ORGANOMETALLICS

Article

pubs.acs.org/Organometallics

Rational Synthesis of Heteroleptic Tris(chelate) Ruthenium Complexes [Ru^{II}(2-Ph-2′-Py)(L^L)(L′^L′)]PF$_6$ by Selective Substitution of the Ligand Trans to the Ruthenated Phenyl Ring

Bastien Boff,[†] Moussa Ali,[†] Larissa Alexandrova,[‡] Noel Ángel Espinosa-Jalapa,[§] Rafael Omar Saavedra-Díaz,[§] Ronan Le Lagadec,*[,§] and Michel Pfeffer*[,†]

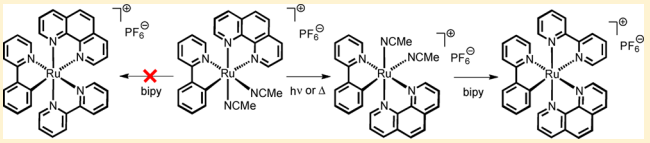
[†]Laboratoire de Synthèses Métallo-Induites of the Institut de Chimie, UMR 7177, CNRS, Université de Strasbourg, 4, rue Blaise Pascal, 67000 Strasbourg, France

[‡]Instituto de Investigaciones en Materiales, UNAM, Circuito Exterior s/n, Ciudad Universitaria, Mexico, D. F., 04510, Mexico

[§]Instituto de Química, UNAM, Circuito Exterior s/n, Ciudad Universitaria, Mexico, D. F., 04510, Mexico

Supporting Information

ABSTRACT: [Ru(N^N)(MeCN)$_2$(2-Ph-2′-Py)]PF$_6$ (2-Ph-2′-Py = ortho-metalated 2-phenylpyridine, N^N = phenanthroline, 2,2′-bipyridine), in which one of the nitrogens of the N^N ligand is bound to Ru trans to the phenyl unit of 2-PhPy, were slowly isomerized (2 days) in refluxing 1,1-dichloroethane/MeCN (9/1) or more rapidly (although with a reduced yield) in the presence of UV light, to afford compounds in which the same N atom was bound to Ru trans to the pyridine of 2-PhPy; these new compounds, in opposition to their well-known isomers, proved to be nicely reactive toward substitution reactions of the MeCN ligands, by other bidentate N-containing ligands such as 4,4′-R$_2$-2,2′-bipyridine (R = H, OMe, COOH) and 4,7-dimethyl-1,10-phenanthroline. These results question the exact structure of the already reported heteroleptic tris(chelate) Ru^{II} complexes obtained from the same starting material in which the incoming bidentate ligands were incorrectly believed to be bound to the Ru atom at positions trans to N atoms.



INTRODUCTION

Cycloruthenated 2-phenylpyridine derivatives[1] have been found to be very interesting organometallic synthons, as many independent studies have shown them to be key ligands in different organometallic molecules that display properties for several applications such as electronic relays for redox enzymes,[2] as photosensitizers for photovoltaic applications[3] or for their in vitro and in vivo cytotoxicities that might be useful for cancer treatments.[4] The molecules that proved recently to be quite interesting ones were those compounds in which the ruthenium center was bound to three bidentate chelates, i.e. the ortho-metalated 2-PhPy ligand (C^N), associated with 2 other chelating N^N ligands; when these latter ligands are different from one another (N^N ≠ N′^N′), this led to heteroleptic [Ru(N^N)(N′^N′)(C^N)]$^+$ complexes.[2a,5] However, no satisfactory rational synthesis of such compounds is known and the aim of this paper is to propose a solution for this. We have discovered a somewhat unexpected behavior of [Ru(N^N)(MeCN)$_2$(2-Ph-2′-Py)]$^+$, which questions the structures of the few heteroleptic compounds obtained so far.[2a,5]

RESULTS AND DISCUSSION

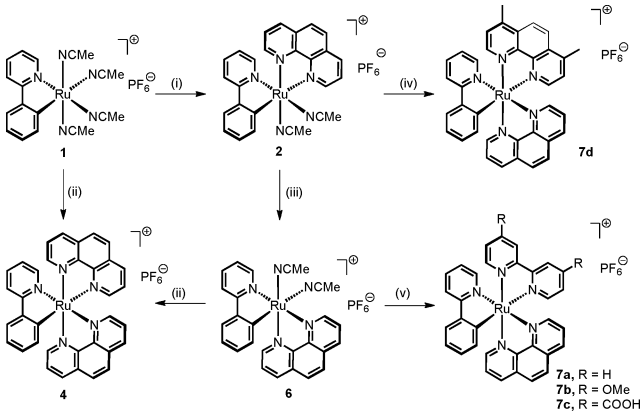
The cycloruthenation of 2-phenylpyridine is well-known, and many routes to its achievement are known.[1] The way via [(η^6-benzene)RuCl$_2$]$_2$ in the presence of a base (NaOH) and KPF$_6$ and in MeCN is among the most used routes, as it afforded good yields of [Ru(MeCN)$_4$(2-Ph-2′-Py)]PF$_6$ (**1**). The η^6-benzene was readily substituted by MeCN at the reaction temperature (45 °C), in marked opposition to the η^6-*p*-cymene, which was not substituted even at refluxing MeCN temperature combined with UV irradiation. The substitution on compound **1** of the four MeCN ligands by two bidentate ligands (N^N) such as phenanthroline (Phen) and 2,2′-bipyridine (Bipy) was problematic, as two different compounds were obtained in competitive reactions. In the case of a 1:1 Ru:N^N stoichiometry, two MeCN ligands only were substituted, leading to [Ru(N^N)(MeCN)$_2$(2-Ph-2′-Py)]PF$_6$ (**2**, N^N = Phen; **3**, N^N = Bipy), where one of the N atoms of N^N is trans to the C−Ru bond,[2c] whereas when a 1:2 Ru:N^N stoichiometry was applied, [Ru(N^N)$_2$(2-Ph-2′-Py)]PF$_6$ (**4**, N^N = Phen; **5**, N^N = Bipy) were obtained in good yield as well (Scheme 1).[2a]

We have long been convinced that **2** could not be an intermediate for the formation of **4**, because when we added a second equivalent of Phen to **2**, we failed to obtain **4**. On the other hand, **3** led to the formation of either **5** or to heteroleptic Ru tris(chelates) by addition of another bidentate ligand[2a,5] (see below) and thus displays, apparently, a different chemistry than **2**. While this paper was in preparation, Turro et al. published a spectroscopic reinvestigation of **2**[6] and found that,

