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Redox Properties of Ferrocenyl Ene-diynyl-Bridged Cp*(dppe)M−C≡C−1,4-(C_6H_4) Complexes

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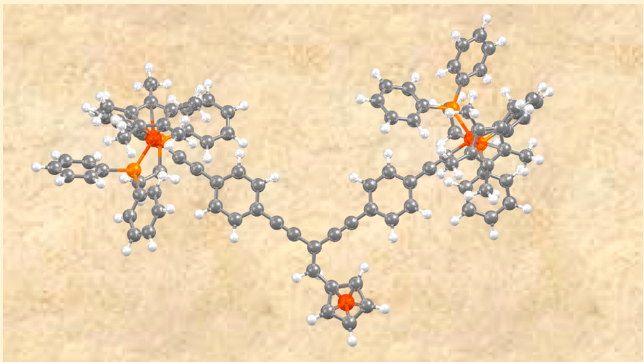
Supporting Information



ABSTRACT: The complexes FcCH═C{1,4-C≡C−C_6H_4−C≡CM(dppe)Cp*}$_2$ (Fc = ferrocenyl (FeCp(η-C_5H_4−); M = Fe (**1**), Ru (**2**)) were prepared from FcCH═C{1,4-C≡C−C_6H_4−C≡CSiMe$_3$}$_2$ (**3**) via a desilylation/metalation protocol in good (**2**; 65%) to excellent (**1**; 97%) yield. The iron compound **1** could also be prepared in a stepwise fashion by desilylation of **3** to give FcCH═C{1,4-C≡C−C_6H_4−C≡CH}$_2$ (**4**), reaction with FeCl(dppe)Cp* to give the vinylidene complex FcCH═C{1,4-C≡C−C_6H_4−CH═C═Fe(dppe)Cp*}$_2$](PF$_6$)$_2$ (**5(PF$_6$)$_2$**; 65%), and deprotonation. The cyclic voltammograms of **1** and **2** are characterized by an initial oxidation wave resulting from the overlap of two closely spaced oxidation processes, the potentials of which are sensitive to the identity of M, and a subsequent, one-electron-oxidation wave. Thus, while the dications $\mathbf{1}^{2+}$ and $\mathbf{2}^{2+}$ could be prepared by oxidation with 2 equiv of ferrocenium hexafluorophosphate and isolated as the PF_6^- salts **1(PF$_6$)$_2$** and **2(PF$_6$)$_2$** at low temperature, the monocations $\mathbf{1}^+$ and $\mathbf{2}^+$ could only be detected and studied as comproportionated mixtures of **1**, **1(PF$_6$)**, **1(PF$_6$)$_2$** and **2**, **2(PF$_6$)**, **2(PF$_6$)$_2$**. A combination of EPR spectroscopy, IR and NIR spectroelectrochemistry, and DFT quantum chemical calculations reveal subtle distinctions in the electronic structures of **1(PF$_6$)$_n$** and **2(PF$_6$)$_n$** (n = 0−2). The HOMOs of **1** and **2** are more heavily distributed over the metal−diethynylbenzene arm trans to the ferrocenyl moiety. While one-electron oxidation of **1** gives **1(PF$_6$)**, in which the spin density is similarly distributed along the branch of the molecule trans to the ferrocenyl group, the spin density in **2(PF$_6$)** is more extensively, but not fully, delocalized. Further analysis of the ESR, NIR, and IR spectra reveals that charges are essentially localized in **1(PF$_6$)** and **1(PF$_6$)$_2$** on the IR time scale, but ground-state exchange between the Fe(dppe)Cp* moieties can take place via the ferrocenyl moiety on the slower ESR time scale. For **2(PF$_6$)** and **2(PF$_6$)$_2$**, optical charge transfer processes between the ferrocenyl moiety and the organometallic branches can also be observed, consistent with the increased coupling between the Ru(dppe)Cp* and Fc moieties that are linked by a linear conjugation pathway through the bridging-ligand backbone.

INTRODUCTION

In recent years, the search for more highly functional systems that access unusual electronic structures and permit greater control and manipulation of intramolecular charge transfer processes has seen attention turned to systems bearing cross-conjugated bridging moieties,[1−4] including mixed-valence derivatives.[5−8] These studies form part of a larger range of investigations that address more general questions about the ability to tune the electrical behavior of cross-conjugated systems through the manipulation of quantum interference features.[9−13]

Quantum interference (QI) arises from the interaction of the de Broglie waves of electrons traversing a molecular system with the accessible molecular energy levels.[15] The sum of these interactions can be constructive, giving rise to resonances and effective electron transport (e.g., through a para-substituted benzene), or destructive, giving rise to anti-resonances and heavily restricted electron transport (e.g., through a meta-substituted benzene).[16,17] It has been proposed that the energy of a QI anti-resonance can not only be influenced by the structure of the molecular backbone such as linear vs cross-conjugated scaffolds or introduction of pendant groups[9,18−20] but also be tuned through the introduction of electron-donating or -withdrawing groups to the molecular backbone (Figure 1).[21] As QI effects are persistent in even quite large molecular

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systems,[14] the opportunity to explore chemical control over QI effects is an exciting area of contemporary chemistry.[22,23]

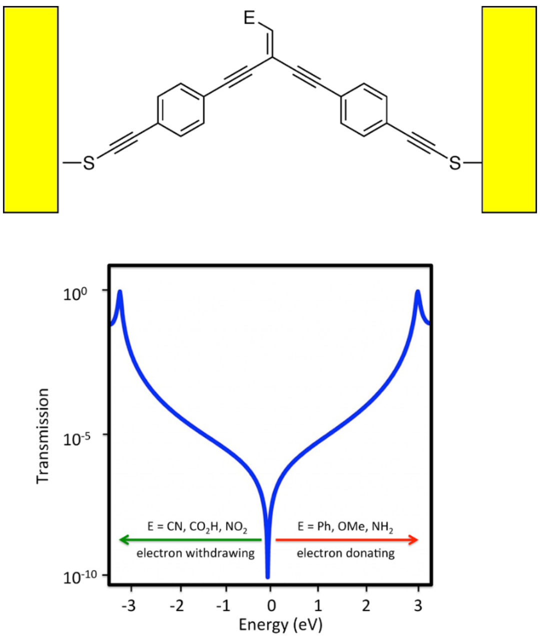

Figure 1. Cartoon sketch of an anti-resonance arising from QI through a molecular junction formed from a cross-conjugated *gem*-diethynylethene, on the basis of the work of Andrews et al.[14] The energy of the anti-resonance is sensitive to the chemical structure of the pendant group, E.

With these concepts in mind, Grozema's proposal of a chemically gated QI-based molecular transistor provided a fascinating structural model through which to explore and modulate molecule-mediated charge transfer processes between a donor and an acceptor (Figure 2).[24] As noted above, the effects of QI can be modulated through the introduction of electron-donating or -withdrawing groups pendant to the electron transfer channel. The Grozema system proposes the protonation of a pendant amine or carboxylate group or alkali-metal ion coordination to a pendant crown to change the electrostatic potential of the pendant group to chemically "gate" the interference patterns of the propagating electron waves between the donor and acceptor sites.

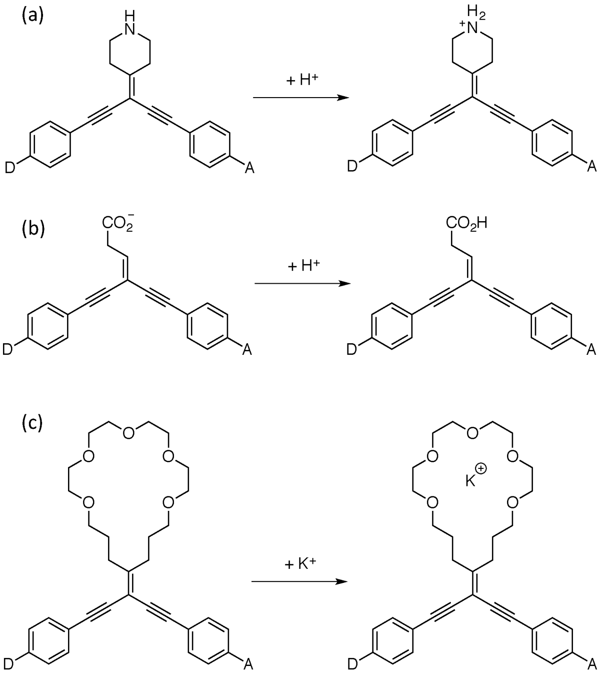

Figure 2. Chemically gated QI systems proposed by Grozema and colleagues.[24]

In seeking to extend these concepts, our attention has been drawn to electrochemically gated systems, with a redox-active pendant introduced to a general donor–bridge–acceptor structure. By tuning of the formal redox state of the gate, a change in the QI patterns between the donor and acceptor should be introduced (Figure 3). We have chosen to base our design strategy around mixed-valence compounds in which the donor and acceptor differ only in their formal oxidation state.[25−28] Indeed, in recent times there has been a resurgence of interest in mixed-valence models of intramolecular charge-transfer processes, from the development of theoretical descriptions and spectroscopic analysis of the charge-transfer event[29] to the development of novel optoelectronic materials and the design of molecular electronic components.[30]

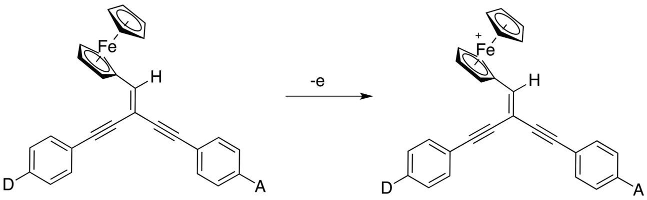

Figure 3. Electrochemically gated analogue of Grozema's QI transistor.

