N}^{\wedge}\text{C})]^+$ complexes remains unclear until temperature-dependent lifetime data are acquired.

Strategies for increasing the phosphorescence quantum yields are proposed. In $[\text{Ru}(\text{N}^{\wedge}\text{N})_2(\text{N}^{\wedge}\text{C})]^+$ complexes emission quenching is dominated the very low emission energies and the efficient tunnelling into high-energy singlet states following the energy gap law (path A). Hence, improving the emission efficiency is very challenging and only achieved by structurally restraining the already small excited state distortions or increasing the emission energy drastically. The latter is possible by making the cyclometalating ligand the π -accepting site of the $^3\text{MLCT}$ state as shown by Chou and coworkers.¹³⁰

In bis(tridentate) cyclometalated ruthenium complexes, emission quenching predominantly arises from the distortion of the $^3\text{MLCT}$ state compared to the ground state. The triplet potential energy surface is relatively flat around the $^3\text{MLCT}$ geometry leading to a $^3\text{MLCT}/^1\text{GS}$ surface intersection less



than 30 kJ mol⁻¹ above the emissive ³MLCT state giving rise to a deactivation channel *via* a direct ³MLCT → ¹GS surface crossing. Minimizing the excited state distortion *via* structural constraints could circumvent this channel. Additionally, by making the cyclometalating ligand the π-accepting site within the ³MLCT state *via* tuning the energy levels of the lowest unoccupied molecular orbitals, a substantial increase of the ³MLCT state energy can be achieved which would be beneficial for suppressing the ³MLCT → ¹GS surface crossing as well. This will, however, also shift the emission well into the visible range of the electronic spectrum.

Furthermore, it is crucial to avoid orthogonal π-donor and π-acceptor sites in *trans* position across the metal center as in [Ru(N[∧]N[∧]N)(N[∧]C[∧]N)]⁺ because this inherently invokes orthogonal, non-emissive ³LL/CT states as quenching channels and also lowers the energy of the ³MC states into a thermally accessible region due to a lower ligand field splitting.

In order to elucidate the excited state properties of cyclometalated complexes, temperature-dependent excited state lifetime or emission quantum yield measurements provide an invaluable tool.^{71,117–119} Additionally, quantum chemical approaches can deliver lots of information about energies and geometries of relevant excited states. Tong, Che and coworkers (*vide supra*) demonstrated this on luminescent cyclometalated gold(III) complexes.¹⁵⁵ They assessed the radiative and non-radiative decay rates from a computational standpoint and quantified key processes that yield or prevent efficient emission in these species. Similarly, Dixon and coworkers studied mono- and bis(cyclometalated) iron(II) complexes using DFT calculations.^{159–161} The ³MC state in [Fe(pbpy)(tpy)]⁺ with peripheral cyclometalation is substantially higher in energy than in [Fe(dpb)(tpy)]⁺ with central cyclometalation, very similar to the results presented here for the ruthenium homologues. Furthermore, they highlighted, that bis(cyclometalated) iron(II) complexes such as [Fe(dpb)(pbpy)] and [Fe(pbpy)₂] have very low-lying ³MLCT states that are, in the case of [Fe(dpb)(pbpy)], only marginally distorted compared to the ground state geometry. We suggest that these findings apply to the analogous ruthenium complexes potentially opening a route to highly luminescent near-IR emitters. However, since only very few bis(cyclometalated) polypyridine ruthenium complexes are known so far^{130,162,163} and none of them contain tridentate ligands, the synthesis of Ru(dpb)(pbpy) and Ru(pbpy)₂ complexes might be challenging. We will devote future work to the design and synthesis of ruthenium-based emitters with cyclometalating ligands to improve and exploit their excited state properties.

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References

- 1 N. Alonso-Vante, J.-F. Nierengarten and J.-P. Sauvage, *J. Chem. Soc., Dalton Trans.*, 1994, 1649–1654.
- 2 T. Bessho, E. C. Constable, M. Graetzel, A. Hernandez Redondo, C. E. Housecroft, W. Kylberg, M. K. Nazeeruddin, M. Neuburger and S. Schaffner, *Chem. Commun.*, 2008, 3717–3719.
- 3 C. E. Housecroft and E. C. Constable, *Chem. Soc. Rev.*, 2015, **44**, 8386–8398.
- 4 S. Ferrere and B. A. Gregg, *J. Am. Chem. Soc.*, 1998, **120**, 843–844.