Received: June 25, 2013
Published: August 29, 2013

   dx.doi.org/10.1021/om400611t | *Organometallics* 2013, 32, 5092−5097

Scheme 1. [a]



[a]Reaction conditions: (i) Phen 1 equiv, MeCN, 12 h, room temperature; (ii) Phen 2 equiv, MeOH, reflux, 24 h; (iii) CH_2Cl_2/MeCN or 1,1′-$C_2H_4Cl_2$/MeCN (9/1), reflux, 4 or 2 days, or acetone/MeCN (7/3), room temperature, UV (5.5 W), 2 h; (iv) 4,7-Me_2Phen 1 equiv, CH_2Cl_2, room temperature, UV (5.5 W), 1 h, 40%, or 4,7-Me_2Phen 1 equiv, CH_2Cl_2/MeCN (9/1), reflux, 12 h, 40%; (v) 4,4′-R_2bipyridine, MeOH, reflux, 12 h.

under UV irradiation, the MeCN ligands could be substituted either by chloride or by one phenanthroline ligand. This result was in line with our previous observations that we have made years ago[2c] and that established the photolability of the acetonitrile ligands versus methanol or water. However, the obtained compounds were never unambiguously characterized, and the aim of the present paper is to show that, in contrast to what was believed, **2** and **3** display the same substitution chemistry and that it is not as straightforward as was anticipated. Indeed, on the basis of the results described in this paper, it is reasonable to think that the proposed mechanism and the stereochemistry assigned to the obtained compounds, where the incoming ligands just replaced the coordinated acetonitrile molecules, should be re-evaluated.

We have now discovered that **2** was in fact metastable, as it could be slowly isomerized by a simple thermal treatment in a neutral solvent such as dichloromethane or 1,1′-dichloroethane, in the presence of 0.1 equiv of MeCN. Thus, such solutions of **2**, in those solvents at reflux temperature for 3 or 2 days, respectively, afforded a mixture of two products in the ratio 9:1 in which the minor species is **2** and the major species is a new isomer of **2**, namely **6**. The most characteristic features of the ^{1}H NMR spectrum of **6** were the appearance at rather high field (6.0−6.75 ppm) of three signals corresponding to three aromatic protons that were assigned by 2D H−H correlations to the three adjacent protons of the ortho-ruthenated phenyl unit.

The photolability of the MeCN ligands[2c] has recently been used for synthetic purposes.[7] Interestingly, the isomerization of **2** to **6** could also be performed under photochemical conditions in acetone or MeCN under the irradiation of a 5.5 W UV lamp or visible light (150 W lamp from a fiber optic illuminator). However, when the reaction was monitored by ^{1}H NMR, we noticed that the conversion from **2** to **6** was not complete. For instance, after 2 h of irradiation by visible light in acetone, only about 30% of isomer **2** was converted into **6**, while under UV irradiation the conversion was 70% of **6** (with 30% of **2** remaining) at the same reaction time. Longer irradiation times only slightly improved the yield of **6**, as some decomposition started to occur after 3−4 h of reaction. Conversions were lower when acetonitrile was used as the solvent. However, slightly better yields were achieved in a 7:3 acetone:acetonitrile mixture (80% of **6** after 2 h under UV irradiation).

The structure of **6** was ascertained by an X-ray diffraction study on a single crystal; the cationic part of the molecule is presented in Figure 1, and selected bond distances and angles

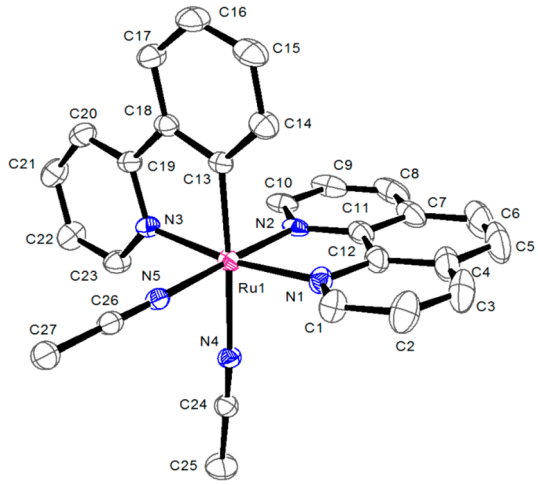


Figure 1. ORTEP view of the cationic part of **6**. Ellipsoids are drawn at a probability level of 50%. Atoms of hydrogen and the PF_6 anion have been omitted for the sake of clarity.

and details of the X-ray structure determination are given in Tables 1 and 2, respectively. The Ru−N4 vs Ru−N5 bond

Table 1. Selected Distances (Å) and Angles (deg) for Crystal Structures

	6		7d
C13−Ru1	2.026(2)	C27−Ru	2.030(5)
N1−Ru1	2.059(2)	N1−Ru	2.071(5)
N2−Ru1	2.042(2)	N10−Ru	2.123(5)
N3−Ru1	2.069(2)	N11−Ru	2.071(4)
N4−Ru1	2.145(2)	N20−Ru	2.052(5)
N5−Ru1	2.037(2)	N21−Ru	2.069(4)
C13−Ru1−N3	80.11(9)	C27−Ru−N21	79.77(19)
N1−Ru1−N2	80.43(8)	N1−Ru−N10	77.8(2)
N4−Ru1−N5	87.69(8)	N11−Ru−N20	79.3(2)

distances (2.145/2.037 Å) are well in line with those found in related molecules and in which MeCN ligands were bonded trans to the carbon and to the nitrogen atoms of the 2-Ph-2′-Py that have large and weak trans influences, respectively (in **2**, where the acetonitrile is trans either to a phenanthroline or a pyridine nitrogen atom, these Ru−N distances were 1.989(5) and 2.002(4) Å, respectively).[2c,4b] It is also apparent from this figure that the ortho proton of the phenyl unit of the ortho-ruthenated 2-phenyl-2′-pyridine is located in the anisotropic region of one pyridinic unit of the phenanthroline, i.e., N1,C1−C4,C12, thus explaining the considerable high-field shift observed for three protons of the ruthenated phenyl ring mentioned above.

