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# Light Activated Release of Nitrile Ligands from trans-Ru(L)(PPh<sub>3</sub>)<sub>2</sub>(nitrile) Complexes

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**ABSTRACT**: A series of *trans*-RuL(PPh<sub>3</sub>)<sub>2</sub>(nitrile) and {RuL(PPh<sub>3</sub>)<sub>2</sub>}, - $\mu$ -(nitrile)-based complexes [where L = 2,2'-(3,4-diphenylpyrrole-2,5-diyl)dipyridine (dpp), di(pyridin-2-yl)isoindoline-1,3-diimine (bpi), or 4-(4-methoxyphenyl)-6-phenyl-2,2'-bipyridine (Pbpy); and nitrile = 1,4-dibenzontirile, 4-ethynylbenzonitrile, or dicyanamide] were synthesized and characterized, and their electrochemical and photochemical behaviors were investigated. Those complexes that contained a significant nitrile contribution to their <sup>3</sup>MLLCT show a release of their nitrile ligand (when L = dpp or Pbpy and the nitrile ligand = 4-dibenzontirile, or 4ethynylbenzonitrile) with dissociation constants up to  $8.09 \times 10^{-4} \text{ s}^{-1}$ 

#### INTRODUCTION

The ability to control the release of a ligand through the use of light has found a variety of applications including initiating catalysts and molecular logic gates,<sup>1,2</sup> particularly in the field of photoactivated chemotherapy.<sup>3,4</sup> In these applications, ligand liberation allows the free ligand to take part in further reactions, the loss of a ligand leaves a vacancy on the metal site making it accessible for further reactions, or it simply causes a change in the complex's physical behavior. One common aspiration of these applications is to design systems that require a minimal amount of energy to trigger ligand release, i.e., have light absorption at a longer wavelength. This reduces the chances of unintended reactions from occurring and allows for improved tissue penetration of the light source in the case of biological applications.

This project examines what combination of ligands could form a complex with absorption in the visible range that is still capable of photoactivated ligand release. Although complexes with a range of metal ions meeting many of these criteria exist, this work focused on ruthenium-based complexes,<sup>5</sup> of which some of the most prevalent are the ruthenium-nitrile family often consisting of pyridyl ligands (e.g., 2,2'-bipyridine or 2,2':6',2"-terpyridine) to generate <sup>1</sup>MLCT bands for photon absorption. The nitrile group coordinated to the ruthenium ion can be simple (e.g., acetonitrile or benzonitrile) or a drug made inert by the metal coordination (e.g., 5-cyanouracil).<sup>6,7</sup> Upon excitation, the former releases the nitrile ligand, and typically, in turn, the metal coordinates to a new ligand, often a solvent.

In this work, we explored the use of trans-RuL- $(PPh_3)_2$ (nitrile)-based complexes for photoreactivity, where L is the tridentate ligands di(pyridin-2-yl)isoindoline-1,3diimine (bpi), 2,5-di(pyridin-2-yl)-1H-pyrrole, and 6-phenyl-2,2'-bipyridine. Previous work using di(pyridin-2-yl)isoindoline-1,3-diimine (bpi) has shown that the RuL-(PPh<sub>3</sub>)<sub>2</sub>Cl complexes have particularly labile chlorides due to the trans-effect of the indolate,<sup>8</sup> suggesting that other ligands coordinated to this site may also be similarly labile. Additionally, each of the chosen ligands has been selected to produce transition-metal complexes with high extinction coefficient <sup>1</sup>MLCT bands extending well into the visible range. In principle, combining these features should result in the favorable release of the nitrile ligand.

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Figure 1. Schematic view of the complexes synthesized and used in this study.

### RESULTS AND DISCUSSION

Synthesis. In addition to the previously reported complexes trans-Ru(bpi)(PPh<sub>3</sub>)<sub>2</sub>Cl (Clb), two new trans- $Ru(L)(PPh_3)_2Cl$  complexes were synthesized, where L is 2,2'-(3,4-diphenyl-pyrrole-2,5-diyl)dipyridine (dppH)<sup>9</sup> or 4-(4methoxyphenyl)-6-phenyl-2,2'-bipyridine (PbpyH).<sup>10</sup> The complexes trans-Ru(dpp)(PPh<sub>3</sub>)<sub>2</sub>Cl (Cla) and trans-Ru- $(Pbpy)(PPh_3)_2Cl$  (Clc) were prepared by heating the respective ligand with cis-Ru(PPh)<sub>3</sub>Cl<sub>2</sub> in an ethanolic solution containing the base Et<sub>3</sub>N. The isolation of the pure compound was dependent upon the formation of crystals. Alternate 6phenyl-2,2'-bipyridine ligands were trialled for the synthesis of Clc analogues but could not be successfully purified as the most effective route for purification of these complexes is reliant on recrystallization, and it appears that the presence of a anisole group favors this. Attempts were also made to synthesize an 1,3-di(pyridin-2-yl)benzene ( $N \land C \land N$ ) analogue to Clc under identical reaction conditions using 2,2'-(4'methoxy-[1,1'-biphenyl]-3,5-diyl)dipyridine, but no evidence of product formation was observed.