- 5 S. Ferrere, *Chem. Mater.*, 2000, **12**, 1083–1089.
- 6 T. C. B. Harlang, Y. Liu, O. Gordivska, L. A. Fredin, C. S. Ponceca, P. Huang, P. Chábera, K. S. Kjaer, H. Mateos, J. Uhlig, R. Lomoth, R. Wallenberg, S. Styring, P. Persson, V. Sundström and K. Wärnmark, *Nat. Chem.*, 2015, **7**, 883–889.
- 7 G. Sauvé, M. E. Cass, S. J. Doig, I. Laueremann, K. Pomykal and N. S. Lewis, *J. Phys. Chem. B*, 2000, **104**, 3488–3491.
- 8 T. Kinoshita, J.-i. Fujisawa, J. Nakazaki, S. Uchida, T. Kubo and H. Segawa, *J. Phys. Chem. Lett.*, 2012, 394–398.
- 9 E. I. Mayo, K. Kilså, T. Tirrell, P. I. Djurovich, A. Tamayo, M. E. Thompson, N. S. Lewis and H. B. Gray, *Photochem. Photobiol. Sci.*, 2006, **5**, 871–873.
- 10 E. Baranoff, J. Yum, I. Jung, R. Vulcano, M. Grätzel and M. K. Nazeeruddin, *Chem. – Asian J.*, 2010, **5**, 496–499.
- 11 B. O'Regan and M. Grätzel, *Nature*, 1991, **353**, 737–740.
- 12 M. K. Nazeeruddin, A. Kay, I. Rodicio, R. Humphry-Baker, E. Mueller, P. Liska, N. Vlachopoulos and M. Graetzel, *J. Am. Chem. Soc.*, 1993, **115**, 6382–6390.
- 13 M. K. Nazeeruddin, S. M. Zakeeruddin, R. Humphry-Baker, M. Jirousek, P. Liska, N. Vlachopoulos, V. Shklover, C.-H. Fischer and M. Grätzel, *Inorg. Chem.*, 1999, **38**, 6298–6305.
- 14 M. K. Nazeeruddin, P. Péchy, T. Renouard, S. M. Zakeeruddin, R. Humphry-Baker, P. Comte, P. Liska, L. Cevey, E. Costa, V. Shklover, L. Spiccia, G. B. Deacon, C. A. Bignozzi and M. Grätzel, *J. Am. Chem. Soc.*, 2001, **123**, 1613–1624.
- 15 M. Grätzel, *J. Photochem. Photobiol., C*, 2003, **4**, 145–153.
- 16 S. H. Wadman, J. M. Kroon, K. Bakker, M. Lutz, A. L. Spek, G. P. M. van Klink and G. van Koten, *Chem. Commun.*, 2007, 1907–1909.
- 17 T. Bessho, E. Yoneda, J.-H. Yum, M. Guglielmi, I. Tavernelli, H. Imai, U. Rothlisberger, M. K. Nazeeruddin and M. Grätzel, *J. Am. Chem. Soc.*, 2009, **131**, 5930–5934.
- 18 A. Hagfeldt, G. Boschloo, L. Sun, L. Kloo and H. Pettersson, *Chem. Rev.*, 2010, **110**, 6595–6663.
- 19 P. G. Bomben, K. C. Robson, B. D. Koivisto and C. P. Berlinguette, *Coord. Chem. Rev.*, 2012, **256**, 1438–1450.



- 20 H. D. Abruna, A. Y. Teng, G. J. Samuels and T. J. Meyer, *J. Am. Chem. Soc.*, 1979, **101**, 6745–6746.
- 21 I. Okura and N. Kim-Thuan, *J. Mol. Catal.*, 1979, **5**, 311–314.
- 22 J.-M. Lehn and R. Ziessel, *Proc. Natl. Acad. Sci. U. S. A.*, 1982, **79**, 701–704.
- 23 J. Hawecker, J.-M. Lehn and R. Ziessel, *J. Chem. Soc., Chem. Commun.*, 1983, 536.
- 24 H. Ozawa, M. Haga and K. Sakai, *J. Am. Chem. Soc.*, 2006, **128**, 4926–4927.
- 25 S. Rau, B. Schäfer, D. Gleich, E. Anders, M. Rudolph, M. Friedrich, H. Görls, W. Henry and J. G. Vos, *Angew. Chem.*, 2006, **118**, 6361–6364, (*Angew. Chem., Int. Ed.*, 2006, **45**, 6215–6218).