In opposition to **2**, compound **6** proved to be rather reactive, as it decomposed quickly (after less than 5 min) in pure CH_2Cl_2, leaving a black intractable residue. It was, however,

dx.doi.org/10.1021/om400611t | Organometallics 2013, 32, 5092−5097

Table 2. Details for the X-ray Crystal Structure Determination

	6	7d
chem formula	$C_{27}H_{22}N_5Ru\cdot F_6P$	$4(C_{37}H_{28}N_5Ru)\cdot 4(F_6P)\cdot CH_2Cl_2$
formula mass/amu	662.54	3239.66
cryst syst	triclinic	monoclinic
a/Å	8.8218(8)	27.441(2)
b/Å	11.8264(10)	14.3073(11)
c/Å	13.2444(12)	18.6044(14)
α/deg	90.326(2)	90.00
β/deg	103.054(2)	96.6210(10)
γ/deg	103.578(2)	90.00
unit cell vol/Å^3	1305.9(2)	7255.5(10)
temp/K	173(2)	298(2)
space group	$P\bar{1}$	$C2/c$
no. of formula units per unit cell, Z	2	2
no. of rflns measd	17847	29524
no. of indep rflns	6843	6643
R_{int}	0.0292	0.0757
final R1 value ($I > 2\sigma(I)$)	0.0347	0.0568
final wR2(F^2) value ($I > 2\sigma(I)$)	0.0749	0.1149
final R1 value (all data)	0.0532	0.1100
final wR2(F^2) value (all data)	0.0829	0.1304

reasonably stable in any solution, provided that MeCN was present as a cosolvent. Its ^{1}H NMR spectrum in CD_3CN revealed that one CH_3CN was coordinated to the Ru (at 2.28 ppm), whereas the second CH_3CN appeared at 1.96 ppm, i.e. close to the resonance for noncoordinated MeCN.

This behavior is obviously due to the large trans effect of the σ-bonded carbon atom of the 2-Ph-2′-Py ligand, which destabilizes the MeCN ligand trans to it, thus allowing its substitution even by weak nucleophiles. Gratifyingly, **6** could also be used for achieving the coordination of a second N^N bidentate ligand, affording a convenient and efficient route under mild reaction conditions to good yields of cationic heteroleptic tris-bidentate ruthenium(II). Thus, compounds **7a−c** were obtained with reasonable yields and purity. An alternative reaction protocol made use of the fast isomerization reaction of **2** under UV light. When a mixture of **2** and 4,7-dimethyl-1,10-phenanthroline in CH_2Cl_2 was irradiated (5.5 W UV lamp) at room temperature for 1 h, [Ru(phen)(4,7-Me_2-phen)(2-Ph-2′-Py)]PF_6 (**7d**) could be isolated in 42% yield after purification by column chromatography. X-ray diffraction studies revealed a stereochemical arrangement similar to that of compounds **7a−c**. It is indeed at once apparent that one of the N atoms of the phen ligand has migrated trans to the N atom of the 2-PhPy ligand. The greater Ru−N10 bond distance (2.123(5) Å) versus those of the other Ru−N bonds (2.05−2.07 Å) here also reflects the significant trans influence of the ruthenated phenyl group of the 2-Ph-2′-Py ligand.

It thus seems that the UV-assisted coordination of the 4,7-Me_2Phen on **2** is more likely to be the result of the isomerization of **2** to **6** followed by the substitution of the MeCN, rather than the labilization of the MeCN ligands by UV. A similar result was obtained while treating **2** in the presence of 4,7-dimethyl-1,10-phenanthroline in CH_2Cl_2:MeCN (10:1) solvent at reflux temperature, as the same compound **7d**, also identified by its crystal structure analysis (Figure 2), was obtained in ca. 40% yields after 12 h.

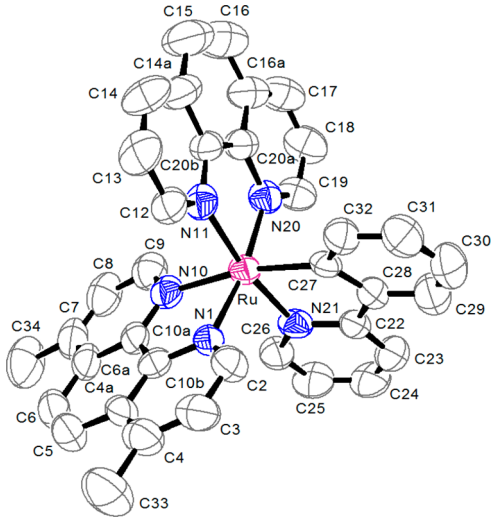


Figure 2. ORTEP view of the cationic part of **7d**. Ellipsoids are drawn at a probability level of 50%. Atoms of hydrogen and the PF_6 anion have been omitted for the sake of clarity.

The thermal isomerization of **2** was also conducted in the strict absence of light ($C_2H_4Cl_2$:MeCN 9:1, 70 °C, 2 days), and we observed exactly the same isomer ratio **2**:**6** (10:90) as above. This result clearly proves that the isomerization process is indeed induced photochemically *or* thermally. Another important feature of the reaction is the need to have a coordinating solvent for the reaction to occur. Indeed, when the reaction was performed in $C_2H_4Cl_2$ or acetone (room temperature, UV (5.5 W), 2 h), isomer **6** was formed in minute amounts, as we observed mainly decomposition of the organoruthenium species. This behavior is in line with that of **6**, whose complete decomposition in pure CH_2Cl_2 has been described above. This reactivity of **6** is indeed astonishing, as it contradicts somehow the fact that **2** is the kinetic (but stable) isomer, whereas **6** is the thermodynamic (but unstable) isomer. However, this latter comportment is only due to the lability of the MeCN ligand trans to C that can be easily displaced by weakly coordinating solvents such as CH_2Cl_2; this reaction destabilizes **6**, as the ruthenium center is electron deficient.

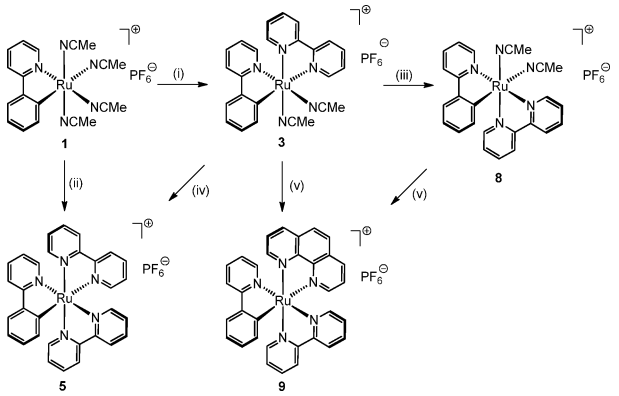
The reactivity of **3** was, at first sight, different from that of **2** because this compound has been previously successfully used for the synthesis of heteroleptic tris-chelate ruthenium(II) derivatives.[2a,5] We have, however, now observed that, as for **2**, **3** could be slowly isomerized under thermal conditions to afford **8**. **8** could then lead to **9** by substitution of both MeCN by phenanthroline.