Some of the present authors have explored aspects, including mixed-valence characteristics, of cross-conjugated 1,1-bis(alkynyl)-2-ferrocenylethene derivatives (**A**),[31] including 1,1-bis(ferrocenylalkynyl)-2-ferrocenylethene (**B**)[32] and tetrakis(ferrocenylethynyl)ethene (**C**)[33] (Chart 1). However, efforts to incorporate the half-sandwich building blocks M(PP)Cp′, which have been so successful in exploring other aspects of organometallic mixed valency when these building blocks are linked through linearly conjugated all-carbon and carbon-rich bridging ligands,[34−40] within the cross-conjugated 1,1-bis(alkynyl)-2-ferrocenylethene framework through desilylation–metalation reactions of 1,1-bis(trimethylsilylethynyl)-2-ferrocenylethene (Chart 1; **A**, R = $SiMe_3$) or via vinylidenes formed from 1,1-bis(ethynyl)-2-ferrocenylethene (Chart 1; **A**, R = H) have so far proved fruitless.[32]

Here we now report the development of an extended derivative of the 1,1-bis(alkynyl)-2-ferrocenylethene building block **A** and the successful preparation of bis-M(dppe)Cp* (M = Fe (**1**), Ru(**2**)) complexes (Chart 1). The electronic structures and intramolecular charge transfer processes through the branched carbon-rich ligand framework within redox families generated from these compounds have been explored through a combination of electrochemical, spectroscopic, and computational methods, revealing the subtle differences that arise from the use of the iron and ruthenium end caps.

■ RESULTS AND DISCUSSION

Syntheses and Characterization. Mono- and binuclear alkynylmetal complexes in the M(dppe)Cp* series (M = Fe, Ru) are usually prepared by one of two general routes.[34,41−43] Most

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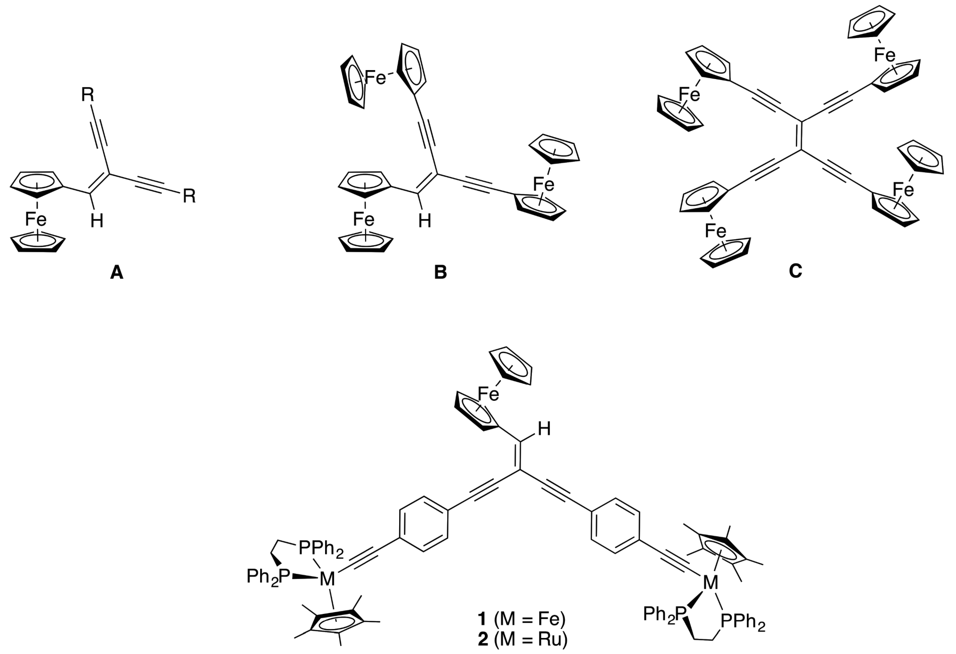
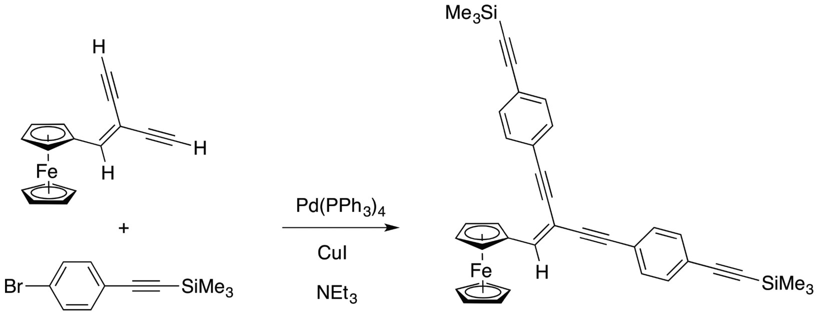
Chart 1



A **B** **C**

1 (M = Fe)
2 (M = Ru)

Scheme 1. Synthesis of 3



2.1 equiv

3

commonly, the readily available MCl(dppe)Cp* precursor[44] is reacted with a terminal alkyne to give the corresponding vinylidene derivative. In turn, deprotonation of the vinylidene gives the alkynyl metal complex.[43,45−47] Alternatively, MCl(dppe)Cp* (M = Fe, Ru) can be reacted with a trimethylsilyl-protected alkyne in the presence of a fluoride source (such as KF or NBu_4F) to give the metal alkynyl complex via an in situ desilylation−metalation sequence.[48−54]

In previous investigations by a number of the current authors the reaction of $FcCH{=}C(C{\equiv}CH)_2$ with $RuCl(PPh_3)_2Cp$ gave the monovinylidene complex $[FcCH{=}C(C{\equiv}CH)\{CH{=}CRu(PPh_3)_2Cp\}]^+$. However, all efforts to prepare trimetallic $FcCH{=}C\{C{\equiv}CRu(PPh_3)_2Cp\}_2$ from either $FcCH{=}C(C{\equiv}CH)_2$ or the trimethylsilyl-protected analogue $FcCH{=}C(C{\equiv}CSiMe_3)_2$ proved unsuccessful,[32] likely due to excessive steric crowding.

In the current study, Sonogashira cross-coupling of $FcCH{=}C(C{\equiv}CH)_2$[31] with 4-(trimethylsilylethynyl)bromobenzene was employed to give the “extended” precursor $FcCH{=}C\{1,4\text{-}C{\equiv}C{-}C_6H_4{-}C{\equiv}C{-}SiMe_3\}_2$ (**3**) (Scheme 1). Reaction of **3** with MCl(dppe)Cp* (M = Ru, Fe) and KF in a 1/1 (v/v) mixture of tetrahydrofuran and methanol gave **1** (97%) and **2** (65%) as red and orange powders, respectively (Scheme 2). Potassium *tert*-butoxide was used as both a base and a reducing agent during the workup of the more acidic and oxidatively sensitive homometallic iron complex **1**. Alternatively, **1** could also be obtained via an intermediate bis(vinylidene) complex (Scheme 2). Desilylation of **3** (K_2CO_3/MeOH) gave $FcCH{=}C\{1,4\text{-}C{\equiv}C{-}C_6H_4{-}C{\equiv}C{-}H\}_2$ (**4**), which was briefly characterized and reacted directly with FeCl(dppe)Cp* in the presence of NH_4PF_6 to give the intermediate vinylidene complex $[FcCH{=}C\{1,4\text{-}C{\equiv}C{-}C_6H_4{-}CH{=}C{=}Fe(dppe)Cp^*\}_2](PF_6)_2$ (**5(PF$_6$)$_2$**). Subsequent deprotonation of **5(PF$_6$)$_2$** with $KOBu^t$ gave **1** in quantitative yield.

The new complexes **1** and **2** were obtained and characterized by mass spectrometry, IR, ^1H and ^{31}P NMR, and UV−vis spectroscopy, and cyclic voltammetry. As previously noted for the organic derivatives $FcCH{=}C(C{\equiv}CR)_2$,[31] the ^1H NMR spectra of **1** and **2** confirm the free rotation of the ferrocenyl moiety around the ferrocene−vinyl C−C bond, with the protons of the $\eta\text{-}C_5H_4$ ring observed as only two signals (δ_H 4.33, 4.80 (**1**); δ 4.41, 4.88 (**2**)). In **1**, the vinyl proton resonance is overlapped by the protons of the C_6H_4 ring (δ_H 6.80−6.89) but is clearly observed in **2** at δ_H 6.86. The protons of the Cp* ligands attached to the iron atoms in **1** are observed as a single, slightly broadened resonance (δ_H 1.33 ppm), while those in **2**