- 26 A. Fihri, V. Artero, M. Razavet, C. Baffert, W. Leibl and M. Fontecave, *Angew. Chem.*, 2008, **120**, 574–577, (*Angew. Chem., Int. Ed.*, 2008, **47**, 564–567).
- 27 J. W. Tucker and C. R. J. Stephenson, *J. Org. Chem.*, 2012, **77**, 1617–1622.
- 28 J. W. Tucker, Y. Zhang, T. F. Jamison and C. R. J. Stephenson, *Angew. Chem.*, 2012, **124**, 4220–4223, (*Angew. Chem., Int. Ed.*, 2012, **51**, 4144–4147).
- 29 M. Majek and A. Jacobi von Wangelin, *Angew. Chem.*, 2013, **125**, 6033–6035, (*Angew. Chem., Int. Ed.*, 2013, **52**, 5919–5921).
- 30 S. Paria and O. Reiser, *ChemCatChem*, 2014, **6**, 2477–2483.
- 31 S. M. Stevenson, M. P. Shores and E. M. Ferreira, *Angew. Chem.*, 2015, **127**, 6606–6610, (*Angew. Chem., Int. Ed.*, 2015, **54**, 6506–6510).
- 32 V. Balzani and S. Campagna, *Top. Curr. Chem.*, 2007, **280**, 1–273.
- 33 V. Balzani and S. Campagna, *Top. Curr. Chem.*, 2007, **281**, 1–327.
- 34 J. P. Paris and W. W. Brandt, *J. Am. Chem. Soc.*, 1959, **81**, 5001–5002.
- 35 V. W.-W. Yam and K. M.-C. Wong, *Chem. Commun.*, 2011, **47**, 11579–11592.
- 36 H. Xiang, J. Cheng, X. Ma, X. Zhou and J. J. Chruma, *Chem. Soc. Rev.*, 2013, **42**, 6128–6185.
- 37 H. Xu, R. Chen, Q. Sun, W. Lai, Q. Su, W. Huang and X. Liu, *Chem. Soc. Rev.*, 2014, **43**, 3259–3302.
- 38 S. M. Fredericks, J. C. Luong and M. S. Wrighton, *J. Am. Chem. Soc.*, 1979, **101**, 7415–7417.
- 39 A. Juris, S. Campagna, I. Bidd, J. M. Lehn and R. Ziessel, *Inorg. Chem.*, 1988, **27**, 4007–4011.
- 40 R. A. Kirgan, B. P. Sullivan and D. P. Rillema, *Top. Curr. Chem.*, 2007, **281**, 45–100.
- 41 K. K.-W. Lo, M.-W. Louie and K. Y. Zhang, *Coord. Chem. Rev.*, 2010, **254**, 2603–2622.
- 42 J. N. Demas, E. W. Harris, C. M. Flynn and D. Diemente, *J. Am. Chem. Soc.*, 1975, **97**, 3838–3839.
- 43 C. Creutz, M. Chou, T. L. Netzel, M. Okumura and N. Sutin, *J. Am. Chem. Soc.*, 1980, **102**, 1309–1319.
- 44 J. P. Sauvage, J. P. Collin, J. C. Chambron, S. Guillerez, C. Coudret, V. Balzani, F. Barigelletti, L. de Cola and L. Flamigni, *Chem. Rev.*, 1994, **94**, 993–1019.
- 45 D. Kumaresan, K. Shankar, S. Vaidya and R. H. Schmehl, *Top. Curr. Chem.*, 2007, **281**, 101–142.
- 46 D. Carstens and G. Crosby, *J. Mol. Spectrosc.*, 1970, **34**, 113–135.
- 47 A. Zilian, U. Maeder, A. von Zelewski and H. U. Guedel, *J. Am. Chem. Soc.*, 1989, **111**, 3855–3859.
- 48 M. T. Indelli, C. Chiorboli and F. Scandola, *Top. Curr. Chem.*, 2007, **280**, 215–255.
- 49 K. A. King, P. J. Spellane and R. J. Watts, *J. Am. Chem. Soc.*, 1985, **107**, 1431–1432.
- 50 M. G. Colombo, A. Hauser and H. U. Guedel, *Inorg. Chem.*, 1993, **32**, 3088–3092.