Equipped with the precursors **Cla**, **Clb**, and **Clc**, each was reacted with either 0.5 or 5 eq of the chosen nitrile ligand (1,4-dibenzontirile, 4-ethynylbenzonitrile, or sodium dicyanamide) by heating in MeOH with  $NH_4PF_6$  as the halide abstractor, similar to the conditions used by Cordiner et al.<sup>11</sup> The

schematic structures of all synthesized complexes are detailed in Figure 1.

For both Cla and Clc, when an excess of the nitrile ligand was used, the corresponding monometallic complexes (1a, 2a, 3a, 1c, 2c, and 3c) were formed, with the nitrile ligand replacing the chloride. When 0.5 eq of the nitrile ligand was used, both 1,4-dibenzontirile and sodium dicyanamide formed bimetallic complexes (4a, 5a, 4c, and 5c) with the nitrile acting as a bridging ligand between the two ruthenium centers, see Figure 1. However, under the same conditions, 4-ethynylbenzonitrile only formed the monometallic complexes (2a and 2c) with only the nitrile group coordinating to the metal, with no evidence of vinylidene formation. The reaction was repeated with the addition of DBU as a base to promote acetylide formation from any transient vinylidenes formed, but again, no coordination via the terminal alkyne was observed. This finding suggests notably different behavior to RuCp(PPh<sub>3</sub>)<sub>2</sub> observed by Cordiner et al.<sup>11</sup>

When using **Clb** with excess nitrile ligand, only 4ethynylbenzonitrile formed a monometallic complex (2b), with the nitrile group coordinated to the ruthenium center, while 1,4-dibenzontirile and sodium dicyanamide both formed bimetallic complexes (4b and 5b). Upon repeating the reactions with 0.5 equiv, the same results were obtained, albeit with higher yields, suggesting that the using bpi ligand resulted in the bimetallic complexes being enthalpically favorable. As observed for the previous systems, even where the reaction was performed with DBU and 4-ethynylbenzonitrile, there was no evidence of coordination via the terminal alkyne. This contrasts with the propensity for acetylide formation with  $Ru(bpi)(PPh_3)_2Cl$ , as observed by Zhang.<sup>8</sup>

Molecular Structures. The structures of compounds 1a, 2a, 4a, 5a, 2b, 4b, 5b, 1c, 2c, 3c, 4c, 5c, Cla, and Clc were confirmed by SCXRD (CCDC 2205853–2205864, 2368041, and 2359149). Example structures of 3c, 4a, and 5b are shown in Figures 2–4, respectively (with the remaining structures



Figure 2. Crystal structure of 3c; solvent molecule, disorder removed for clarity, and thermal ellipsoids displayed at 50% probability.

shown in the Supporting Information). In all of the studied complexes, the central Ru atom adopts slightly distorted octahedral coordination with trans configuration of PPh<sub>3</sub> ligands. To date the CDS contains just one Ru complex, containing a heterocyclic N-coordinated ligand, a benzonitrile ligand, and two PPh<sub>3</sub> groups.<sup>12</sup> Neither the Ru– $N_{\text{nitrile}}$  nor C= N bond lengths show a variation associated with the tridentate ligand, the nitrile ligand, or a comparison between the monoand bimetallic complexes. This behavior is due to the poor mixing of the Ru(d) and nitrile  $(\pi)$  orbitals.<sup>11</sup> The orientation of the benzene ring connected to the nitrile group is noteworthy. In complexes with dpp and bpi ligands, this ring is almost coplanar with the plane of the heterocyclic ligand, while in complexes with the Pbpy ligand, these planes are nearly perpendicular to each other. Thus, most probably the "steric factors" between PPh<sub>3</sub> and NC-C<sub>6</sub>H<sub>4</sub> fragments are not



Figure 4. Crystal structure of 5b; solvent molecule, disorder removed for clarity; and thermal ellipsoids displayed at 50% probability.

the major contributors to the coplanar geometry. Interestingly, the central planar NCNCN fragment in **5c** is also significantly out of the plane of both chelate cycles (26.6 and 35.5°), while in **5a** and **5b**, the fragments are almost coplanar (see the Supporting Information). The chelate heterocycles of the two metal centers in **5c** are rotated by  $60.9(1)^\circ$ , and the corresponding values for **5a** and **5b** are 7.2(2) and  $17.8(1)^\circ$ , respectively. Thus, while the coordination geometry of the metal centers is similar for all of the studied complexes, the molecular geometries of the complexes with the Pbpy ligand are different from those with dpp and bpi ligands.