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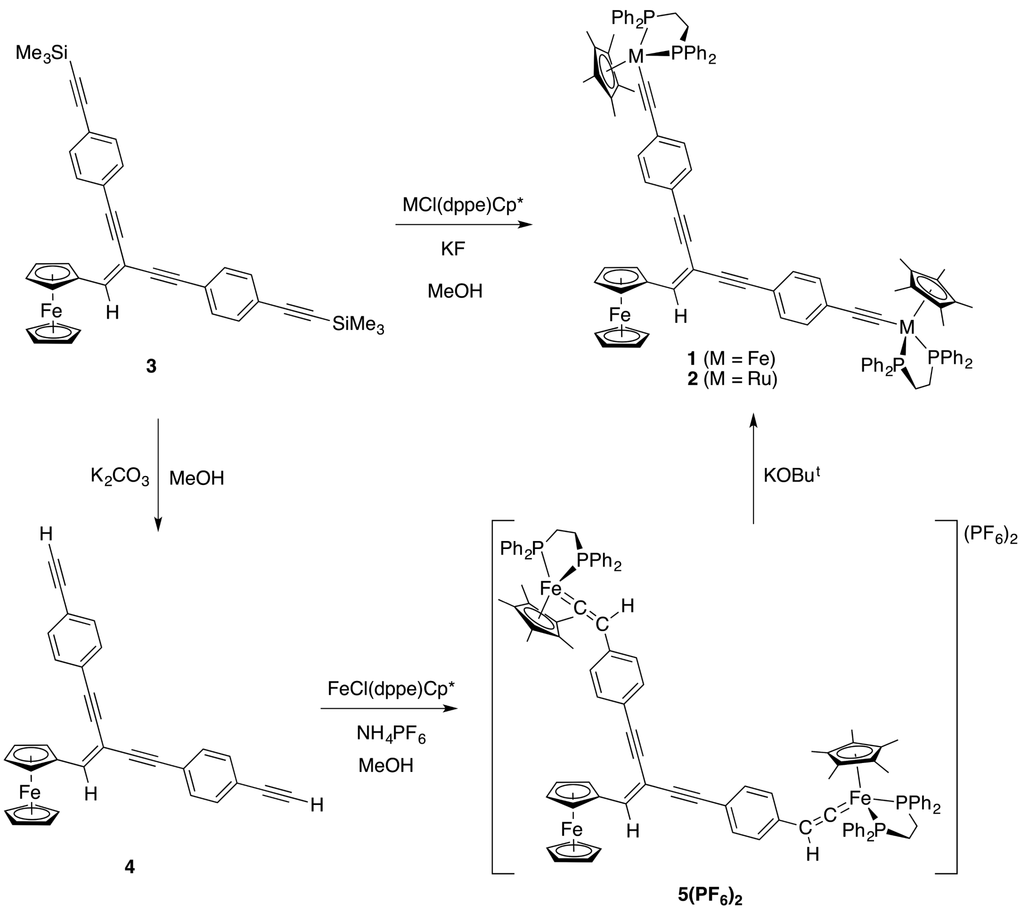
Scheme 2. Synthesis of 1, 2, 4, and 5($(PF_6)_2$)



are observed as two very closely spaced, but well-resolved, singlets (δ_H 1.57 and 1.58 ppm), as the *E* and *Z* arms of the double bonds are not strictly equivalent. However, the electronic and stereochemical differences are not detected in ^{31}P NMR spectra, with the phosphorus atoms on the two M(dppe)Cp* moieties resonating as singlets at δ_P 99.3 and 80.6 for **1** and **2**, respectively.

The IR spectra of **1** and **2** exhibit strong $\nu_{M-C\equiv C}$ bands at 2046 and 2062 cm^{-1}, respectively. As is generally observed for iron and ruthenium complexes M(C≡CR)(dppe)Cp*, the frequency of the $\nu_{M-C\equiv C}$ stretch is somewhat higher for the ruthenium complex than for its iron homologue.[55,56] Two weak $\nu_{C\equiv C}$ bands at 2201 (sh) and 2187 cm^{-1} (**1**) and a broad stretch at 2189 cm^{-1} (**2**) arise from the triple bonds which connect the vinyl ferrocenyl moiety to the phenyl rings. The spectra of **1** and **2** also show an intense band at 1591/1592 cm^{-1} which can be assigned to the $\nu_{C=C}$ vibration of the vinyl group. The significant intensity of this band is likely due to the dipole across the Cp*(dppe)M−donor ferrocene−acceptor fragment.

Cyclic Voltammetry of 1 and 2. The initial scans in the cyclic voltammetry of **1** and **2** were recorded between −1.2 and 0.6 V (vs. $FeCp_2/FeCp_2^+$ at 0.00 V) in 0.1 M NBu_4PF_6/CH_2Cl_2. In each case, the voltammograms are characterized by two quasi-reversible and well-separated waves, the separation between the anodic and cathodic peaks for each redox wave ($\Delta E_p = 0.08 \pm 0.01$ V) being somewhat larger than the value expected for electrochemically reversible systems ($\Delta E_p = 0.06$ V) (Figure 4 and Table 1). The first wave, which consumes approximately double the current of the second, corresponds to the near-simultaneous oxidation of the two M(C≡CR)(dppe)Cp* units, while the second waves can safely be assigned to the ferrocenyl moiety. The (i_p^a/i_p^c) current ratios indicate some chemical irreversibility of the second wave, reflecting chemical instability of the electrochemically generated trications. In line with these assignments, the first oxidation process(es) of the Fe(dppe)Cp*

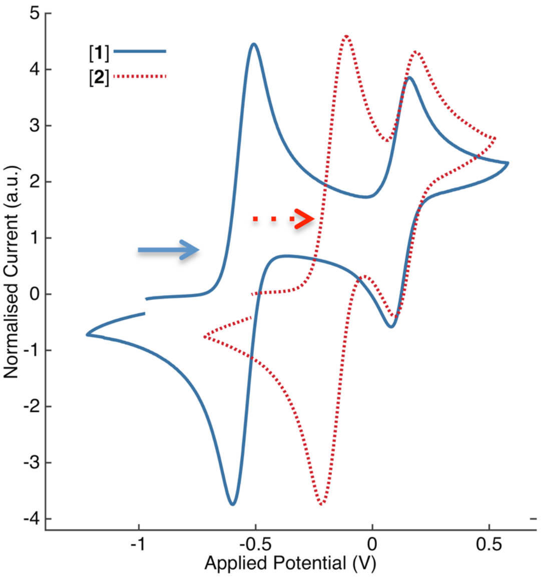


Figure 4. Cyclic voltammograms for **1** (0.2 mM) and **2** (0.2 mM) recorded at $\nu = 0.100$ V s^{-1} in 0.1 M NBu_4PF_6/CH_2Cl_2.

Table 1. Electrochemical Data[a] for 1 and 2

compd	redox site	$E_{1/2}$ (V)	ΔE_p (V)	i_p^a/i_p^c
1	Fe(dppe)Cp*	−0.55[b]	0.09	0.99
	Fc	+0.12	0.08	0.77
2	Ru(dppe)Cp*	−0.17[b]	0.08	~1[c]
	Fc	+0.15	0.09	0.76

[a] Potentials in 0.1 M CH_2Cl_2, $NBu_4(PF_6)$, platinum electrode, sweep rate 0.100 V s^{-1}, potentials are relative to external $FeCp_2/FeCp_2^+$ at 0.00 V (internal reference $Cp_2Co/[Cp_2Co]^+ = -1.30$ V).[57] [b] Apparent half-wave potential from two unresolved redox processes. [c] The small separation of the redox processes E(1) and E(2) makes precise measurement of the current ratio i_p^a/i_p^c difficult.

complex **1** occur(s) some 0.37 V more negative than that of the ruthenium analogue **2**, while oxidation potentials assigned to the ferrocenyl groups in **1** and **2** differ by only 0.02 V (Figure 4).

In Situ ESR Spectra of 1(PF$_6$)$_n$ and 2(PF$_6$)$_n$ (n = 1, 2). The facile oxidation of **1** and **2** revealed by the electrochemical measurements prompted consideration of the redox-related products. The complexes **1** and **2** were each reacted with 2 equiv of $[Cp_2Fe](PF_6)$ in THF at −60 °C for 1 h, and the resulting solutions of **1(PF$_6$)$_2$** or **2(PF$_6$)$_2$** transferred to an ESR quartz tube and immediately cooled to liquid nitrogen temperature. ESR monitoring established that while the iron complex diradical is stable in a glass at 66 K (−207 °C) or even as a fluid THF solution below −60 °C, the concentration of ESR-active iron species decreases above −40 °C and completely decomposes within 5 min at 20 °C.

The ESR spectra of **1(PF$_6$)$_2$** and **2(PF$_6$)$_2$** recorded at 66 K (Figure 5) are each characterized by one broad signal (**1(PF$_6$)$_2$**, $g = 2.1265$; **2(PF$_6$)$_2$**, $g = 2.1034$) with a width from peak to peak of ca. 330 G for **1(PF$_6$)$_2$** and 120 G for **2(PF$_6$)$_2$** (Figure 5). The ESR spectra of **1(PF$_6$)$_2$** and **2(PF$_6$)$_2$** strongly contrast with the spectra of the iron and ruthenium radical cations $[M(C\equiv CR)(dppe)Cp^*]PF_6$ (M = Fe, Ru), which show one signal with three features (g_1, g_2, and g_3) characteristic of low-spin d^5 complexes with a pseudo-octahedral geometry,[45,56,58] while substituted ferrocenyl cations exhibit one signal with two tensor components ($g_{\parallel}$ and $g_{\perp}$).[59]

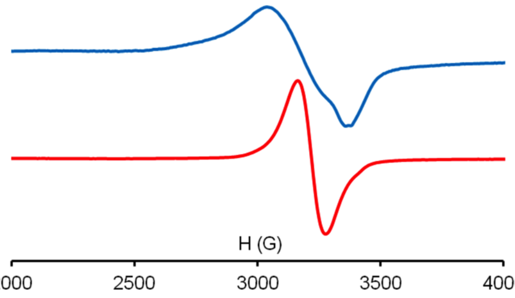


Figure 5. X-band ESR spectra of **1(PF$_6$)$_2$** (top) and **2(PF$_6$)$_2$** (bottom) at 66 K.