- 51 L. Flamigni, A. Barbieri, C. Sabatini, B. Ventura and F. Barigelletti, *Top. Curr. Chem.*, 2007, **281**, 143–203.
- 52 F. Barigelletti, D. Sandrini, M. Maestri, V. Balzani, A. von Zelewski, L. Chassot, P. Jolliet and U. Maeder, *Inorg. Chem.*, 1988, **27**, 3644–3647.
- 53 H.-K. Yip, L.-K. Cheng, K.-K. Cheung and C.-M. Che, *J. Chem. Soc., Dalton Trans.*, 1993, 2933–2938.
- 54 D. R. McMillin and J. J. Moore, *Coord. Chem. Rev.*, 2002, **229**, 113–121.
- 55 J. A. G. Williams, *Top. Curr. Chem.*, 2007, **281**, 205–268.
- 56 W. H. Lam, E. S.-H. Lam and V. W.-W. Yam, *J. Am. Chem. Soc.*, 2013, **135**, 15135–15143.
- 57 E. S.-H. Lam, W. H. Lam and V. W.-W. Yam, *Inorg. Chem.*, 2015, **54**, 3624–3630.
- 58 V. W.-W. Yam and E. C.-C. Cheng, *Top. Curr. Chem.*, 2007, **281**, 269–309.
- 59 C. Bronner and O. S. Wenger, *Dalton Trans.*, 2011, **40**, 12409–12420.
- 60 N. A. P. Kane-Maguire and C. H. Langford, *J. Chem. Soc. D*, 1971, 895–896.
- 61 M. Maestri, F. Bolletta, L. Moggi, V. Balzani, M. S. Henry and M. Z. Hoffman, *J. Am. Chem. Soc.*, 1978, **100**, 2694–2701.
- 62 A. D. Kirk and G. B. Porter, *J. Phys. Chem.*, 1980, **84**, 887–891.
- 63 N. A. P. Kane-Maguire, *Top. Curr. Chem.*, 2007, **280**, 37–67.
- 64 S. Otto, M. Grabolle, C. Förster, C. Kreitner, U. Resch-Genger and K. Heinze, *Angew. Chem.*, 2015, **127**, 11735–11739, (*Angew. Chem., Int. Ed.*, 2015, **54**, 11572–11576).
- 65 A. Juris and R. Ziessel, *Inorg. Chim. Acta*, 1994, **225**, 251–254.
- 66 N. Armaroli, *Chem. Soc. Rev.*, 2001, **30**, 113–124.
- 67 N. Armaroli, G. Accorsi, F. Cardinali and A. Listorti, *Top. Curr. Chem.*, 2007, **280**, 69–115.
- 68 M. Iwamura, S. Takeuchi and T. Tahara, *Acc. Chem. Res.*, 2015, **48**, 782–791.
- 69 J. Nitsch, C. Kleeberg, R. Fröhlich and A. Steffen, *Dalton Trans.*, 2015, **44**, 6944–6960.
- 70 M. W. Mara, K. A. Fransted and L. X. Chen, *Coord. Chem. Rev.*, 2015, **282–283**, 2–18.
- 71 G. Capano, U. Rothlisberger, I. Tavernelli and T. J. Penfold, *J. Phys. Chem. A*, 2015, **119**, 7026–7037.
- 72 L.-Y. Zhang, G.-F. Liu, S.-L. Zheng, B.-H. Ye, X.-M. Zhang and X.-M. Chen, *Eur. J. Inorg. Chem.*, 2003, **2003**, 2965–2971.



- 73 K. Kalyanasundaram, *Coord. Chem. Rev.*, 1982, **46**, 159–244.
- 74 A. Juris, V. Balzani, F. Barigelletti, S. Campagna, P. Belser and A. von Zelewsky, *Coord. Chem. Rev.*, 1988, **84**, 85–277.
- 75 V. Balzani and A. Juris, *Coord. Chem. Rev.*, 2001, **211**, 97–115.
- 76 J. R. Winkler, T. L. Netzel, C. Creutz and N. Sutin, *J. Am. Chem. Soc.*, 1987, **109**, 2381–2392.
- 77 G. D. Hager and G. A. Crosby, *J. Am. Chem. Soc.*, 1975, **97**, 7031–7037.
- 78 T. J. Meyer, *Pure Appl. Chem.*, 1986, **58**, 1193–1206.
- 79 J. N. Demas and D. G. Taylor, *Inorg. Chem.*, 1979, **18**, 3177–3179.