Electrochemistry. Cyclic voltammograms were recorded for all the complexes in 0.1 M tetrabutylammonium hexafluorophosphate (TBAPF<sub>6</sub>) in dichloromethane (DCM). All the bimetallic complexes (4a, 4b, 4c, 5a, 5b, and 5c) were additionally recorded in 0.1 M tetrabutylammonium tetrakis- $(3,5-bis(trifluoromethyl)phenyl)borate (TBArF_{24})$ . All measurements were referenced against an internal reference of ferrocene  $[E_{1/2} \text{ Fc/Fc}^+] = 0.00 \text{ V}$  (see Table 1). Each of the monometallic complexes 1a, 1c, 2a, 2b, 2c, 3a, 3c, Cla, Clb, and Clc had a single reversible oxidation event attributed to the Ru(II)/Ru(III) redox couple. Each of the complexes containing either 1,4-dibenzontirile or 4-ethynylbenzonitrile displayed a cathodic shift of 0.43-0.81 V relative to the respective parent chloride complexes Cla, Clb, and Clc. However, for the dicyanamide complexes (3a and 3c), the cathodic shifts were only 0.25 and 0.11 V, respectively, which can be attributed to the anionic nature of dicyanamide.



Figure 3. Crystal structure of 4a; solvent molecule, disorder removed for clarity, and thermal ellipsoids displayed at 50% probability.

Table 1. Electrochemical Data for the Reported Complexes

	$E_{1/2OX}$ (V)		$E_{1/20}$	<sub>X</sub> (V)
complex	TBAPF <sub>6</sub>	complex	$TBAPF_6$	TBArF <sub>24</sub>
Cla	-0.24	4a	0.32, 0.35	0.43
Clb	0.08	4b	0.54	0.63
Clc	-0.51	4c	0.27, 0.33	0.44
1a	0.32	5a	0.07	0.09, 0.24
1c	0.30	5b	0.27	0.29, 0.48
2a	0.28	5c	-0.16, -0.01	-0.12, -0.14
2b	0.51			
2c	0.28			
3a	0.01			
3c	-0.40			

The bimetallic complexes 4a and 4c each showed two oxidation events, separated by 0.03 and 0.06 V, respectively, with oxidation potentials near that of monometallic analogues 1a and 1c, while 4b demonstrated only a single oxidation wave. This suggests that complexes have negligible electronic coupling via the 1,4-dibenzontirile, i.e., each of the metal centers behave independently.

To examine whether any through space interactions were possible with these systems,  $\text{TBArF}_{24}$  was used as the electrolyte. Vincent et al. previously demonstrated that the use of such a large anion typically increases the separation of oxidation events linked by through-space interactions.<sup>13,14</sup> However, for **4a**, **4b**, and **4c**, only a single oxidation event was observed, confirming the absence of electronic coupling between the metal centers. This is consistent with density functional theory (DFT) predicting negligible contributions to the HOMO orbitals from 1,4-dibenzontirile and in line with observations made by Cordiner et al. for analogous RuCp-(PPh<sub>3</sub>)<sub>2</sub> systems.<sup>11</sup>

Complexes 5a and 5b showed only a single-step oxidation event, 5a having a similar oxidation potential to 3a, indicating a lack of electronic coupling between the metal centers. 5c showed a two-step oxidation separated by 150 mV, with the first oxidation 240 mv higher than its monometallic analogue 3c, indicative of electronic coupling. Similar behavior has been observed by Cordiner for RuCp(PPh<sub>3</sub>)<sub>2</sub>.<sup>11</sup> However, upon using the  $\text{TBArF}_{24}$  electrolyte, complexes 5a, 5b, and 5c displayed two-step oxidations separated by 150, 190, and 20 mV. This indicates that these systems are capable of throughspace interactions between the metal centers, which may not be surprising given the Ru-Ru distance of ca. 8.5 Å. Unfortunately, the oxidized complexes proved to be insufficiently stable for spectro-electrochemical measurement to be able to confirm the nature of the coupling, but the results are consistent with the low presence of dicyanamide character in the HOMOs described by DFT.

**Electronic Absorbance.** The UV–visible spectra of each of the complexes was recorded in acetonitrile and assigned using TD-DFT (see the Supporting Information for details). Each of the complexes displayed  $\pi \rightarrow \pi^*$  transitions,  $\lambda < 330$  nm and CT  $\lambda = 300-650$  nm. For the bpi complexes (2b, 4b, and 5b), the CT bands were attributed to <sup>1</sup>MLCT transitions, with the relevant HOMO orbitals consisting of ruthenium(d) character and LUMOs being significantly bpi in character. The CT transitions of the dicyanamide complexes (3a, 3c, 4a, and 4c) are assigned to be <sup>1</sup>MLLCT, with the relevant HOMOs containing varied contributions from ruthenium(d), the tridentate ligand ( $\pi$ ), and dicyanamide( $\pi$ ), while the LUMOs

contain negligible contribution from the dicyanamide. For 3a and 5a, the triphenylphosphine( $\pi^*$ ) orbitals contribute, while for 3c and 5c, the LUMOs are dominated by the bipyridine-( $\pi^*$ ) orbitals.

The dpp complexes with 1,4-dibenzontirile or 4-ethynylbenzonitrile (1a, 2a, and 4a) show similar CT bands for both the mono- and bimetallic analogues, with the most significant difference being that 4a has a  $\varepsilon$  approximately twice that of 1a and 2a, a result of orbital degeneracy. The CT band was determined to contain both <sup>1</sup>MLCT and <sup>1</sup>MLLCT transitions, with the relevant HOMOs containing varied combinations of ruthenium and pyrrole character, while the LUMOs were dominated by either 1,4-dibenzontirile or 4-ethynylbenzonitrile character.