In the case of the iron complex **1(PF$_6$)$_2$**, the presence of partially resolved features in the rather broad ESR spectrum suggests that the signal is close to decoalescence, consistent with a degree of electron exchange between the Fe(dppe)Cp* and Fc moieties on a rate comparable with the ESR time scale. In the case of **2(PF$_6$)$_2$**, the ESR spectra shown in Figure 5 can be regarded as averaged signals resulting from a fast intramolecular electron transfer at the ESR time scale (faster than 10^{-9} s) between the M(dppe)Cp* moieties and the ferrocenyl group. A very similar spectrum was reported by Sato and co-workers for the highly delocalized mixed-valence complex $[Cp(dppe)Fe{-}C\equiv C{-}(\eta\text{-}C_5H_4)FeCp](PF_6)$.[60] Moreover, the smaller g value and the narrower ESR signal obtained for the ruthenium derivatives might result from a larger carbon character of the SOMOs which contains the unpaired electrons.

Given the failure to observe **1(PF$_6$)** in spectroelectrochemical experiments (vide infra), in an additional experiment, complex **1** was reacted with 1 equiv of $[Cp_2Fe](PF_6)$ under the same conditions to give a solution containing **1(PF$_6$)** comproportionated with **1** and **1(PF$_6$)$_2$**. The ESR spectrum collected from this solution is less intense but otherwise identical with that obtained from **1(PF$_6$)$_2$**. In other words, the mono- and dications give rise to sufficiently similar ESR spectra that a distinction cannot be drawn. This is consistent with DFT calculations in which the spin density in 1^+ and 1^{2+} is localized on one or both Fe(dppe)Cp* fragments.

IR Spectroelectrochemical Studies of 1(PF$_6$)$_n$ (n = 0−3) and 2(PF$_6$)$_n$ (n = 0−2). UV−vis−NIR and IR spectroelectrochemical investigations of **1(PF$_6$)$_n$** (n = 0−3) and **2(PF$_6$)$_n$** (n = 0−2) were undertaken to complement the electrochemical and ESR studies of the chemically oxidized compounds. In the IR spectra, the stepwise oxidation of **1** and **2** from the neutral species to the dication induces a shift to lower wavenumbers of the $\nu_{M-C\equiv C}$ bands from 2046 to 1991 cm^{-1} and from 2062 to 1927 cm^{-1} in the iron and ruthenium series, respectively. As the oxidation of complexes **1** and **2** proceeds, the $\nu_{Fc-C=C}$ band stretch at 1591/1592 cm^{-1} corresponding to the vinyl group decreases while new less intense band envelopes appear at lower energy, indicating a degree of delocalization along at least one of the $M{-}C\equiv CCH{=}CHFc$ branches.

In the iron series, the intensity of the band corresponding to the neutral complex **1** continuously decreases while the band corresponding to the dication **1(PF$_6$)$_2$** gradually appears. An intermediate band associated with the transient formation of the monocation **1(PF$_6$)** could not be detected. In contrast, for the ruthenium analogue, transient features in the IR spectroelectrochemical experiment were observed at 2131 (w), 2040 (sh), 1994 (m), 1891 (s), 1572 (m), and 1547 (m) cm^{-1} during the oxidation of **2** to **2(PF$_6$)$_2$**, corresponding to the presence of **2(PF$_6$)** in the comproportionated mixture (Figure 6 and Table 2). Taken together, the IR spectra suggest that the E and Z arms of the molecule are completely independent in the iron complexes, while a degree of delocalization leading to enhanced stability of the mixed-valence form **2(PF$_6$)** can be observed in the case of the ruthenium complexes.

On further oxidation of **2(PF$_6$)$_2$** the sample evinced significant and rapid decomposition on the time scale of the spectroelectrochemical experiment, which prevented confident assignment of the resulting spectra. However, in the case of the iron complex oxidation to a trication with sufficient chemical stability to be observed could be achieved, with the assignment being made with confidence following the recovery of the spectrum of the dication on back-reduction. Oxidation of **1(PF$_6$)$_2$** to **1(PF$_6$)$_3$**, which could be followed by observing the low-energy edge of the electronic transitions that fall in the window of the spectrometer (1000−10000 cm^{-1}), had little effect on the $\nu_{M-C\equiv C}$ and $\nu_{Fc-C=C}$ IR bands, consistent with a ferrocenyl-localized oxidation.

NIR Spectroelectrochemical Studies of 1(PF$_6$)$_n$ (n = 0, 2, 3) and 2(PF$_6$)$_n$ (n = 0−2). Upon oxidation of **1** to **1(PF$_6$)$_2$** in the spectroelectrochemical cell (Figures 7 and 8), the characteristic MLCT absorption band near 20000 cm^{-1}[61] collapses,

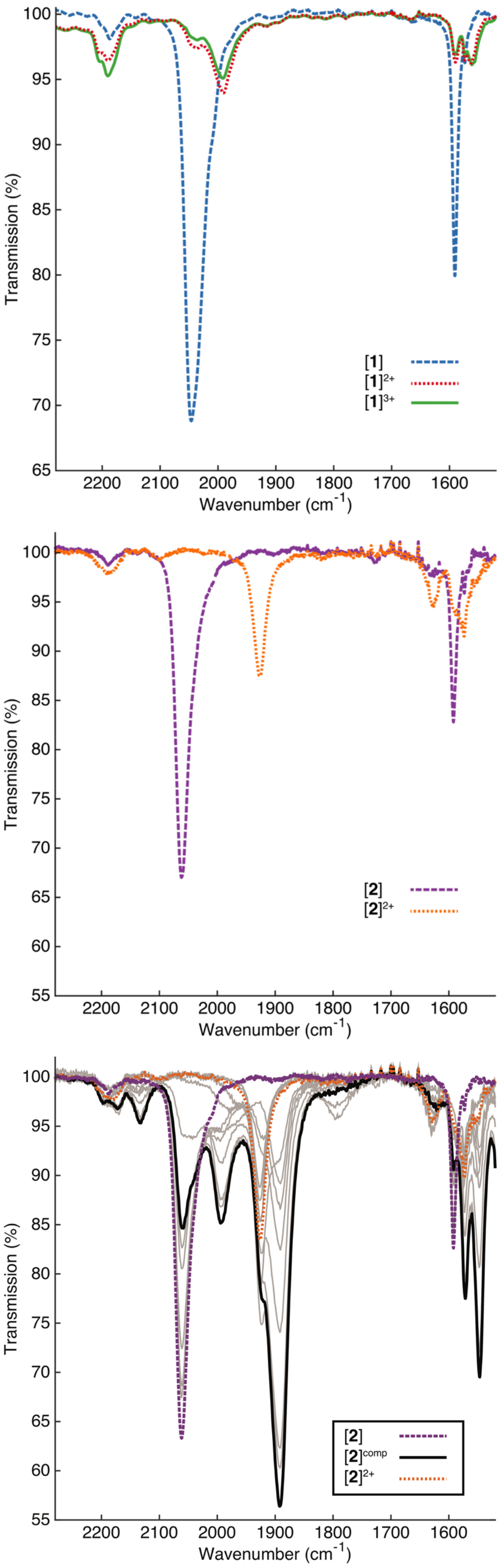


Figure 6. IR spectra of **1** and **2** collected spectroelectrochemically in 0.1 M CH_2Cl_2/NBu_4PF_6. The spectra of the transiently observed comproportionated mixture between the neutral and dicationic states is shown as a solid black trace in the lowest panel, the unique features being attributed to $\mathbf{2}^+$.

giving way to a lower-intensity LMCT feature near 12000 cm^{-1}.[58] To even lower energy (ca. 5000 cm^{-1}), the characteristic d−d (mixed with C≡C π character) transition of an Fe(III) pseudo-octahedral $[Fe^{III}(C\equiv CR)(dppe)Cp^*]^+$ complex can be observed growing in concurrently.[58] Further oxidation to $\mathbf{1(PF_6)_3}$ does not affect the Fe(III) d−d transitions associated with the $[Fe^{III}(C\equiv CR)(dppe)Cp^*]^+$ moieties but does cause a collapse of the LMCT band and the appearance of a weak absorption band envelope around 8000−10000 cm^{-1}. Absorption bands at similar energy have been observed on oxidation of other ferrocenyl ene-diynes and assigned to the ferrocenium-like d−d transitions and LMCT transitions within the vinylferrocenium moiety.[31] These data are consistent with the suggestions made from other spectroscopic observations, with largely independent oxidation of the Fe(dppe)Cp* moieties being followed by oxidation of the ferrocene fragment. There is no detectable absorption band that can be confidently assigned to an intramolecular intervalence charge transfer (or IVCT) transition.