- 80 S. Yoon, P. Kukura, C. M. Stuart and R. A. Mathies, *Mol. Phys.*, 2006, **104**, 1275–1282.
- 81 K. Suzuki, A. Kobayashi, S. Kaneko, K. Takehira, T. Yoshihara, H. Ishida, Y. Shiina, S. Oishi and S. Tobita, *Phys. Chem. Chem. Phys.*, 2009, **11**, 9850–9860.
- 82 G. A. Crosby, *Acc. Chem. Res.*, 1975, **8**, 231–238.
- 83 G. D. Hager, R. J. Watts and G. A. Crosby, *J. Am. Chem. Soc.*, 1975, **97**, 7037–7042.
- 84 J. van Houten and R. J. Watts, *J. Am. Chem. Soc.*, 1976, **98**, 4853–4858.
- 85 M. Kasha, *Discuss. Faraday Soc.*, 1950, **9**, 14–19.
- 86 R. Englman and J. Jortner, *Mol. Phys.*, 1970, **18**, 145–164.
- 87 J. V. Caspar, E. M. Kober, B. P. Sullivan and T. J. Meyer, *J. Am. Chem. Soc.*, 1982, **104**, 630–632.
- 88 J. V. Caspar and T. J. Meyer, *J. Phys. Chem.*, 1983, **87**, 952–957.
- 89 J. van Houten and R. J. Watts, *Inorg. Chem.*, 1978, **17**, 3381–3385.
- 90 B. Durham, J. V. Caspar, J. K. Nagle and T. J. Meyer, *J. Am. Chem. Soc.*, 1982, **104**, 4803–4810.
- 91 F. Barigelletti, A. Juris, V. Balzani, P. Belser and A. von Zelewsky, *Inorg. Chem.*, 1983, **22**, 3335–3339.
- 92 G. H. Allen, R. P. White, D. P. Rillema and T. J. Meyer, *J. Am. Chem. Soc.*, 1984, **106**, 2613–2620.
- 93 M. Maestri, N. Armaroli, V. Balzani, E. C. Constable and A. M. W. C. Thompson, *Inorg. Chem.*, 1995, **34**, 2759–2767.
- 94 M. Abrahamsson, M. Jäger, T. Österman, L. Eriksson, P. Persson, H.-C. Becker, O. Johansson and L. Hammarström, *J. Am. Chem. Soc.*, 2006, **128**, 12616–12617.
- 95 F. Schramm, V. Meded, H. Fliegl, K. Fink, O. Fuhr, Z. Qu, W. Klopffer, S. Finn, T. E. Keyes and M. Ruben, *Inorg. Chem.*, 2009, **48**, 5677–5684.
- 96 A. Breivogel, C. Kreitner and K. Heinze, *Eur. J. Inorg. Chem.*, 2014, **2014**, 5468–5490.
- 97 R. D. Gerardi, N. W. Barnett and S. W. Lewis, *Anal. Chim. Acta*, 1999, **378**, 1–41.
- 98 S. Ji, W. Wu, W. Wu, P. Song, K. Han, Z. Wang, S. Liu, H. Guo and J. Zhao, *J. Mater. Chem.*, 2010, **20**, 1953–1963.
- 99 F. G. Gao and A. J. Bard, *J. Am. Chem. Soc.*, 2000, **122**, 7426–7427.
- 100 H. J. Bolink, L. Cappelli, E. Coronado and P. Gaviña, *Inorg. Chem.*, 2005, **44**, 5966–5968.
- 101 H. J. Bolink, L. Cappelli, E. Coronado, M. Grätzel and M. K. Nazeeruddin, *J. Am. Chem. Soc.*, 2006, **128**, 46–47.
- 102 H. J. Bolink, L. Cappelli, E. Coronado, M. Grätzel, E. Ortí, R. D. Costa, P. M. Viruela and M. K. Nazeeruddin, *J. Am. Chem. Soc.*, 2006, **128**, 14786–14787.
- 103 X. Yang, D. Neher, D. Hertel and T. K. Däubler, *Adv. Mater.*, 2004, **16**, 161–166.
- 104 M. S. Lowry and S. Bernhard, *Chem. – Eur. J.*, 2006, **12**, 7970–7977.
- 105 Y. Chi and P.-T. Chou, *Chem. Soc. Rev.*, 2010, **39**, 638–655.