The CT absorbance bands of the Pbpy 1c and 2c display little difference with a  $\lambda_{max} = 428$  nm; however, the bimetallic complex 4c had both the enhanced  $\varepsilon$  observed for the other complexes but also showed a significant red-shift of the CT band to  $\lambda_{max} = 507$  nm (see Figure 5). While the CT band can



Figure 5. UV-visible data for complexes 1c, 2c, 3c, 4c, and 5c were recorded in acetonitrile.

be assigned to <sup>1</sup>MLLCT for both mono- and bimetallic complexes, the orbital contributions are different. The relevant HOMOs for both sets of complexes are both ruthenium and phenylate in nature. The LUMOs of **1c** and **2c** contain a mixture of contributions from the bipyridine and nitrile ligand, while **4c** is exclusively localized to the 1,4-dibenzontirile ( $\pi^*$ ) orbitals.

Photodissociation. Based upon the work of Zhao, Respondek, and Sgambellone et al.,<sup>6,15,16</sup> when some ruthenium nitrile complexes are irradiated by visible light, the Ru-N<sub>nitrile</sub> bond dissociates releasing the free nitrile ligand. To examine the photodissociation behavior of the complexes, they were irradiated. To this end, solutions containing the respective complex in 0.1 M tetrabutylammonium chloride (TBACl) in anhydrous acetonitrile were degassed by three freeze-pump-thaw cycles. Each of the solutions were irradiated by a xenon lamp (300 W) with an UV cutoff filter. At the specified intervals, the UV-visible spectra of the solution were recorded. The dpp and Pbpy complexes with 1,4-dibenzontirile and 4-ethynylbenzonitrile (1a, 2a, 1c, 2c, 4a, and 4c) displayed a significant decrease in the <sup>1</sup>MLLCT band associated with the nitrile ligands (see example Figure 6), fitting the behavior reported by Respondek et al. for their

Article



Figure 6. UV-visible spectra of complex 4c irradiated with light at specified times.

Ru(2,2'-bpyridine)<sub>2</sub>(nitrile)<sub>2</sub> system.<sup>16</sup> By measuring the change in absorbance of these transitions, the dissociation constant  $(k_{\rm dis})$  was determined to be 2.3–8.0  $\times$  10<sup>-4</sup> s<sup>-1</sup> (summarized in Table 2), notably higher than that of Respondek's system  $k_{dis} = 2.3 - 2.8 \times 10^{-7} \text{ s}^{-1}$ .

Table 2. Ru-N<sub>nitrile</sub> Bond Dissociation Constants for Complexes 1a, 2a, 4a, 1c, 2c, and 4c

complex	$k_{ m dis}~(s^{-1}) imes 10^{-4}$	
1a	2.64	
2a	8.09	
4a	6.77	
1c	2.33	
2c	5.63	
4c	7.80	

The bpi complexes (2b, 4b, and 5b) displayed a decrease in absorbance in the region  $\lambda$  < 450 nm and an increase in the region  $\lambda > 600$  nm. Based on comparisons to the work of Zhang et al., this is more consistent with generation of a Ru(III) species, rather than the release of the nitrile ligand.<sup>8</sup> The dicyanamide complexes (3a, 3b, 5a, 5b, and 5c) displayed negligible differences, even after having been irradiated for over 1 h.

To further elucidate the behavior of the photodissociation and NMR study of the complexes 1a, 2a, 4a, 1c, 2c, and 4c, the photodissociation experiments were repeated in a solution of 0.1 M TBACl in CD<sub>3</sub>CN. For each complex, the "free" nitrile was observed; however, for the bimetallic complexes, 4a and 4c (see example Figure 7) were observed, no evidence of the monometallic analogues 1a and 1c was observed. This indicates that upon irradiation, both Ru-Nnitrile bonds dissociate simultaneously, which may account for the similar dissociation constants between the band monometallic complexes. Despite being performed in a TABCl solution, no signals relating to the chloride precursors (Cla and Clc) were observed rather it is most likely that the solvent (acetonitrile) occupying the vacant coordination site as Sgambellone et al. has observed.<sup>6</sup> In order to compare this, a TD-DFT comparison was made between the observed spectra and the corresponding acetonitrile complexes (CH<sub>3</sub>CN-a and

CH<sub>3</sub>CN). The calculated spectra provide a reasonable fit for the irradiation product (see the Supporting Information). However, upon further irradiation, an intractable mixture of species is formed, making it impossible to isolate the proposed acetonitrile complexes and suggests that they may not be stable.