We checked that, 2,2′-bipyridine or phenanthroline could indeed be coordinated to the ruthenium center from **3** (reactions iv and v in Scheme 2). However, the structure of **9** that was obtained through this reaction was exactly the same as that of **9** obtained from **8** via route v, as proven by their spectroscopic data. They are indeed both different from that of **7a** obtained by treating **6** with bipy, as evidenced by its NMR data and 2D NMR assignment.

Thus, the behavior of **3** is in fact similar to that of **2**, as the coordination of a phen ligand from **2** or **3** must have occurred through the decoordination of the N atom of the Phen or the bipy chelates trans to C. We thus believe that all the heteroleptic compounds that were obtained previously via **3** by us or other colleagues should have a structure similar to that of **9**: i.e., the incoming N^N ligands did not just simply

dx.doi.org/10.1021/om400611t | *Organometallics* 2013, 32, 5092−5097

Scheme 2. [a]



[a]Reaction conditions: (i) Bipy 1 equiv, CH_2Cl_2, 20 h, room temperature; (ii) Bipy 2 equiv, CH_2Cl_2, 20 h, reflux; (iii) CH_2Cl_2/MeCN (9/1) reflux, 48 h; (iv) Bipy 1 equiv, MeOH, reflux, 12 h; (v) Phen 1 equiv, MeOH, reflux, 12 h.

substitute the two MeCN ligands but were coordinated trans to the C atom of the cyclometalated ligand. This result ascertains our previous observations that the two MeCN ligands of these compounds are strongly bound to the Ru atom and that they should not be considered as good leaving groups.

One point about the mechanism of the isomerization of **2** or **3** deserves to be discussed in detail. The apparent thermal stability of **2** toward substitution of the two MeCN ligands militates in favor of the nonlabilization of these ligands while they are trans to N (of a pyridine or a phenanthroline). Thus, the first step of the thermal or photo reaction of **2** or **3** is very likely to be the cleavage of the N−Ru bond trans to the ruthenated phenyl ring, this leading to Ru(κ^1-phenanthroline) or Ru(κ^1-bipyridine) units, respectively. We have not been able to isolate any intermediate species en route to either **6** or **8**. We believe, however, that after the N−Ru cleavage has occurred it is very likely that a MeCN coordinates to the Ru center, hence stabilizing it, and that the κ^1-phenanthroline or the κ^1-bipyridine should then recoordinate their second N atom to the Ru center trans to the pyridine of the cyclometalated 2-Ph-2′-Py ligand. About the question raised as to whether two isomers could be formed by addition of a bidentate ligand on **2** or **3**, the fact that one isomer was exclusively obtained is a strong indication that only one coordination site should be available on the ruthenium center, this being the position trans to the carbon atom.

CONCLUSION

In this paper we have demonstrated that compounds of the general formula $[Ru(C^\wedge N)(N^\wedge N)(MeCN)_2]PF_6$ may indeed lead to heteroleptic compounds such as $[Ru(C^\wedge N)(N^\wedge N)(N'^\wedge N')]PF_6$ (C^N, N^N, and N′^N′ being three different bidentate anionic or neutral ligands). However, in contrast to what was believed, the structures of the resulting heteroleptic Ru tris-adducts are not simply the results of the substitution of the MeCN ligands by N′^N′ in the starting material, because a rearrangement of the precursor occurred in such a way that the incoming N′^N′ has substituted the N^N ligand, one of its N′ atoms being trans to the carbon atom. Thus, it seems that the driving force for the coordination of the third bidentate ligand to Ru is mainly due to the huge trans effect of the σ-bonded C atom rather than to the (supposed) lability of the MeCN ligands.

It thus appears from this study that the MeCN ligand is a poor leaving group when coordinated trans to an imine ligand but is a good leaving group only when it is coordinated trans to a strong trans effect ligand such as a phenyl group.

EXPERIMENTAL SECTION

General Remarks. Experiments were carried out under an argon atmosphere using a vacuum line. Diethyl ether and pentane were distilled over sodium/benzophenone, dichloromethane and acetonitrile over calcium hydride, and methanol and ethanol over magnesium under argon immediately before use. Chromatography columns were carried out on Merck aluminum oxide 90 standardized. The other starting materials were purchased from Sigma Aldrich, Alfa Aesar, or Strem Chemicals and used as received without further purification.

Ruthenium complexes listed hereafter were synthesized following reported procedures: $[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(NCMe)_4]PF_6$ (**1**),[8] $[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(phen)(NCMe)_2]PF_6$ (**2**),[2c] $[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(bpy)(NCMe)_2]PF_6$ (**3**),[2c] $[Ru(2\text{-}C_6H_4\text{-}2'\text{-}Py\text{-}\kappa C,N)(phen)_2]PF_6$ (**4**),[2a] and $[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(bipy)_2]PF_6$ (**5**).[2a]

The NMR spectra were obtained at room temperature on Bruker or JEOL spectrometers. ^1H NMR spectra were recorded at 300.13 MHz (AC-300), 300.53 MHz (GX300), or 400.13 MHz (AM-400) and referenced to $SiMe_4$. $^{13}C\{^1H\}$ NMR spectra were recorded at 75.48 MHz (AC-300), 75.56 MHz (GX300), or 100.62 MHz (AC-400) and referenced to $SiMe_4$. The NMR assignments were supported by COSY spectra for ^1H NMR. The chemical shifts are referenced to the residual solvent peak. Chemical shifts (δ) and coupling constants (J) are expressed in ppm and Hz, respectively. Multiplicity: s = singlet, d = doublet, t = triplet, q = quadruplet, m = multiplet.

The infrared spectra were recorded on an Alpha ATR spectrometer from Bruker Optics and analyzed with OPUS software. UV/vis spectra (absorption spectroscopy) were recorded with a Kontron Instruments UVIKON 860 spectrometer at room temperature.

ES-MS spectra and elemental analyses were carried out by the corresponding facilities at the Institut de chimie, Université de Strasbourg, or at the Instituto de Química, UNAM.