The stepwise oxidation of the ruthenium-based complex **2** was also carried out in a spectroelectrochemical cell (Figure 9). As the potential in the cell is increased to more positive values, the MLCT (or dπ−π*) band near 25000 cm^{-1}, which typifies Ru(C≡CR)(PP)Cp′ complexes,[62] begins to collapse, giving way to a complex series of band envelopes in the NIR region. The band shape evolves with increasing applied potential, with the presence of an isosbestic point near 20000 cm^{-1} and the reversibility of the spectral changes on the reverse potential sweep consistent with the establishment of the comproportionated equilibrium of **2**, $\mathbf{2(PF_6)}$, and $\mathbf{2(PF_6)_2}$. The definitive assignment of the transitions responsible for the NIR absorption features is an extraordinarily difficult task, given the range of conformations that can be adopted by the rotation of the sandwich, half-sandwich, and phenylene moieties relative to each other.[38−40] However, the distinct feature near 5500 cm^{-1} is similar to the IVCT band observed in weakly coupled mixed-valence Ru(dppe)Cp* complexes.[52,63] This band grows during the early stages of oxidation at lower (less positive) potentials, where the equilibrated solution contains $\mathbf{2(PF_6)}$ comproportionated with **2** and $\mathbf{2(PF_6)_2}$, and collapses at higher (more positive) potentials, where the solution is expected to be essentially wholly $\mathbf{2(PF_6)_2}$. It is therefore very likely that this band envelope near 5500 cm^{-1} can be assigned to an IVCT transition between the Ru(dppe)Cp* moieties. The NIR bands nearer 10000−15000 cm^{-1} likely arise from a combination of Fc → $\{C\equiv CRu(dppe)Cp^*\}^+$ charge transfer[49,64,65] and LMCT transitions[62] in $\mathbf{2(PF_6)_2}$, which is the principal species in the solution at higher potentials. While these spectroscopic changes were reversible within the cell, as noted for the IR spectroelectrochemical experiments, attempts to generate $\mathbf{2(PF_6)_3}$ by further electrolysis resulted only in extensive decomposition of the sample.

Computational Studies. Density functional theory (DFT) calculations were carried out on compounds **1** and **2** and their cationic species to gain further insight into the structural arrangements, electronic structures, and bonding properties at the PBE0/LANL2DZ level of theory (see the Experimental Section for computational details), which complement earlier studies of cross-conjugated carbon scaffolds and complexes cited above and elsewhere.[66−68] The optimized molecular structure of the energetically most stable conformer found in each case and atom labels are shown in Figure 10, and important bond lengths and angles are summarized in Table 3.

Table 2. Characteristic IR Data for 1^{n+} and 2^{n+} (n = 0−3) (CH_2Cl_2/0.1 M NBu_4PF_6)

n		**1** (cm^{-1})	*calcd* (cm^{-1})[a]	**2** (cm^{-1})	*calcd* (cm^{-1})[a]
0	$\nu_{C\equiv C}$	2202 (w,sh), 2187 (w)	*2182* (129)	2189 (vw)	*2184* (138)
	$\nu_{M-C\equiv C}$	2046 (vs)	*2047* (1779)	2062 (s)	*2057* (2028)
	$\nu_{Fc-C=C}$	1591 (s)	*1590* (278), *1472* (291)	1592 (s)	*1590* (314), *1472* (304)
1	$\nu_{C\equiv C}$		*2191* (1148), *2000* (2580)	2135 (w)	*2156* (1036)
	$\nu_{M-C\equiv C}$		*2040* (1999)	1994 (m), 1891 (s)	*1953* (62580)
	$\nu_{Fc-C=C}/\nu_{C=C(Ar)}$		*1548* (2130)	1572 (m), 1547 (m)	
2	$\nu_{C\equiv C}$	2206 (w, sh), 2191 (w)	*2181* (436)	2191 (w)	*2150* (3974)
	$\nu_{M-C\equiv C}$	2045 (vw, sh), 1991 (w)	*2025* (458)	1927 (m)	*1914* (1729)
	$\nu_{Fc-C=C}/\nu_{C=C(Ar)}$	1590 (w), 1574 (w), 1563 (w)	*1551* (574)	1629 (w), 1581 (w, br)	*1512* (1975)
3	$\nu_{C\equiv C}$	2205 (w, sh), 2190 (w)			
	$\nu_{M-C\equiv C}$	2040 (vw, sh), 1993 (w)			
	$\nu_{Fc-C=C}/\nu_{C=C(Ar)}$	1591 (w), 1575 (w), 1562 (w)			

[a] Values in parentheses are given in km/mol.

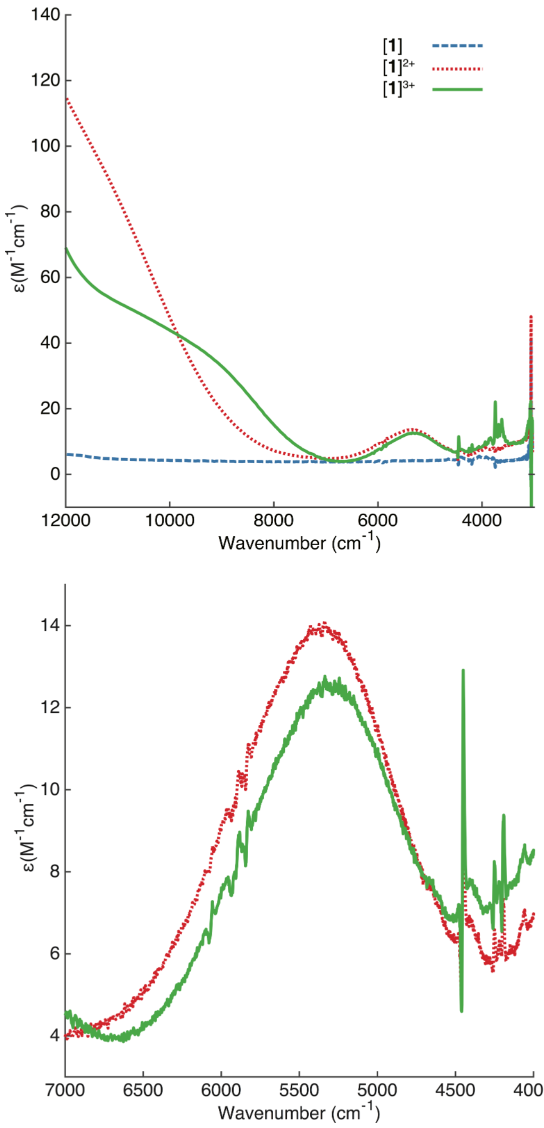


Figure 7. NIR spectra of 1^{n+} collected spectroelectrochemically (CH_2Cl_2/0.1 M NBu_4PF_6) (top). The expansion of the lower energy region (bottom) highlights the extremely weak, approximately Gaussian shaped bands observed for 1^{2+} and 1^{3+}. In this lower energy region, neutral **1** is featureless.

The molecular geometry around the $-C\equiv C$-M(dppe)Cp* end-cap units in **1** (M = Fe) and **2** (M = Ru) is similar to that of

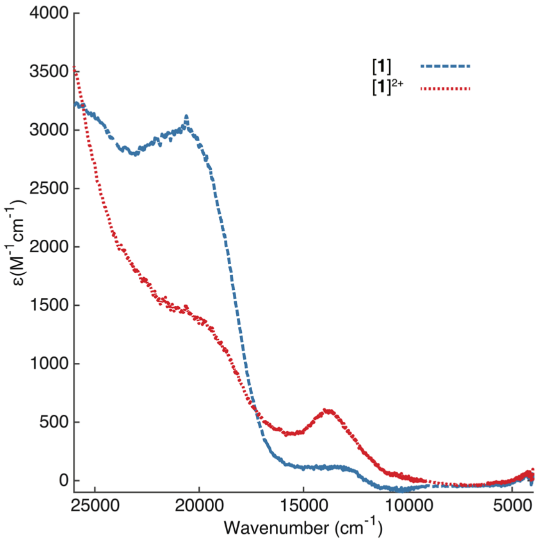


Figure 8. Expanded view of the UV−vis−NIR spectra of 1^{n+} collected spectroelectrochemically (CH_2Cl_2/0.1 M NBu_4PF_6). At this scale the difference between the spectra of 1^{2+} and 1^{3+} cannot be discerned and hence 1^{3+} is omitted.

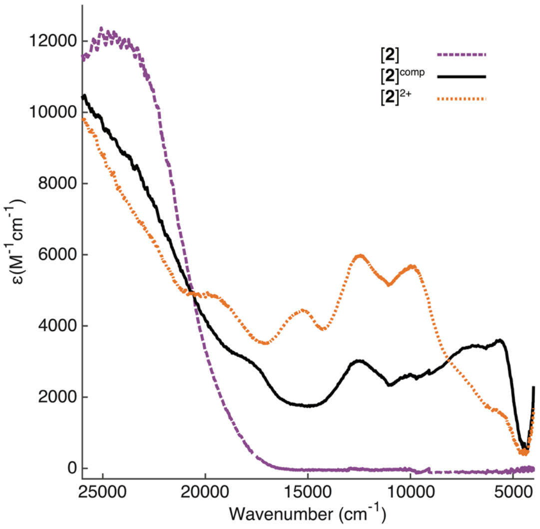
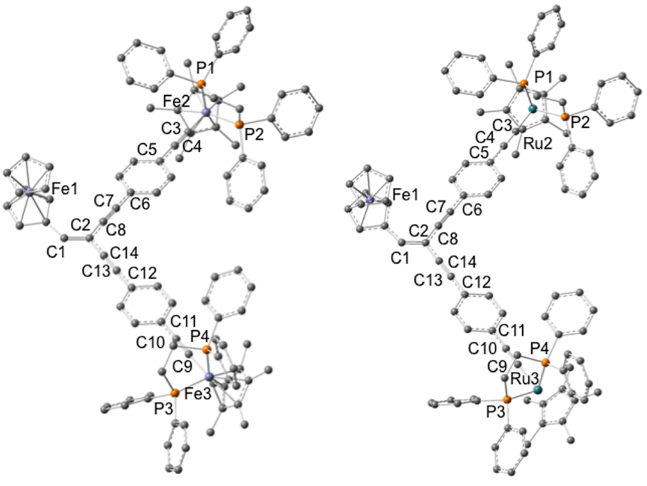


Figure 9. UV−vis−NIR spectra of 2^{n+} collected spectroelectrochemically (CH_2Cl_2/0.1 M NBu_4PF_6), including the unique spectroscopic features of the comproportionated mixture.