DFT Calculations. To provide insights for the behavior of the complexes, calculations were performed to establish the energy associated with the nitrile dissociation. To this end, the a scan calculation was performed along the Ru-N<sub>nitirile</sub> bond sequentially increasing the distance until a length of 4 Å was achieved, a distance greater than the sum of Van der Waal radii of ruthenium and nitrogen (see the Supporting Information). Using this approach, we can observe that the energy difference ranges from 58.19 (4b) to 105.15 (3a) kJ mol<sup>-1</sup>, but there is no correlation between those that dissociate and the energy difference. Tu et al. determined that the Ru-Nnitrile bond dissociation is facilitated by the <sup>3</sup>MLCT states.<sup>17</sup> The  $S_0 \rightarrow T_n$ transitions were determined by using TD-DFT to calculate the energies of the lowest triplet states (see the Supporting Information). Although each of the transitions was determined to be CT in nature, no correlation between the T<sub>1</sub> energy and  $k_{\rm dis}$  was determined. However, both the T<sub>1-3</sub> states of the bpi and dicyanamide complexes were dominated by the tridentate ligand  $\pi^*$  orbitals, while the same triplet states for complexes 1a, 2a, 4a, 1c, 2c, and 4c were dominated by the respective nitrile ligand  $\pi^*$  orbitals, indicating that this is a requirement for the dissociation to occur. This was further examined by following the change in behavior for the T<sub>1</sub> transition as the ruthenium nitrile bond length was increased. This demonstrated a significant change in the  $T_1$  energy for 1a, 2a, 4a, 1c, 2c, and 4c as the length was increased coupled with the character of the transition changing from that of CT (involving the nitrile ligand) to metal centered (see Figure 8 and Supporting Information). However, the cyanamide and bpi complexes (2b, 4b, 5a, 5b, and 5c) each only displayed a modest change in energy, and the CT transition remained localized to the tridentate ligand system.

#### CONCLUSIONS

A series of mono- and bimetallic *trans*-RuL(PPh<sub>3</sub>)<sub>2</sub>(nitrile) complexes (where L = dpp, bpi, or Pbpy and nitrile = dicyanamide, 1,4-dibenzontirile or 4-ethynylbenzonitrile) were synthesized and characterized including X-ray crystallography. Through the use of electrochemistry, the metal centers of the bimetallic complexes were proven to be electronically independent, regardless of the tridentate ligand or nitrile used.

By studying the photodissociation behavior of this series, the crucial role of the ligand character in the triplet states was demonstrated. This shows that for effective photodissociation to occur, the triplet states must contain significant contributions from the nitrile ligand and that this can be regulated by both the choice of nitrile and complementary ligands in the complex. Due to the stability of these complexes in the dark, rapid dissociation, and modular construction, these systems will provide a useful construct for examining photoactivated ligand dissociation.

# MATERIALS AND METHODS

Instrumentation. Nuclear magnetic resonance (NMR) spectra were recorded in deuterated solvent solutions on a VNMRS-600 and VNMRS-700 spectrometer (Varian Tech-



Figure 7. <sup>1</sup>H NMR spectra of 4c; (a) before irradiation, (b) after irradiation for 60 s, and (c) 1c as a reference.



Figure 8. Plot of natural transition orbitals of 1c for  $S_0 \rightarrow T_1$  for Ru–N<sub>nitrile</sub> length: (a) 2.08 and (b) 3.80 Å.

nologies, Palo Alto, CA, USA) and were referenced against solvent resonances (<sup>1</sup>H, <sup>13</sup>C{<sup>1</sup>H}, <sup>31</sup>P{<sup>1</sup>H}), compressive sampling for all unstable compounds.<sup>6–8</sup> Electrospray mass spectra data were recorded on a TQD mass spectrometer

(Waters Ltd., UK) in acetonitrile; MALDI–TOF MS data were recorded on an Autoflex II TOF/TOF (Bruker Daltonics, Inc., Billerica, MA, USA), using a DCTB as the matrix. Vibrational data were recorded by using a PerkinElmer Spectrum Two FT-IT spectrometer. Microanalyses were performed by the Elemental Analysis Service, London Metropolitan University, UK or Elemental Microanalysis Service, Durham University, UK.

**General Details.** The compounds 4-(4-methoxyphenyl)-6phenyl-2,2'-bipyridine (PbpyH),<sup>10</sup> *cis*-Ru(PPh)<sub>3</sub>Cl<sub>2</sub>,<sup>18</sup> 2,2'-(3,4-diphenyl-1*H*-pyrrole-2,5-diyl)dipyridine (Hdpp),<sup>9</sup> *trans*-Ru(bpi)(PPh<sub>3</sub>)<sub>2</sub>Cl<sup>8</sup>, and 4-ethynylbenzonitrile<sup>19</sup> were prepared according to literature methods. All other chemicals were sourced from standard chemical suppliers.