$[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(phen)(NCMe)_2]PF_6$ (6). A solution of **2** (100 mg, 151 mmol) in a 10/1 dichloromethane/acetonitrile mixture (15 mL) was refluxed for 72 h. After reduction of the volume, the solution was immediately filtered through Al_2O_3 using a 90/10 CH_2Cl_2/NCMe mixture as eluent. The dark purple fraction was collected and evaporated to dryness under vacuum. Flash chromatography in CH_2Cl_2/MeCN (9/1) allowed the elimination of the remaining **2**. Crystallization from dichloromethane/pentane gave dark purple microcrystals (80 mg, 80%), which were washed with pentane and dried under vacuum.

Anal. Calcd for $C_{27}H_{22}F_6N_5PRu$: C, 48.95; H, 3.35; N, 10.57. Found: C, 48.45; H, 3.40; N, 10.45. MS (ES, m/z): calcd for $C_{25}H_{19}N_4{}^{101}Ru$ (**6** − MeCN) 477.07 (M), found 477.06. IR (cm^{-1}): 2287 (weak, $\nu_{N\equiv C}$), 830 (strong, ν_{PF}), 562 (medium, δ_{PF}). ^1H NMR (400 MHz, CD_3CN, 300 K): 9.61 (d, 1H, $^3J_{HH}$ = 4.9), 9.25 (d, 1H, $^3J_{HH}$ = 5.3), 8.55 (d, 1H, $^3J_{HH}$ = 8.1), 8.20 (d, 1H, $^3J_{HH}$ = 8.1), 8.12 (d, 1H, $^3J_{HH}$ = 8.9), 8.05 (d, 1H, $^3J_{HH}$ = 8.1), 8.00−7.96 (m, 2H), 7.91 (t, 1H, $^3J_{HH}$ = 7.6), 7.87 (d, 1H, $^3J_{HH}$ = 5.0), 7.69 (d, 1H, $^3J_{HH}$ = 7.8), 7.41−7.36 (m, 2H), 6.68 (t, 1H, $^3J_{HH}$ = 7.3), 6.47 (t, 1H, $^3J_{HH}$ = 7.3), 6.02(d, 1H, $^3J_{HH}$ = 7.6), 2.28 (s, 3H), 1.97 (s, 3H). $^{13}C\{^1H\}$ NMR (100.62 MHz, CD_3CN, 300 K): 186.1, 168.2, 153.05, 153.0, 152.0, 149.6, 149.3, 147.6, 137.0, 136.5, 134.2, 131.2, 130.7, 129.0, 128.8, 128.6, 128.45, 128.4, 128.2, 126.3, 125.4, 124.5, 123.1, 121.5, 120.0, 4.5, 1.4

$[Ru(2\text{-}C_6H_4\text{-}2'\text{-}py\text{-}\kappa C,N)(phen)(bpy)]PF_6$ (7a). A solution of **6** (100 mg, 0.151 mmol) with 2,2′-bipyridine (24 mg, 0.151) in methanol (10 mL) was refluxed for 24 h. The solvent was evaporated under vacuum, and the dark residue was dissolved in 10 mL of CH_2Cl_2 and filtered through Al_2O_3 using a 10/1 CH_2Cl_2/NCMe mixture as eluent. The purple fraction was collected and evaporated to dryness under vacuum. Crystallization from CH_2Cl_2/pentane gave dark red

dx.doi.org/10.1021/om400611t | Organometallics 2013, 32, 5092−5097

crystals, which were washed with diethyl ether and dried under vacuum (100 mg, 90%).

Anal. Calcd for $C_{33}H_{24}F_6N_5PRu$: C, 53.81; H, 3.28; N, 9.51. Found: C, 53.32; H, 3.37; N, 9.24. MS (ES, *m/z*): calcd for $C_{33}H_{24}N_5{}^{102}Ru$ 592.1075 (M), found 592.11. ^{1}H NMR (500 MHz, CD_3CN, 300 K): 8.45 (d, 1H, $^3J_{HH}$ = 8.2), 8.41 (d, 1H, $^3J_{HH}$ = 8.2), 8.37 (d, 1H, $^3J_{HH}$ = 8.1), 8.31 (d, 1H, $^3J_{HH}$ = 8.1), 8.18 (d, 1H, $^3J_{HH}$ = 5.6), 8.13 (d, 1H, $^3J_{HH}$ = 5.3), 8.11−8.04 (m, 4H), 7.94−7.90 (m, 1H), 7.87−7.82 (m, 2H), 7.75−7.69 (m, 3H), 7.59−7.55 (m, 2H), 7.26−7.24 (m, 2H), 6.98 (t, 1H, $^3J_{HH}$ = 6.2), 6.82 (t, 1H, $^3J_{HH}$ = 7.3), 6.65 (t, 1H, $^3J_{HH}$ = 7.3), 6.17 (d, 1H, $^3J_{HH}$ = 7.3 Hz). $^{13}C\{^1H\}$ NMR (125 MHz, CD_3CN, 300 K): 193.8, 168.7, 159.0, 156.3, 155.6, 151.7, 151.4, 150.4, 149.1, 148.7, 146.7, 137.3, 136.8, 136.4, 136.0, 133.8, 133.6, 131.4, 129.4, 128.63, 128.61, 127.9, 127.2, 126.4, 126.1, 125.1, 124.5, 124.2, 123.3, 121.8, 119.9.

[Ru(2-C_6H_4-2′-py-*κC,N*)(phen)(4,4′-dimethoxy-2,2′-bipyridine)]PF_6 (7b). A solution of **6** (100 mg, 0.151 mmol) with 4,4′-dimethoxy-2,2′-bipyridine (33 mg, 0.151) in methanol (10 mL) was refluxed for 24 h. The solvent was evaporated under vacuum, and the dark residue was dissolved in 10 mL of CH_2Cl_2 and filtered through Al_2O_3 using a 10/2 CH_2Cl_2/NCMe mixture as eluent. The purple fraction was collected and evaporated to dryness under vacuum. Crystallization from CH_2Cl_2/pentane gave dark red crystals, which were washed with diethyl ether and dried under vacuum (102 mg, 85%).