1 2

Figure 10. Plots illustrating the DFT-optimized molecular structures of complexes **1** (top) and **2** (bottom). Blue, orange, and gray spheres are metal, phosphorus, and carbon atoms, respectively. Hydrogen atoms are omitted for clarity.

model component monometallic complexes Fe(C≡CPh)(dppe)Cp* and Ru(C≡CPh)(dppe)Cp*,[53,55,56] with bond lengths and angles in the previously established ranges.[34,69] The two end caps are twisted relative to each other with the torsion angle (τ) between planes defined by Cp#−M2−M3 and M2−M3−Cp# (Cp# represents the centroid of the respective Cp* rings here or Cp in the case of the ferrocenyl moiety described below) determined as τ = 67 and 46° for **1** and **2**, respectively. To favor π delocalization, the two phenyl rings are nearly coplanar in both compounds. With regard to the ferrocene moiety, an average Fe−Cp# distance of 1.65 Å is computed for **1** and **2**. This value compares very well with that experimentally measured in $FeCp_2$.[70]

The HOMOs of complexes **1** and **2** are substantially energetically separated from the LUMO by 3.19 and 3.20 eV, respectively (Figure 11). The nodal properties of the HOMOs

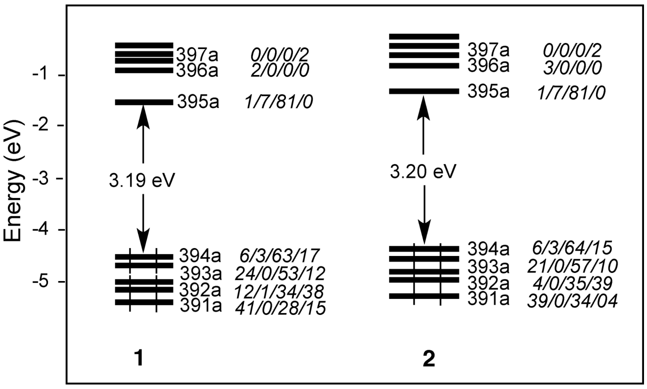


Figure 11. DFT molecular orbital diagram of **1** (left) and **2** (right). M2/Fe1(Fc)/carbon-backbone/M3 percentage contributions are given in italics (M = Fe, Ru).

Table 3. Important DFT-Optimized Bond Lengths (Å) and Angles (deg) for Complexes 1^{n+} and 2^{n+} (n = 0−2)

	1	1^+	$1^{2+\,a}$	2	2^+	$2^{2+\,a}$
M2−Cp*# (centroid)	1.741	1.742	1.770	1.909	1.918	1.931
M3−Cp*# (centroid)	1.741	1.768	1.770	1.908	1.920	1.931
Fe1-Cp# (centroid)	1.646/1.645	1.647/1.646	1.649/1.644	1.646/1.645	1.654/1.649	1.652/1.646
M2−C3	1.869	1.846	1.868	1.986	1.952	1.923
M3−C9	1.870	1.855	1.867	1.987	1.944	1.924
C1−C2	1.396	1.373	1.373	1.369	1.384	1.379
C2−C8	1.427	1.424	1.425	1.427	1.417	1.421
C2−C14	1.428	1.425	1.427	1.428	1.418	1.422
C7−C8	1.222	1.222	1.221	1.222	1.225	1.223
C13−C14	1.221	1.222	1.221	1.221	1.225	1.224
C6−C7	1.424	1.423	1.423	1.424	1.415	1.417
C12−C13	1.424	1.418	1.422	1.424	1.412	1.416
C4−C5	1.424	1.421	1.426	1.424	1.410	1.410
C3−C4	1.239	1.240	1.237	1.237	1.246	1.252
C9−C10	1.239	1.238	1.237	1.237	1.248	1.253
M2−P1	2.212	2.212	2.306	2.293	2.309	2.343
M2−P2	2.203	2.204	2.280	2.285	2.300	2.329
M3−P3	2.211	2.295	2.308	2.293	2.313	2.343
M3−P4	2.202	2.274	2.280	2.285	2.304	2.329
M2−C3−C4	176.4	176.1	175.2	175.2	174.5	174.5
M3−C9−C10	176.3	175.7	175.7	175.3	174.6	174.5
C3−C4−C5	179.0	179.6	179.4	179.3	179.4	179.0
C9−C10−C11	179.3	178.7	177.9	179.2	179.1	179.0
C6−C7−C8	179.5	178.4	176.6	179.0	179.0	177.4
C12−C13−C14	179.8	179.5	178.2	179.9	179.7	178.7
C2−C14−C13	179.1	179.3	178.0	179.4	179.9	178.2
C1−C2−C8	124.5	125.0	123.5	124.3	124.1	123.6
C1−C2−C14	119.7	118.7	118.8	119.6	118.6	118.7
τ[b]	67.6	84.6	114.3	46.0	99.0	156.9

[a] Triplet state configuration. [b] See text.

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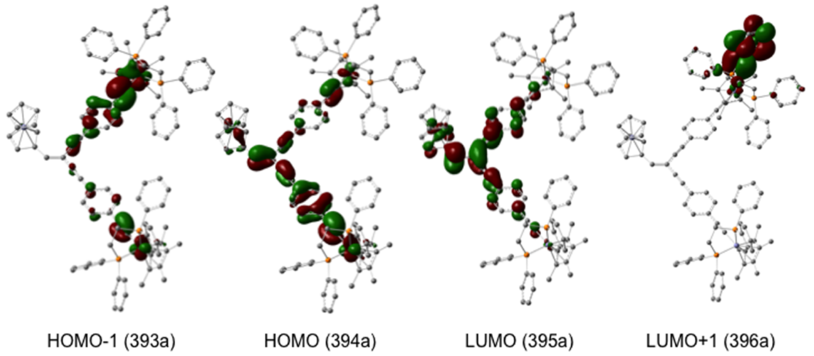


Figure 12. Plots (from left to right) of the HOMO-1 (−4.78 eV), HOMO (−4.63 eV), LUMO (−1.44 eV), and LUMO+1 (−0.85 eV) of complex **1**. Contour values are ±0.03 $(e/bohr^3)^{1/2}$.

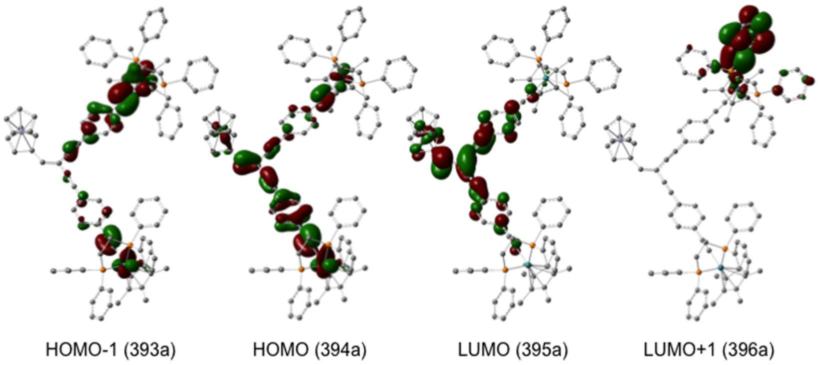


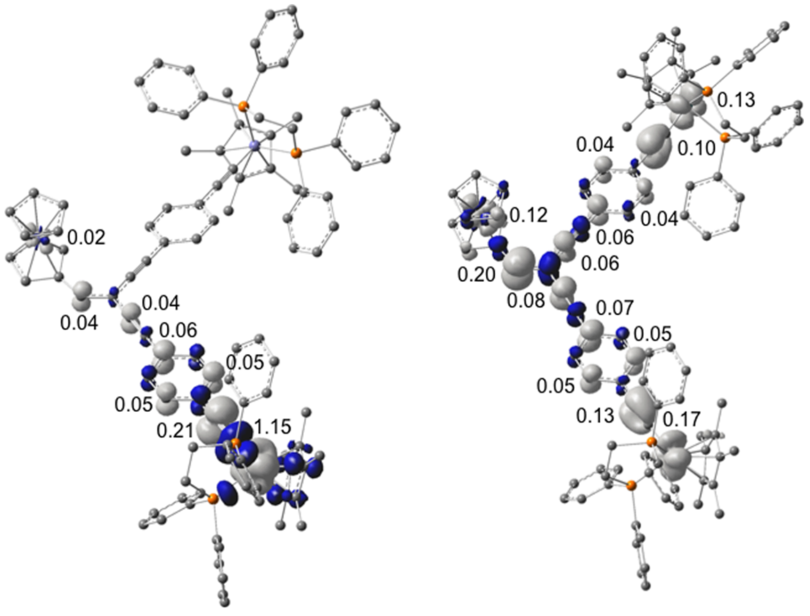
Figure 13. Plots (from left to right) of the HOMO-1 (−4.74 eV), HOMO (−4.59 eV), LUMO (−1.39 eV), and LUMO+1 (−0.86 eV) of complex **2**. Contour values are ±0.03 $(e/bohr^3)^{1/2}$.

of **1** (Figure 12) and **2** (Figure 13) are comparable, forming part of the "t_{2g}" set expected for pseudo-octahedral metal centers, and are π in character, heavily weighted on the metal centers and on the carbon backbone with little to no (HOMO-1) or only a weak (HOMO) contribution of the Fc and ethenyl moieties (Figures 11−13). It is noteworthy that the closely lying HOMO and HOMO-1 are not equally distributed over the two branches of the molecules; rather, each largely forms the π system associated with one "branch" of the cross-conjugated carbon backbone. These orbitals have significant M2−C3 and M3−C9 antibonding and C3−C4 and C9−C10 bonding character. The LUMO of **1** and **2** is mostly centered on the ethenyl group and shows a strong π* character. A noticeable participation of the ferrocenyl moiety in the LUMO of **1** and **2** is observed (Figure 11).