Synthesis. Ru(dpp)(PPh<sub>3</sub>)<sub>2</sub>Cl (Cla). Cis-Ru(PPh<sub>3</sub>)<sub>3</sub>Cl<sub>2</sub> (1.28 g, 1.34 mmol) and Hdpp (0.5 g, 1.34 mmol) were added to ethanol (100 mL) and refluxed for 3 h before Et<sub>3</sub>N (20 mL) was added to the solution, and refluxing continued for an additional hour. The solution was cooled, forming a precipitate that was collected via filtration and thoroughly diluted with MeOH. The solid was purified via column silica chromatography eluted with neat DCM, collecting the orange band. The solvent was removed, leaving a solid that was washed with MeOH a final time, leaving a bright orange powder. Crystals were grown by layering MeOH onto a DCM solution. Yield: 1.14 g (80%). <sup>1</sup>H NMR (700 MHz; CD<sub>2</sub>Cl<sub>2</sub>):  $\delta_{\rm H}$  8.09 (dd,  ${}^{3}J_{\rm HH}$  = 5.7 Hz,  ${}^{4}J_{\rm HH}$  = 1.7 Hz, 2H, H<sub>a</sub>), 7.29–7.22 (m, 24H,  $H_f + H_g + H_h + H_j$ ), 7.12 (t,  ${}^{3}J_{HH} = 7.67$  Hz, 12H,  $H_i$ ), 6.97 (d,  ${}^{3}J_{HH}$  = 7.4 Hz, 4H,  $H_e$ ), 6.93 (ddd,  ${}^{3}J_{HH}$  = 8.5 Hz,  ${}^{3}J_{\rm HH} = 7.2$  Hz,  ${}^{4}J_{\rm HH} = 1.6$  Hz, 2H, H<sub>c</sub>), 6.75 (dd,  ${}^{3}J_{\rm HH} = 8.0$  Hz,  ${}^{4}J_{\rm HH}$  = 1.4 Hz, 2H, H<sub>d</sub>), 6.25 (ddd,  ${}^{3}J_{\rm HH}$  = 7.1 Hz,  ${}^{3}J_{\rm HH}$  = 5.5 Hz,  ${}^{4}J_{HH}$  = 1.4 Hz, 2H, H<sub>b</sub>) ppm.  ${}^{13}C{}^{1}H$  NMR (176 MHz;  $CD_2Cl_2$ ):  $\delta_C$  159.5, 157.5, 135.9, 135.4, 134.8, 133.9, 133.2, 132.1, 131.5, 128.7, 127.7, 127.4, 125.6, 119.3, 115.8 ppm. <sup>31</sup>P{<sup>1</sup>H} NMR (283 MHz;  $CD_2Cl_2$ ):  $\delta_P$  23.3 (s) ppm. Anal. Calc. for C<sub>62</sub>H<sub>48</sub>ClN<sub>3</sub>P<sub>2</sub>Ru: C, 72.05; H, 4.68; N, 4.07%. Found: C, 71.93; H, 4.61; N, 4.14%.<sup>a</sup>

*trans-Ru(PBpy)(PPh*<sub>3</sub>)<sub>2</sub>*Cl* (*Clc*). A suspension of PbpyH (1.00 g, 2.95 mmol), Ru(PPh<sub>3</sub>)<sub>3</sub>Cl<sub>2</sub> (2.83 g, 2.95 mmol), and Et<sub>3</sub>N (10 mL) in ethanol (150 mL) was refluxed under nitrogen for 16 h. The solvent was removed under vacuo, and the residue was passed through a silica plug, the red fraction was collected, and the solvent was removed. The solid was dissolved in a minimal amount of DCM, and then a layer of methanol (MeOH) was added before being refrigerated overnight, producing dark red crystals that were collected by filtration. Yield: 702 mg (23%).<sup>6</sup> MS (MALDI): m/z 998.3 [M]<sup>+</sup>, 736.1 [M-PPh<sub>3</sub>]<sup>+</sup>. Anal. Calc. for C<sub>59</sub>H<sub>47</sub>ClN<sub>2</sub>OP<sub>2</sub>Ru: C, 70.97; H, 4.74; N, 2.81%. Found: C, 70.66; H, 4.67; N, 2.73%.

trans- $[Ru(L)(PPh_3)_2(NC-R)]^{n+}$  General Synthesis. A suspension of trans-Ru(L)(PPh\_3)\_2Cl (1 equiv), nitrile (5 equiv), and NH<sub>4</sub>PF<sub>6</sub> (5 equiv) in MeOH (40 mL) was refluxed for 12 h. The solution was cooled to room temperature, and the precipitate was collected by filtration and washed thoroughly with MeOH. Final purification was achieved by crystallization. Full synthetic and characterization details are given in the Supporting Information.

 $[[trans-Ru(L)(PPh_3)_2]_2(\mu$ -NC-R-CN)]<sup>n+</sup> General Synthesis. A suspension of trans-Ru(L)(PPh\_3)\_2Cl (1 equiv), NC-R-CN (0.5 equiv), and NH<sub>4</sub>PF<sub>6</sub> (5 equiv) in MeOH (40 mL) was refluxed for 12 h. After cooling to room temperature, the precipitate was collected by filtration and thoroughly washed with MeOH. Final purification was achieved by crystallization. Full synthetic and characterization details are given in the Supporting Information.