Anal. Calcd for $C_{35}H_{28}F_6N_5O_2PRu$: C, 52.77; H, 3.54; N, 8.79. Found: C, 52.19; H, 3.64; N, 8.88. MS (ES, *m/z*): calcd for $C_{35}H_{28}N_5O_2{}^{102}Ru$ 652.1286 (M), found 652.12. ^{1}H NMR (500 MHz, CD_3CN, 300 K): 8.34 (d, 1H, $^3J_{HH}$ = 7.9), 8.25 (d, 1H, $^3J_{HH}$ = 8.1), 8.16 (d, 1H, $^3J_{HH}$ = 5.1), 8.12 (d, 1H, $^3J_{HH}$ = 5.1), 8.09−8.02 (m, 3H), 7.97−7.95 (m, 2H), 7.87 (d, 1H, $^3J_{HH}$ = 6.5), 7.82 (d, 1H, $^3J_{HH}$ = 7.8), 7.78 (d, 1H, $^3J_{HH}$ = 5.4), 7.74−7.70 (m, 1H), 7.59 (dd, 1H, $^3J_{HH}$ = 8.1, $^4J_{HH}$ = 5.4), 7.53−7.49 (m, 2H), 6.99 (t, 1H, $^3J_{HH}$ = 6.7), 6.87 (dd, 1H, $^3J_{HH}$ = 6.6, $^4J_{HH}$ = 2.8), 6.82 (dd, 1H, $^3J_{HH}$ = 6.6, $^4J_{HH}$ = 2.8), 6.76 (t, 1H, $^3J_{HH}$ = 7.2), 6.61 (t, 1H, $^3J_{HH}$ = 7.2), 6.12 (d, 1H, $^3J_{HH}$ = 7.2), 3.96 (s, 3H), 3.93 (s, 3H). $^{13}C\{^1H\}$ NMR (125 MHz, CD_3CN, 300 K): 168.6, 167.4, 167.7, 159.8, 157.5, 155.9, 151.9, 151.6, 151.5, 151.3, 149.4, 149.3, 147.1, 136.7, 136.4, 133.1, 132.9, 131.4, 129.0, 128.58, 128.55, 126.3, 125.9, 124.9, 123.2, 121.7, 119.7, 114.2, 113.9, 111.3, 110.8, 57.34, 57.29

[Ru(2-C_6H_4-2′-py-*κC,N*)(phen)([2,2′-bipyridine]-4,4′-dicarboxylic acid)]PF_6 (7c). A degassed aqueous MeOH solution (5 mL, H_2O/MeOH, 1/4 v/v) containing [2,2′-bipyridine]-4,4′-dicarboxylic acid (37 mg, 0.150 mmol) and crushed NaOH (12 mg, 0.30 mmol) was stirred for 40 min prior to the addition of **6** (100 mg, 0.151 mmol). The solution was brought to reflux overnight and cooled to room temperature followed by the removal of solvent in vacuo. The resultant product was reconstituted in H_2O followed by the dropwise addition of 0.2 M HPF_6 until the formation of a precipitate was observed. The powder thus obtained was washed with water and dissolved in MeOH, and the solution was filtered on a Büchner funnel (porosity 4) to remove unreacted dicarboxylic acid. Crystallization from MeOH/Et_2O gave dark red crystals, which were washed with diethyl ether and dried under vacuum (111 mg, 90%).

Anal. Calcd for $C_{35}H_{24}F_6N_5O_4PRu$: C, 50.98; H, 2.93; N, 8.49. Found: C, 50.55; H, 2.83; N, 8.57. MS (ES, *m/z*): calcd for $C_{35}H_{24}N_5O_4{}^{102}Ru$ 680.0872 (M), found 680.09. ^{1}H NMR (500 MHz, DMSO-d_6, 300 K): 9.09 (s, 1H), 9.04 (s, 1H), 8.16 (d, 1H, $^3J_{HH}$ = 5.1), 8.55−8.52 (m, 2H), 8.22−8.17 (m, 4H), 8.03 (t, 1H, $^3J_{HH}$ = 5.0), 7.89 (d, 1H, $^3J_{HH}$ = 7.8), 7.81−7.68 (m, 6H), 7.58 (d, 1H, $^3J_{HH}$ = 5.3), 7.07 (t, 1H, $^3J_{HH}$ = 6.5), 6.80 (t, 1H, $^3J_{HH}$ = 6.9), 6.63 (t, 1H, $^3J_{HH}$ = 7.2), 6.04 (d, 1H, $^3J_{HH}$ = 7.2). $^{13}C\{^1H\}$ NMR (125 MHz, DMSO-d_6, 300 K): 192.1, 166.8, 165.5, 165.5, 158.0, 155.0, 154.4, 150.2, 150.0, 149.1, 147.0, 146.5, 144.9, 136.2, 134.5, 133.3, 133.2, 129.9, 129.8, 128.3, 127.6, 127.5, 126.6, 125.7, 125.5, 125.3, 124.2, 122.8, 122.7, 122.6, 120.7, 119.0.

[Ru(2-C_6H_4-2′-py-*κC,N*)(phen)(4,7-Me_2Phen)]PF_6 (7d). A solution of **2** (100 mg, 0.151 mmol) and 4,7-dimethyl-1,10-phenanthroline (35 mg, 0.168 mmol) in 12 mL of CH_2Cl_2 was placed in a Ace microphotochemical quartz reactor and irradiated (5.5 W Ace microphotochemical UV lamp) at 25 °C for 1 h. The solvent was evaporated to dryness and the residue purified through Al_2O_3 using a 95/5 CH_2Cl_2/NCMe mixture as eluent. The dark purple fraction was collected and evaporated to dryness under vacuum. Crystallization from dichloromethane/ether gave dark purple crystals, which were washed with diethyl ether and dried under vacuum (50 mg, 42%).

Anal. Calcd for $C_{37}H_{28}F_6N_5PRu{\cdot}0.5CH_2Cl_2$: C, 54.19; H, 3.52; N, 8.43. Found: C, 54.02; H, 3.72; N, 8.44. ^{1}H NMR (300 MHz, CD_3CN, 300 K): 8.36−8.27 (m, 6H), 8.11 (s, 2H), 8.06 (d, 1H, $^3J_{HH}$ = 9), 7.98 (d, 1H, $^3J_{HH}$ = 6), 7.94 (d, 1H, $^3J_{HH}$ = 6), 7.88 (d, 1H, $^3J_{HH}$ = 9), 7.68 (t, 1H, $^3J_{HH}$ = 9), 7.63 (m, 2H), 7.48−7.42 (m, 3H), 6.91−6.82 (m, 2H), 6.73 (t, 1H, $^3J_{HH}$ = 6), 6.32 (d, 1H, $^3J_{HH}$ = 9), 2.87 (s, 3H), 2.85 (s, 3H). $^{13}C\{^1H\}$ NMR (75 MHz, CD_3CN, 300 K): 193.6, 168.2, 154.8, 151.4, 151.1, 150.8, 149.8, 149.1, 148.7, 148.5, 146.4, 145.9, 144.7, 136.1, 136.0, 132.9, 132.8, 130.9, 130.8, 130.7, 129.3, 128.8, 128.1, 128.0, 127.2, 126.8, 126.5, 125.6, 125.5, 124.6, 124.3, 124.5, 122.6, 121.2, 119.2, 18.5, 18.42.