- 106 C.-H. Yang, M. Mauro, F. Polo, S. Watanabe, I. Muenster, R. Fröhlich and L. de Cola, *Chem. Mater.*, 2012, **24**, 3684–3695.
- 107 P. G. Bomben, K. C. D. Robson, P. A. Sedach and C. P. Berlinguette, *Inorg. Chem.*, 2009, **48**, 9631–9643.
- 108 T. Funaki, H. Funakoshi, O. Kitao, N. Onozawa-Komatsuzaki, K. Kasuga, K. Sayama and H. Sugihara, *Angew. Chem.*, 2012, **124**, 7646–7649, (*Angew. Chem., Int. Ed.*, 2012, **51**, 7528–7531).
- 109 C. Kreitner, A. K. Mengel, T. K. Lee, W. Cho, K. Char, Y. S. Kang and K. Heinze, *Chem. – Eur. J.*, 2016.
- 110 M. Beley, J. P. Collin and J. P. Sauvage, *Inorg. Chem.*, 1993, **32**, 4539–4543.
- 111 C. Patoux, J.-P. Launay, M. Beley, S. Chodorowski-Kimmes, J.-P. Collin, S. James and J.-P. Sauvage, *J. Am. Chem. Soc.*, 1998, **120**, 3717–3725.
- 112 W.-W. Yang, J. Yao and Y.-W. Zhong, *Organometallics*, 2012, **31**, 1035–1041.
- 113 C.-J. Yao, R.-H. Zheng, Q. Shi, Y.-W. Zhong and J. Yao, *Chem. Commun.*, 2012, **48**, 5680–5682.
- 114 C.-J. Yao, H.-J. Nie, W.-W. Yang, J.-Y. Shao, J. Yao and Y.-W. Zhong, *Chem. – Eur. J.*, 2014, **20**, 17466–17477.
- 115 J.-J. Shen and Y.-W. Zhong, *Sci. Rep.*, 2015, **5**, 13835.
- 116 Y.-W. Zhong, Z.-L. Gong, J.-Y. Shao and J. Yao, *Coord. Chem. Rev.*, 2016, **312**, 22–40.
- 117 B. Schulze, D. Escudero, C. Friebe, R. Siebert, H. Görls, S. Sinn, M. Thomas, S. Mai, J. Popp, B. Dietzek, L. González and U. S. Schubert, *Chem. – Eur. J.*, 2012, **18**, 4010–4025.
- 118 C. Kreitner, E. Erdmann, W. W. Seidel and K. Heinze, *Inorg. Chem.*, 2015, **54**, 11088–11104.
- 119 C. Kreitner and K. Heinze, *Dalton Trans.*, 2016, **45**, 5640–5658.
- 120 A. C. Benniston, G. Chapman, A. Harriman, M. Mehrabi and C. A. Sams, *Inorg. Chem.*, 2004, **43**, 4227–4233.
- 121 L. A. Fredin, M. Pápai, E. Rozsályi, G. Vankó, K. Wärnmark, V. Sundström and P. Persson, *J. Phys. Chem. Lett.*, 2014, **5**, 2066–2071.
- 122 L. L. Jamula, A. M. Brown, D. Guo and J. K. McCusker, *Inorg. Chem.*, 2014, **53**, 15–17.
- 123 A. K. C. Mengel, C. Förster, A. Breivogel, K. Mack, J. R. Ochsmann, F. Laquai, V. Ksenofontov and K. Heinze, *Chem. – Eur. J.*, 2015, **21**, 704–714.
- 124 K. A. King and R. J. Watts, *J. Am. Chem. Soc.*, 1987, **109**, 1589–1590.



- 125 P. Revecó, J. H. Medley, A. R. Garber, N. S. Bhacca and J. Selbin, *Inorg. Chem.*, 1985, **24**, 1096–1099.
- 126 E. C. Constable and J. M. Holmes, *J. Organomet. Chem.*, 1986, **301**, 203–208.
- 127 M. L. Muro-Small, J. E. Yarnell, C. E. McCusker and F. N. Castellano, *Eur. J. Inorg. Chem.*, 2012, **2012**, 4004–4011.
- 128 C. D. Ertl, D. P. Ris, S. C. Meier, E. C. Constable, C. E. Housecroft, M. Neuburger and J. A. Zampese, *Dalton Trans.*, 2015, **44**, 1557–1570.
- 129 P. G. Bomben, K. D. Thériault and C. P. Berlinguette, *Eur. J. Inorg. Chem.*, 2011, **2011**, 1806–1814.