**Electrochemistry.** Electrochemical analyses of the ruthenium complexes were carried out using a PalmSens EmStat<sup>2</sup> potentiometer, with platinum working, platinum counter, and platinum pseudo reference electrodes, from solutions in acetonitrile containing 0.1 M supporting electrolyte (tetrabutylammonium hexafluorophosphate, TBAPF<sub>6</sub>). All of the bimetallic complexes (**4a**, **4b**, **4c**, **5a**, **5b**, and **5c**) were additionally recorded in 0.1 M tetrabutylammonium tetrakis-(3,5-bis(trifluoromethyl)phenyl)borate (TBArF<sub>24</sub>). The ferrocene/ferrocenium couple was used as the internal reference.

**Electronic Absorbance.** The UV-visible spectra were obtained using an Unicam UV2-100 spectrometer operated with Unicam Vison software in quartz cuvettes with path length l = 1 cm. Solutions of the respective complexes in acetonitrile were prepared in the absence of light.

**Photodissociation.** To monitor the photodissociation of the complexes by electronic absorbance, a solution of the respective complex was prepared with 0.1 M TBACl in anhydrous acetonitrile and degassed by three freeze-pump-thaw cycles. Young's tap-modified quartz cuvettes with path length l = 1 cm were used for both irradiation and UV-visible absorbance measurements. Each of the solutions was irradiated by a xenon lamp (300 W) with an UV cutoff filter. At the specified intervals, the UV-visible spectrum of the solution was recorded by using an Unicam UV2-100 spectrometer operated with Unicam Vison software.

To monitor the photodissociation of the complexes by NMR, a solution of the respective complex was prepared with 0.1 M TBACl in  $CD_3CN$  and degassed by three freeze–pump–thaw cycles. Young's NMR tubes were used for both irradiation and UV–visible absorbance measurements. Each of the solutions was irradiated by a xenon lamp (300 W) with an UV cutoff filter. At the specified intervals, the <sup>1</sup>H and <sup>31</sup>P NMR spectra of the solution were recorded using a Varian VNMRS-600 spectrometer and referenced against solvent resonances.<sup>c</sup>

**DFT Calculations.** DFT calculations were carried out using the Gaussian 09 package (Gaussian, Inc.).<sup>20</sup> All results were displayed using GaussView<sup>21</sup> and GaussSum.<sup>22</sup> All calculations used the B3LYP level set employing a 6-31G(d)/LANL2DZ basis set, geometrically optimized in a acetonitrile solvent field using the SCRF-PCM method, where available initial structures were based on crystallographic data. Frequency calculations were performed on each of the structures to confirm that a minimum has been reached. TD-DFT calculations were performed on the geometrically optimized structures using the same method.

### ASSOCIATED CONTENT

#### **1** Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.4c04917.

Experimental procedures, NMR spectra, photophysical data, and computational details (PDF)

Crystallographic data (CIF)

DFT optimized structures (XYZ)

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#### Notes

The authors declare no competing financial interest.

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# ADDITIONAL NOTES

<sup>a</sup>No identifiable ions were observed using MALDI or ES.

<sup>b</sup>Recorded NMR spectra gave broad unresolved signals (see Figure S4a,b) on both 400 and 600 MHz NMR indicating ligand (likely PPh<sub>3</sub>) dissociation in solution and making signal assignment impossible.

<sup>c</sup>Complex 4a's low solubility in CD<sub>3</sub>CN gave a poor signal-tonoise ratio, preventing the measurement.

# REFERENCES

(1) Wenger, O. S. Photoactive Nickel Complexes in Cross-Coupling Catalysis. *Chem.*—*Eur. J.* **2021**, *27* (7), 2270–2278.

(2) G, U. R.; Axthelm, J.; Hoffmann, P.; Taye, N.; Gläser, S.; Görls, H.; Hopkins, S. L.; Plass, W.; Neugebauer, U.; Bonnet, S.; Schiller, A. Co-Registered Molecular Logic Gate with a CO-Releasing Molecule Triggered by Light and Peroxide. *J. Am. Chem. Soc.* **2017**, *139* (14), 4991–4994.

(3) Bonnet, S. Why Develop Photoactivated Chemotherapy? *Dalton Trans.* **2018**, 47 (31), 10330–10343.

(4) White, J. K.; Schmehl, R. H.; Turro, C. An Overview of Photosubstitution Reactions of Ru(II) Imine Complexes and their Application in Photobiology and Photodynamic Therapy. *Inorg. Chim. Acta* **2017**, *454*, 7–20.

(5) Chen, Y.; Bai, L.; Zhang, P.; Zhao, H.; Zhou, Q. The Development of Ru(II)-Based Photoactivated Chemotherapy Agents. *Molecules* **2021**, *26* (18), 5679.

(6) Sgambellone, M. A.; David, A.; Garner, R. N.; Dunbar, K. R.; Turro, C. Cellular Toxicity Induced by the Photorelease of a Caged Bioactive Molecule: Design of a Potential Dual-Action Ru(II) Complex. J. Am. Chem. Soc. **2013**, 135 (30), 11274–11282.

(7) Garner, R. N.; Gallucci, J. C.; Dunbar, K. R.; Turro, C.  $[\text{Ru}(\text{bpy})_2(5\text{-cyanouracil})_2]^{2+}$  as a Potential Light-Activated Dual-Action Therapeutic Agent. *Inorg. Chem.* **2011**, *50* (19), 9213–9215.