[Ru(2-C_6H_4-2′-py-*κC,N*)(bipy)$(NCMe)_2$]PF_6 (8). A solution of **3** (100 mg, 0.157 mmol) in a 10/1 dichloromethane/acetonitrile mixture (15 mL) was refluxed for 48 h. After reduction of the volume, the solution was immediately filtered through Al_2O_3 using a 90/10 CH_2Cl_2/NCMe mixture as eluent. The dark purple fraction was collected and evaporated to dryness under vacuum. Crystallization from dichloromethane/pentane gave dark purple microcrystals (80 mg, 80%), which were washed with pentane and dried under vacuum. Compound **3** was always contaminated by ca. 10% of **5** that could not be removed either from **3** or from **8**; hence, no combustion analyses of **8** were performed.

IR (cm^{-1}): 2285 (weak, $\nu_{N\equiv C}$), 830 (strong, ν_{PF}), 562 (medium, ν_{PF}). ^{1}H NMR (500 MHz, CD_3CN, 300 K): 9.38 (d, 1H, $^3J_{HH}$ = 5.4), 8.45 (d, 1H, $^3J_{HH}$ = 8.2), 8.22 (d, 2H, $^3J_{HH}$ = 7.6), 8.17 (td, 1H, $^3J_{HH}$ = 7.9, $^4J_{HH}$ = 1.7), 7.91 (d, 1H, $^3J_{HH}$ = 5.7), 7.87−7.83 (m, 3H), 7.67 (td, 1H, $^3J_{HH}$ = 7.9, $^4J_{HH}$ = 1.7), 7.54 (td, 1H, $^3J_{HH}$ = 7.8, $^4J_{HH}$ = 1.6), 7.46 (d, 1H, $^3J_{HH}$ = 5.7), 7.26 (td, 1H, $^3J_{HH}$ = 7.3, $^4J_{HH}$ = 1.4), 7.07 (td, 1H, $^3J_{HH}$ = 7.3, $^4J_{HH}$ = 1.3), 7.00 (td, 1H, $^3J_{HH}$ = 6.5, $^4J_{HH}$ = 1.4), 6.74 (td, 1H, $^3J_{HH}$ = 6.5, $^4J_{HH}$ = 1.4), 2.22 (s, 3H), 1.99 (s, 3H). $^{13}C\{^1H\}$ NMR (125 MHz, CD_3CN, 300 K): 193.1, 169.7, 160.1, 156.5, 155.7, 155.7, 151.9, 151.3, 146.8, 139.0, 137.7, 136.7, 136.1, 129.4, 128.0, 126.2, 124.9, 123.9, 123.8, 122.2, 121.6, 119.0, 4.5, 4.2

[Ru(2-C_6H_4-2′-py-*κC,N*)(phen)(bipy)]PF_6 (9). A solution of **8** (100 mg, 0.157 mmol) with 1,10-phenanthroline (28 mg, 0.157) in methanol (10 mL) was refluxed for 24 h. The solvent was evaporated under vacuum, and the dark residue was dissolved in 10 mL of CH_2Cl_2 and the solution filtered through Al_2O_3 using a 10/1 CH_2Cl_2/NCMe mixture as eluent. The purple fraction was collected and evaporated to dryness under vacuum. Crystallization from CH_2Cl_2/pentane gave dark red crystals, which were washed with diethyl ether and dried under vacuum (104 mg, 90%). As was the case for **8**, **9** was contaminated by 10% of **5**; therefore, no combustion analyses of **9** were performed.

MS (ES, *m/z*): calcd for $C_{33}H_{24}N_5{}^{102}Ru$: 592.1075 (M), found 592.11.^{1}H NMR (500 MHz, CD_3CN, 300 K): 8.53 (dd, 1H, $^3J_{HH}$ = 8.2, $^3J_{HH}$ = 1.3), 8.36−8.29 (m, 4H), 8.24 (dd, 1H, $^3J_{HH}$ = 4.9, $^3J_{HH}$ = 1.6), 8.14 (dd, 2H, $^3J_{HH}$ = 12.6, $^3J_{HH}$ = 8.8), 7.99 (d, 1H, $^3J_{HH}$ = 8.2), 7.92 (d, 1H, $^3J_{HH}$ = 5.9), 7.87 (d, 1H, $^3J_{HH}$ = 8.0), 7.81 (t, 1H, $^3J_{HH}$ = 7.7), 7.77 (d, 1H, $^3J_{HH}$ = 8.2), 7.76 (d, 1H, $^3J_{HH}$ = 8.1), 7.61 (t, 1H, $^3J_{HH}$ = 7.7), 7.55 (dd, 1H, $^3J_{HH}$ = 8.1, $^3J_{HH}$ = 8.0), 7.53 (d, 1H, $^3J_{HH}$ = 5.9), 7.41 (d, 1H, $^3J_{HH}$ = 6.0), 7.25 (td, 1H, $^3J_{HH}$ = 6.6, $^4J_{HH}$ = 1.3), 7.04 (td, 1H, $^3J_{HH}$ = 6.6, $^4J_{HH}$ = 1.3), 6.93 (td, 1H, $^3J_{HH}$ = 7.5, $^4J_{HH}$ = 1.4), 6.88 (td, 1H, $^3J_{HH}$ = 7.5, $^4J_{HH}$ = 1.4), 6.75 (td, 1H, $^3J_{HH}$ = 6.6, $^4J_{HH}$ = 1.3), 6.53 (d, 1H,, $^3J_{HH}$ = 7.4). $^{13}C\{^1H\}$ NMR (125 MHz, CD_3CN, 300 K): 193.5, 168.4, 158.0, 157.9, 155.6, 151.55, 151.50, 151.3, 150.7, 149.8, 147.2, 146.9, 136.7, 136.6, 136.4, 135.1, 134.8, 134.7, 131.8, 131.6, 129.5, 128.8, 128.7, 127.2, 127.1, 126.9, 126.2, 125.2, 124.1, 124.0, 123.9, 123.2, 121.9, 119.8.