The geometries of the redox-related monocationic $\mathbf{1}^+$ and $\mathbf{2}^+$ and dicationic $\mathbf{1}^{2+}$ and $\mathbf{2}^{2+}$ species were also calculated, the results of which are summarized in Table 3 (metrical parameters of only the triplet states are given for the dicationic species, being largely energetically preferred over the singlet states by more than 1.8 eV). In the absence of a complete set of spectroscopic data permitting comparison of $\mathbf{1}^{3+}$ and $\mathbf{2}^{3+}$, these tricationic species were not calculated. Unsurprisingly given the M−C antibonding and C≡C bonding character of the HOMOs, oxidation of **1** and **2** leads to some shortening of the M2−C3 and M3-C9 distances and a slight lengthening of the adjacent C≡C bonds in the case of **2** (Table 3). The ethenyl C1−C2 bond length remains almost constant across each series. The Fe−C(alkynyl) bond length is rather insensitive to changes in the metal oxidation state in Fe(C≡CR)(dppe)Cp* complexes, differences falling within the experimental statistical differences in the examples that have been crystallographically characterized to date.[58,61] From the data in Table 3 it can be seen that the Fe2−C3 and Fe3−C9 distances contract by only some 0.02 Å on oxidation of **1** to $\mathbf{1}^+$, before elongating again in the triplet dication. The changes in formal metal oxidation state are more readily observed through the Fe−Cp*(centroid) and Fe−P distances. Therefore, if we consider the optimized geometries of **1**, $\mathbf{1}^+$, and $\mathbf{1}^{2+}$ we see that on oxidation from **1** to $\mathbf{1}^+$ the Fe(3)−$Cp^*_{centroid}$ distance increases from 1.741 to 1.768 Å and the Fe(3)−P(3)/Fe(3)−P(4) distances elongate from 2.211/2.202 to 2.295/2.274 Å, consistent with oxidation of this metal site, whereas Fe(2) parameters are largely unchanged (i.e., localized oxidation at Fe(3)). On oxidation to $\mathbf{1}^{2+}$, the parameters at Fe(3) remain similar to those of $\mathbf{1}^+$, while Fe(2) exhibits the expected changes that accompany oxidation. In contrast, the ruthenium analogues $[Ru(C{\equiv}CR)(dppe)Cp^*]^{n+}$ feature more Ru−C≡C character in the HOMO/SOMO and hence structural changes are more evident in the Ru−C and C≡C distances on oxidation (Table 3).

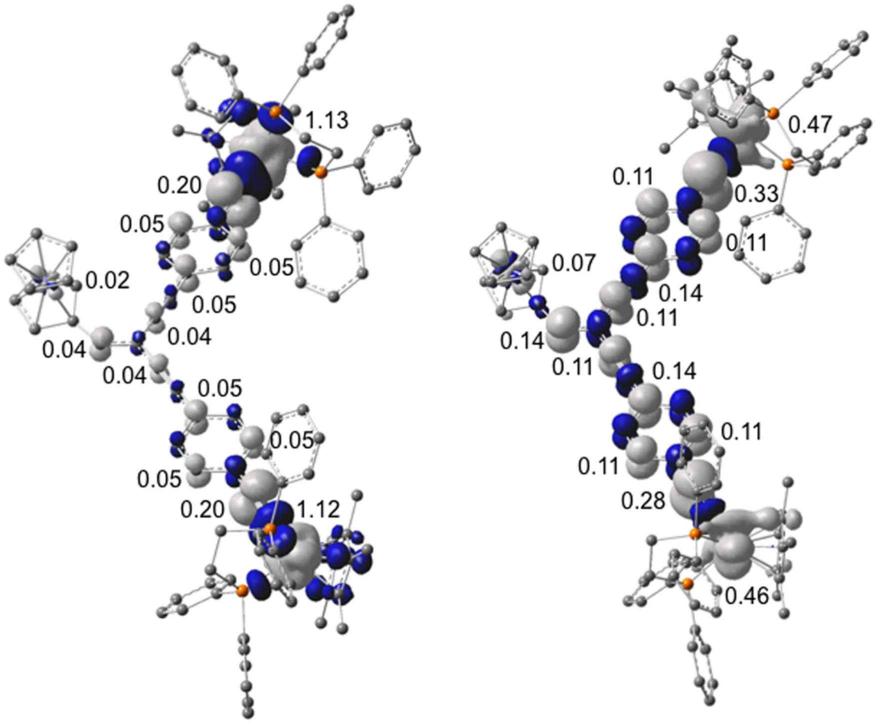
Despite the fact that the energies of the HOMO and LUMO are rather similar in both **1** and **2** (Figure 11), the computed adiabatic ionization potentials (IPs) differ; values of 10.53 and 11.39 eV for the dications $\mathbf{1}^{2+}$ and $\mathbf{2}^{2+}$ were found, respectively. The higher IP of $\mathbf{2}^{2+}$ in comparison with that of $\mathbf{1}^{2+}$ is consistent with the higher oxidation potential of **2** in comparison to **1** (Table 1). We note that a direct correlation of the gas-phase IPs and electrochemical potentials should not be expected, given the sensitivity of the electrochemical data to solvation, ion pairing, and inner-sphere reorganization energies.

The energies of the key molecular vibrations were computed for $\mathbf{1}^{n+}$ and $\mathbf{2}^{n+}$ ($n = 0−2$) to provide a point of reference between the experimental observations and the computational results.



1^+ 2^+

Figure 14. Spatial distribution of the computed spin density of 1^+ (left) and 2^+ (right). Isocontour value: ±0.002 e/bohr^3.



1^{2+} 2^{2+}

Figure 15. Spatial distribution of the computed spin density of the triplet states of 1^{2+} (left) and 2^{2+} (right). Isocontour value: ±0.002 e/bohr^3.

For the neutral complexes **1** and **2**, the $\nu_{M-C\equiv C}$ and $\nu_{C\equiv C}$ vibrational frequencies are computed at 2047 cm^{-1} (1779 km/mol) and 2183 cm^{-1} (129 km/mol) (**1**) and at 2057 cm^{-1} (2028 km/mol) and 2184 cm^{-1} (138 km/mol) (**2**) in excellent agreement with the experimentally determined values (Table 2). The vinyl $\nu_{C=C}$ bands are calculated at 1472 cm^{-1} (291 km/mol) and 1590 cm^{-1} (278 km/mol) for **1**, and 1472 cm^{-1} (304 km/mol) and 1590 cm^{-1} (314 km/mol) for **2**. Again, these values are in excellent agreement with the observed bands at 1591 and 1592 cm^{-1}, the bands calculated to fall below 1500 cm^{-1} not being clearly resolved in the experimental spectra. For the monocationic system $\mathbf{1}^+$ for which no experimental values are observed, strong and moderate $\nu_{C\equiv C}$ bands are calculated at 2000 cm^{-1} (2580 km/mol) and 2191 cm^{-1} (1148 km/mol), whereas a $\nu_{M-C\equiv C}$ band is calculated at 2040 cm^{-1} (1999 km/mol). Overall, these values reflect localized oxidation of one Fe(dppe)Cp* moiety. The vinyl $\nu_{C=C}$ band shifts somewhat to 1548 cm^{-1} (2130 km/mol) for $\mathbf{1}^+$.

In the case of $\mathbf{2}^+$, a very intense $\nu_{M-C\equiv C}$ band is calculated at 1953 cm^{-1} (62580 km/mol) and involved a coupled oscillation of both Ru−C≡C fragments. Vibration of the C≡C bonds associated with the vinyl moiety are calculated at 2156 cm^{-1} (1036 km/mol). The very high oscillator strength of the $\nu_{M-C\equiv C}$ band arising from vibration along the electron-transfer axis in **2**$^{+}$ accounts for the observation of a band from this species in the experimental spectroelectrochemical experiment, despite the low equilibrium concentration of this species.