(8) Zhang, D.-B.; Wang, J.-Y.; Wen, H.-M.; Chen, Z.-N. Electrochemical, Spectroscopic, and Theoretical Studies on Diethynyl Ligand Bridged Ruthenium Complexes with 1,3-Bis(2-pyridylimino)isoindolate. *Organometallics* **2014**, 33 (18), 4738–4746.

(9) McSkimming, A.; Diachenko, V.; London, R.; Olrich, K.; Onie, C. J.; Bhadbhade, M. M.; Bucknall, M. P.; Read, R. W.; Colbran, S. B. An Easy One-Pot Synthesis of Diverse 2,5-Di(2-pyridyl)pyrroles: A Versatile Entry Point to Metal Complexes of Functionalised, Meridial and Tridentate 2,5-Di(2-pyridyl)pyrrolato Ligands. *Chem.—Eur. J.* 2014, 20 (36), 11445–11456.

(10) Patel, M. N.; Bhatt, B. S.; Dosi, P. A. Spectroscopic Study of DNA Hydrolysis, DNA Intercalative, and Electrostatic Interaction Activity Exerted by Drug Based Coordination Compounds. *Z. Anorg. Allg. Chem.* **2012**, 638 (1), 152–162.

(11) Cordiner, R. L.; Albesa-Jové, D.; Roberts, R. L.; Farmer, J. D.; Puschmann, H.; Corcoran, D.; Goeta, A. E.; Howard, J. A. K.; Low, P. J. Syntheses and Molecular Structures of Group 8 Benzonitrile Complexes. J. Organomet. Chem. **2005**, 690 (21–22), 4908–4919.

(12) Oyama, D.; Fukuda, A.; Yamanaka, T.; Takase, T. Facile and Selective Synthetic Approach for Ruthenium Complexes Utilizing a Molecular Sieve Effect in the Supporting Ligand. *Inorganics* **2013**, *1* (1), 32–45.

(13) Vincent, K. B.; Gluyas, J. B. G.; Gückel, S.; Zeng, Q.; Hartl, F.; Kaupp, M.; Low, P. J. Tetrakis(ferrocenylethynyl)ethene: Synthesis, (Spectro)electrochemical and Quantum Chemical Characterisation. *J. Organomet. Chem.* **2016**, *821*, 40–47.

(14) Barrière, F.; Camire, N.; Geiger, W. E.; Mueller-Westerhoff, U. T.; Sanders, R. Use of Medium Effects to Tune the  $\Delta E_{1/2}$  Values of Bimetallic and Oligometallic Compounds. *J. Am. Chem. Soc.* **2002**, 124 (25), 7262–7263.

(15) Zhao, J.; Liu, N.; Sun, S.; Gou, S.; Wang, X.; Wang, Z.; Li, X.; Zhang, W. Light-Activated Ruthenium (II)-Bicalutamide Prodrugs for Prostate Cancer. *J. Inorg. Biochem.* **2019**, *196*, 110684.

(16) Respondek, T.; Garner, R. N.; Herroon, M. K.; Podgorski, I.; Turro, C.; Kodanko, J. J. Light Activation of a Cysteine Protease Inhibitor: Caging of a Peptidomimetic Nitrile with  $Ru^{II}(bpy)_2$ . J. Am. Chem. Soc. **2011**, 133 (43), 17164–17167.

(17) Tu, Y.-J.; Mazumder, S.; Endicott, J. F.; Turro, C.; Kodanko, J. J.; Schlegel, H. B. Selective Photodissociation of Acetonitrile Ligands in Ruthenium Polypyridyl Complexes Studied by Density Functional Theory. *Inorg. Chem.* **2015**, *54* (16), 8003–8011.

(18) Fox, M. A.; Harris, J. E.; Heider, S.; Pérez-Gregorio, V.; Zakrzewska, M. E.; Farmer, J. D.; Yufit, D. S.; Howard, J. A. K.; Low, P. J. A Simple Synthesis of trans-RuCl(CCR)(dppe)<sub>2</sub> Complexes and Representative Molecular Structures. *J. Organomet. Chem.* **2009**, 694 (15), 2350–2358.

(19) Janka, M.; Anderson, G. K.; Rath, N. P. Synthesis of Neutral Molecular Squares Composed of Bis(phosphine)platinum Corner Units and Dialkynyl Linkers. Solid-State Characterization of  $[Pt(\mu-C:C:C)(dppp)]_4$ . Organometallics **2004**, 23 (19), 4382–4390.

(20) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A.; Peralta, J. J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, J. M.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, Ö.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. Gaussian 09, A.1; Gaussian, Inc.: Wallingford CT, 2009.

(21) Dennington, R.; Keith, T.; Millam, J. *GaussView*. Version 5; Semichem Inc.: Shawnee Mission KS, 2009.

(22) O'Boyle, N. M.; Tenderholt, A. L.; Langner, K. M. cclib: A Library for Package-Independent Computational Chemistry Algorithms. J. Comput. Chem. 2008, 29 (5), 839–845.