dx.doi.org/10.1021/om400611t | *Organometallics* 2013, 32, 5092−5097

■ ASSOCIATED CONTENT

Supporting Information

CIF files giving detailed experimental procedures, characterization data, and crystallographic details for complexes **6** and **7d**. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: M.P., pfeffer@unistra.fr; R.L.L, ronan@unam.mx.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The Laboratory of Excellence (LABEX) "Chemistry of Complex Systems" (UdS), the FRC (UdS) through the project "synergie", DGAPA (PAPIIT IN204812), and CONACyT (153151) are thanked for partial support of this work. Lydia Brelo and Corinne Bailly (UdS) and Simón Hernández-Ortega (UNAM) are gratefully acknowledged for determining the crystal structures of compounds **6** and **7d**, respectively.

■ REFERENCES

(1) Djukic, J.-P.; Sortais, J.-B.; Barloy, L.; M. Pfeffer, M. *Eur. J. Inorg. Chem.* **2009**, 817−853.

(2) (a) Ryabov, A. D.; Sukharev, V. S.; Alexandrova, L.; Le Lagadec, R.; Pfeffer, M. *Inorg. Chem.* **2001**, *40*, 6529−6532. (b) Alpeeva, I. S.; Soukharev, V. S.; Alexandrova, L.; Shilova, N. V.; Bovin, N. V.; Csöregi, E.; Ryabov, A. D.; Sakharov, I. Yu. *J. Biol. Inorg. Chem.* **2003**, *8*, 683−688. (c) Ryabov, A. D.; Le Lagadec, R.; Estevez, H.; Toscano, R. A.; Hernandez, S.; Alexandrova, L.; Kurova, V. S.; Fischer, A.; Sirlin, C.; Pfeffer, M. *Inorg. Chem.* **2005**, *44*, 1626−1634. (d) Ryabov, A. D.; Kurova, V. S.; Ivanova, E. V.; Le Lagadec, R.; Alexandrova, L. *Anal. Chem.* **2005**, *77*, 1132−1139. (e) Le Lagadec, R.; Alexandrova, L.; Estevez, H.; Pfeffer, M.; Laurinavicius, V.; Razumiene, J.; Ryabov, A. D. *Eur. J. Inorg. Chem.* **2006**, 2735−2738. (f) Kurzeev, S. A.; Vilesov, A. S.; Fedorova, T. V.; Stepanova, E. V.; Koroleva, O. V.; Bukh, C.; Bjerrum, M. J.; Kurnikov, I. V.; Ryabov, A. D. *Biochemistry* **2009**, *48*, 4519−4527.

(3) (a) Wadman, S. H.; Kroon, J. M.; Bakker, K.; Lutz, M.; Spek, A. L.; van Klink, G. P. M.; van Koten, G. *Chem. Commun.* **2007**, 1907. (b) Bomben, P. G.; Robson, K. C. D.; Bryan, D.; Koivisto, B. D.; Berlinguette, C. P. *Coord. Chem. Rev.* **2012**, *256*, 1438−1450 and references cited. therein.

(4) (a) Gaiddon, C.; Jeannequin, P.; Bischoff, P.; Pfeffer, M.; Sirlin, C.; Loeffler, J. P. *J. Pharmacol. Exp. Ther.* **2005**, *315*, 1403−1411. (b) Leyva, L.; Sirlin, C.; Rubio, L.; Franco, C.; Le Lagadec, R.; Spencer, J.; Bischoff, P.; Gaiddon, C.; Loeffler, J. P.; Pfeffer, M. *Eur. J. Inorg. Chem.* **2007**, 3055−3066. (c) Meng, X.; Leyva, M. L.; Jenny, M.; Gross, I.; Benosman, S.; Fricker, B.; Harlepp, S.; Hebraud, P.; Boos, A.; Wlosik, P.; Bischoff, P.; Sirlin, C.; Pfeffer, M.; Loeffler, J. P.; Gaiddon, C. *Cancer Res.* **2009**, *69*, 5458−5466. (d) Fetzer, L.; Boff, B.; Ali, M.; Xiangjun, M.; Collin, J.-P.; Sirlin, C.; Gaiddon, C.; Pfeffer, M. *Dalton Trans.* **2011**, *40*, 8869−8878. (e) Bergamo, A.; Gaiddon, C.; Schellens, J. H.; Beijnen, J. H.; Sava, G. *J. Inorg. Biochem.* **2012**, *106*, 90−99. (f) Vidimar, V.; Meng, X.; Klajner, M.; Licona, C.; Fetzer, L.; Harlepp, S.; Hébraud, p.; Sidhoum, M.; Sirlin, C.; Loeffler, J. P.; Mellitzer, G.; Sava, G.; Pfeffer, M.; Gaiddon, C. *Biochem. Pharmacol.* **2012**, *84*, 1428−1436.

(5) (a) Bomben, P. G.; Thériault, K. D.; Berlinguette, C. P. *Eur. J. Inorg. Chem.* **2011**, 1806−1814. (b) Bomben, P. G.; Gordon, T. J.; Schott, E.; Curtis, P.; Berlinguettec, C. P. *Angew. Chem., Int. Ed.* **2011**, *50*, 10682−10685. (c) Peña, B.; Leed, N. A.; Dunbar, K. R.; Turro, C. *J. Phys. Chem. C* **2012**, *116*, 22186−22195. (d) Pogozhev, D. V.; Bezdek, M. J.; Schauer, P. A.; Berlinguette, C. P. *Inorg. Chem.* **2013**, *52*, 3001−3006.

(6) Sears, R. B.; Joyce, L. E.; Ojaimi, M.; Galluci, J. C.; Thummel, R. P.; Turro, C. *J. Inorg. Biochem.* **2013**, *121*, 77−87.

(7) Vargas Alfredo, N.; Espinosa Jalapa, N.; Lopez Morales, S.; Ryabov, A. D.; Le Lagadec, R.; Alexandrova, L. *Macromolecules* **2012**, *45*, 8135−8146.

(8) Fernandez, S.; Pfeffer, M.; Ritleng, V.; Sirlin, C. *Organometallics* **1999**, *18*, 2390−2394.