- 130 E. Y. Li, Y.-M. Cheng, C.-C. Hsu, P.-T. Chou, G.-H. Lee, I.-H. Lin, Y. Chi and C.-S. Liu, *Inorg. Chem.*, 2006, **45**, 8041–8051.
- 131 M. Beley, J. P. Collin, R. Louis, B. Metz and J. P. Sauvage, *J. Am. Chem. Soc.*, 1991, **113**, 8521–8522.
- 132 E. C. Constable, A. M. W. C. Thompson and S. Greulich, *J. Chem. Soc., Chem. Commun.*, 1993, 1444–1446.
- 133 P. G. Bomben, B. D. Koivisto and C. P. Berlinguette, *Inorg. Chem.*, 2010, **49**, 4960–4971.
- 134 H. Kisserwan, A. Kamar, T. Shoker and T. H. Ghaddar, *Dalton Trans.*, 2012, **41**, 10643–10651.
- 135 Z. Ji, G. Natu, Z. Huang, O. Kokhan, X. Zhang and Y. Wu, *J. Phys. Chem. C*, 2012, **116**, 16854–16863.
- 136 I. M. Dixon, F. Alary and J.-L. Heully, *Dalton Trans.*, 2010, **39**, 10959–10966.
- 137 S. H. Wadman, M. Lutz, D. M. Tooke, A. L. Spek, F. Hartl, R. W. A. Havenith, G. P. M. van Klink and G. van Koten, *Inorg. Chem.*, 2009, **48**, 1887–1900.
- 138 F. Alary, J.-L. Heully, L. Bijeire and P. Vicendo, *Inorg. Chem.*, 2007, **46**, 3154–3165.
- 139 J.-L. Heully, F. Alary and M. Boggio-Pasqua, *J. Chem. Phys.*, 2009, **131**, 184308.
- 140 T. Guillon, M. Boggio-Pasqua, F. Alary, J.-L. Heully, E. Lebon, P. Sutra and A. Igau, *Inorg. Chem.*, 2010, **49**, 8862–8872.
- 141 R. D. Costa, E. Ortí, D. Tordera, A. Pertegás, H. J. Bolink, S. Graber, C. E. Housecroft, L. Sachno, M. Neuburger and E. C. Constable, *Adv. Energy Mater.*, 2011, **1**, 282–290.
- 142 F. Monti, A. Baschieri, I. Gualandi, J. J. Serrano-Pérez, J. M. Junquera-Hernández, D. Tonelli, A. Mazzanti, S. Muzzioli, S. Stagni, C. Roldan-Carmona, A. Pertegás, H. J. Bolink, E. Ortí, L. Sambri and N. Armaroli, *Inorg. Chem.*, 2014, **53**, 7709–7721.
- 143 S. Yi, J.-H. Kim, Y.-J. Cho, J. Lee, T.-S. Choi, D. W. Cho, C. Pac, W.-S. Han, H.-J. Son and S. O. Kang, *Inorg. Chem.*, 2016, **55**, 3324–3331.
- 144 I. Krivokapic, M. Zerara, M. L. Daku, A. Vargas, C. Enachescu, C. Ambrus, P. Tregenna-Piggott, N. Amstutz, E. Krausz and A. Hauser, *Coord. Chem. Rev.*, 2007, **251**, 364–378.
- 145 R. G. Miller, S. Narayanaswamy, J. L. Tallon and S. Brooker, *New J. Chem.*, 2014, **38**, 1932–1941.
- 146 J. P. Claude and T. J. Meyer, *J. Phys. Chem.*, 1995, **99**, 51–54.
- 147 N. H. Damrauer, T. R. Boussie, M. Devenney and J. K. McCusker, *J. Am. Chem. Soc.*, 1997, **119**, 8253–8268.
- 148 J. V. Caspar and T. J. Meyer, *J. Am. Chem. Soc.*, 1983, **105**, 5583–5590.
- 149 K.-C. Hwang, J.-L. Chen, Y. Chi, C.-W. Lin, Y.-M. Cheng, G.-H. Lee, P.-T. Chou, S.-Y. Lin and C.-F. Shu, *Inorg. Chem.*, 2008, **47**, 3307–3317.
- 150 S. H. Wadman, J. M. Kroon, K. Bakker, R. W. A. Havenith, G. P. M. van Klink and G. van Koten, *Organometallics*, 2010, **29**, 1569–1579.
- 151 B. Schulze, D. G. Brown, K. C. D. Robson, C. Friebe, M. Jäger, E. Birckner, C. P. Berlinguette and U. S. Schubert, *Chem. – Eur. J.*, 2013, **19**, 14171–14180.
- 152 C. Kreitner, M. Grabolle, U. Resch-Genger and K. Heinze, *Inorg. Chem.*, 2014, **53**, 12947–12961.
- 153 F. Barigelletti, P. Belser, A. von Zelewsky, A. Juris and V. Balzani, *J. Phys. Chem.*, 1985, **89**, 3680–3684.
- 154 A. J. Wilkinson, H. Puschmann, J. A. K. Howard, C. E. Foster and J. A. G. Williams, *Inorg. Chem.*, 2006, **45**, 8685–8699.
- 155 G. S. M. Tong, K. T. Chan, X. Chang and C.-M. Che, *Chem. Sci.*, 2015, **6**, 3026–3037.
- 156 A. Breivogel, C. Förster and K. Heinze, *Inorg. Chem.*, 2010, **49**, 7052–7056.
- 157 A. Breivogel, M. Meister, C. Förster, F. Laquai and K. Heinze, *Chem. – Eur. J.*, 2013, **19**, 13745–13760.
- 158 K. Heinze, K. Hempel and M. Beckmann, *Eur. J. Inorg. Chem.*, 2006, **2006**, 2040–2050.
- 159 I. M. Dixon, F. Alary, M. Boggio-Pasqua and J.-L. Heully, *Inorg. Chem.*, 2013, **52**, 13369–13374.
- 160 I. M. Dixon, S. Khan, F. Alary, M. Boggio-Pasqua and J.-L. Heully, *Dalton Trans.*, 2014, **43**, 15898–15905.
- 161 I. M. Dixon, F. Alary, M. Boggio-Pasqua and J.-L. Heully, *Dalton Trans.*, 2015, **44**, 13498–13503.
- 162 J. M. Patrick, A. H. White, M. I. Bruce, M. J. Beatson, D. C. St. Black, G. B. Deacon and N. C. Thomas, *J. Chem. Soc., Dalton Trans.*, 1983, 2121–2123.
- 163 M. I. Bruce, M. J. Liddell, G. N. Pain, M. A. Bennett and H. Neumann, *Inorg. Synth.*, 1989, **26**, 171–180.
- 164 K. C. D. Robson, B. D. Koivisto, A. Yella, B. Spornova, M. K. Nazeeruddin, T. Baumgartner, M. Grätzel and C. P. Berlinguette, *Inorg. Chem.*, 2011, **50**, 5494–5508.
- 165 K. C. D. Robson, B. D. Koivisto, T. J. Gordon, T. Baumgartner and C. P. Berlinguette, *Inorg. Chem.*, 2010, **49**, 5335–5337.
- 166 K. C. D. Robson, B. Spornova, B. D. Koivisto, E. Schott, D. G. Brown and C. P. Berlinguette, *Inorg. Chem.*, 2011, **50**, 6019–6028.
- 167 W. A. Herrmann and C. Köcher, *Angew. Chem.*, 1997, **109**, 2256–2282, (*Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 2162–2187).
- 168 Y.-M. Zhang, J.-Y. Shao, C.-J. Yao and Y.-W. Zhong, *Dalton Trans.*, 2012, **41**, 9280–9282.
- 169 F. Neese, *WIREs Comput. Mol. Sci.*, 2012, **2**, 73–78.
- 170 A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648–5652.



- 171 F. Neese, F. Wennmohs, A. Hansen and U. Becker, *Chem. Phys.*, 2009, **356**, 98–109.
- 172 R. Izsák and F. Neese, *J. Chem. Phys.*, 2011, **135**, 144105.
- 173 D. A. Pantazis, X.-Y. Chen, C. R. Landis and F. Neese, *J. Chem. Theory Comput.*, 2008, **4**, 908–919.
- 174 S. Sinnecker, A. Rajendran, A. Klamt, M. Diedenhofen and F. Neese, *J. Phys. Chem. A*, 2006, **110**, 2235–2245.
- 175 A. Schäfer, H. Horn and R. Ahlrichs, *J. Chem. Phys.*, 1992, **97**, 2571–2577.
- 176 A. Schäfer, C. Huber and R. Ahlrichs, *J. Chem. Phys.*, 1994, **100**, 5829–5835.