For the dicationic (triplet) system **1**$^{2+}$, two moderately intense $\nu_{M-C\equiv C}$ and $\nu_{C\equiv C}$ vibrations are calculated at 2025 cm^{-1} (458 km/mol) and 2181 cm^{-1} (436 km/mol), respectively, while the vinyl $\nu_{C=C}$ band at 1551 cm^{-1} (574 km/mol) would be experimentally indistiguishable from that in **1**$^{+}$. These values compare very well with the spectroelectrochemically observed bands at 2191 ($\nu_{C\equiv C}$), 1991 ($\nu_{M-C\equiv C}$), and 1563 ($\nu_{C=C}$) cm^{-1}. The observation of additional bands in the experimental spectra is not unexpected, given the conformational flexibility of these complexes with regard to the dihedral angles among the key Fe(dppe)Cp*, C_6H_4, and Fc moieties. For the Ru analogue **2**$^{2+}$, $\nu_{M-C\equiv C}$ and $\nu_{C\equiv C}$ vibrations are calculated at 1914 cm^{-1} (1729 km/mol) and 2150 cm^{-1} (3974 km/mol), respectively. The vinyl $\nu_{C=C}$ vibration is computed at 1512 cm^{-1} (1975 km/mol). These values are comparable to those experimentally measured (Table 2).

With the vibrational data giving confidence in the relevance of the optimized molecular geometries to the experimental samples, attention was turned to further exploration of the electronic structures. Mulliken atomic spin densities of the monocationic species **1**$^{+}$ and **2**$^{+}$ were computed and compared to gain insight concerning the (de)localization of the unpaired electron over the molecule, as well as some indication about the electronic communication between the metal end groups via the Fc-carbon backbone. The results reveal a quite asymmetric iron cation **1**$^{+}$ with the unpaired electron mostly localized on one branch, especially on the −C≡C−Fe(dppe)Cp* end-cap unit (Figure 14, left). The spin density on Fc is very small (0.02 e), indicating that the oxidation occurs mainly at one iron−ethynyl unit. For **2**$^{+}$, the situation differs, with the unpaired electron more extensively delocalized over the whole molecule with comparable contribution on the Ru atoms and Fc (Ru2, 0.13 e; Ru3, 0.17 e; Fc, 0.12 e; carbon backbone, 0.88 e) (Figure 14, right). This indicates that electron density is removed from three metal centers and the carbon backbone upon oxidation of **2**. Finally, it is worth mentioning that a more substantial spin density on the β-carbon atom close to the ferrocenyl group is computed for **2**$^{+}$ (0.20 e) in comparison to **1**$^{+}$ (0.04 e).

Mulliken atomic spin densities of the dicationic species **1**$^{2+}$ and **2**$^{2+}$ with their triplet electronic configuration were also computed (Figure 15). Note that the broken-symmetry singlets (BSs) featuring the antiferromagnetic states are computed to be almost isoenergetic (less stable by 0.001 eV (ca. 0.2 kcal/mol)). For the iron species, the spin density is mainly localized on the iron atoms of the Fe(dppe)Cp* fragments (Fe2, 1.13 e; Fe3, 1.13 e) and to a lesser extent on the carbon bridge (0.67 e), consistent with the formal assignment of Fe(III) oxidation states for these fragments. The contribution on the Fe atom of the ferrocenyl (Fc) moiety is very weak (0.02 e). In the case of the ruthenium species, the spin density is more evenly distributed over the whole molecule with 1.69 e on the carbon bridge and 0.47 and 0.46 e on the Ru2 and Ru3 ruthenium centers, respectively. Note that, while the participation of the ferrocenyl iron atom Fe1 is small (0.07 e), this is still significantly greater than in the iron species (0.02 e).

ESR properties of the complexes **1**$^{n+}$ (n = 1, 2) and **2**$^{n+}$ (n = 1, 2) were also computed. The resulting **g** tensor components are given in Table 4 for a comparison with experiment. The agreement is moderately satisfactory, although the computed values indicate some anisotropy of the rhombic **g** tensor ($\Delta g = g_1 - g_3$) for both compounds, which is not observed experimentally. Moreover, the values calculated for **1**$^{+}$ and **1**$^{2+}$ differ substantially; this suggests that the concentration of **1**$^{+}$ in the comproportionated mixture studied experimentally is too low to be observed. In addition, the small values of Δg computed for the mono-oxidized forms **1**$^{+}$ (0.111) and **2**$^{+}$ (0.069) are consistent with an important degree of delocalization of the odd electron in these mixed-valence species, especially for the ruthenium compound.[34] However, these results must be taken with caution, as it is known that the rotational orientation of the M(dppe)Cp* fragments around the M−C≡C axis relative to the conjugated ligand can strongly influence the **g**-tensor values.[71] Despite these ambiguities, the smaller values of the **g**-tensor components for **2**$^{+}$ and **2**$^{2+}$ with respect to **1**$^{+}$ and **1**$^{2+}$ reflect more delocalization in the ruthenium compounds, as inferred from the experimental spectroscopic data and electronic structure calculations.

Table 4. Computed (*Experimental*) ESR Parameters for 1^{n+} and 2^{n+} (n = 1, 2)

compd	g_1	g_2	g_3	g_{iso}	Δg
1^{+}	2.003	2.083	2.114	2.067 (*2.1265*)	0.111
1^{2+}	1.980	2.114	2.222	2.106 (*2.1265*)	0.242
2^{+}	2.006	2.044	2 0.075	2.042	0.069
2^{2+}	1.880	1.947	2.019	1.949 (*2.1034*)	0.139
6^{+}	1.165	1.181	4.473	2.273	3.308
7^{+}	1.994	2.105	2.140	2.079	0.146

In order to explore the involvement of the Fc group in the ESR properties of **1**$^{n+}$ and **2**$^{n+}$ (n = 1, 2), **g**-tensor computations were performed on the iron models $[FcCH{=}CH_2]^+$ (**6**$^{+}$) and $[CH_2{=}C\{1,4\text{-}C{\equiv}C{-}C_6H_4{-}C{\equiv}C{-}Fe(dppe)Cp^*\}_2]^+$ (**7**$^{+}$) for comparison. As expected, an axial **g** tensor is obtained for **6**$^{+}$ with two different tensor components ($g_{\parallel}$ = 1.173 and $g_{\perp}$ = 4.473). Such values are comparable to those expected for Fc^{+} complexes.[72−74] Computations on model **7**$^{+}$ predict a g_{iso} value of 2.079 and a rhombic splitting of the **g** tensor with g_1 = 1.994, g_2 = 2.105, and g_3 = 2.140 which differs very slightly from that computed for **1**$^{+}$ (Table 4). These results seem to indicate a relatively minor role of the Fc group on the ESR properties of **1**$^{n+}$ and **2**$^{n+}$.

■ CONCLUSION

The complexes FcCH=C{1,4-C≡C−C_6H_4−C≡CM(dppe)-Cp*}$_2$ (Fc = ferrocenyl (FeCp(η-C_5H_4-); M = Fe (**1**), Ru (**2**)) and their redox-related products have provided further opportunities to explore the electronic differences and characteristics of putative mixed-valence complexes derived from the half-sandwich {M(dppe)Cp*} moieties, through an "extended" cross-conjugated bridging ligand. Despite the low (unresolved) separation of the first two oxidation processes, in the case of the ruthenium species **2** a combination of UV−vis−NIR and IR spectroelectrochemistry can be used to detect the presence of mixed-valence **2**$^{+}$ in the comproportionated mixture. Electron exchange between the metal complex "branches" of **2**$^{+}$ appears to be fast on the EPR time scale, with significant contributions from the carbon chain and organic-like singlet in the EPR spectrum. Quantum chemical analysis supports the description of 2^+ in terms of a polarized, but still rather extensively delocalized, system with substantial spin density over the bridging ligand framework. In contrast, the iron complex **1** gives rise to much more metal localized redox behavior. Apparently the more limited delocalization into the carbon-rich bridging ligand lowers the thermodynamic stability of mixed-valence 1^+, which cannot be detected spectroscopically using the methods available here. Thus, as has been observed recently in linearly conjugated systems,[37] the limited d−π mixing associated with 3d metals such as Fe promotes more localized behavior in mixed-valence complexes featuring carbon-rich bridging ligands, while heavier 4d metals such as Ru mix more extensively with the ligand, leading to more bridge-based redox character.

■ EXPERIMENTAL SECTION

All reactions were carried out using standard Schlenk techniques under dry, inert atmospheres of argon (reactions involving FeCl(dppe)Cp*) or nitrogen (all other reactions). Triethylamine was distilled over potassium hydroxide; hexanes, diethyl ether, and tetrahydrofuran were dried by passage over an alumina column or distilled from sodium benzophenone ketyl. Methanol was dried and distilled from magnesium methoxide. Dichloromethane was dried either by distillation under argon from P_2O_5 and then Na_2CO_3 or on an Inert Technologies solvent purification system. Triethylamine and methanol were further deoxygenated by sparging with N_2 or Ar before use. Other solvents were standard reagent grade and used as received. No special precautions were taken to exclude air or moisture during workup, except where otherwise indicated. The compounds FeCl(dppe)Cp*·CH_2Cl_2 and RuCl(dppe)Cp*,[44] FcCH=C{C≡CH}$_2$,[31] and Pd(PPh_3)$_4$[75] were prepared according to published procedures. The compound 4-(trimethylsilylethynyl)bromobenzene was prepared by a minor variation of the published route,[76] as detailed in the Supporting Information. Other chemicals were purchased from commercial sources and used without further purification.

Instruments. Solid-state infrared spectra were obtained as KBr pellets with a Bruker IFS28 FT-IR infrared spectrophotometer (4000−400 cm^{-1}), and solution spectra on a Cary 660 instrument. Near-IR and UV−visible spectra were recorded in solution using a 1 cm length quartz cell on a Cary 5000 spectrophotometer. NMR spectra were recorded at 25 °C on a Bruker Avance III 600 (^1H, 600.1 MHz; ^{13}C, 150.9 MHz; ^{31}P, 242.9 MHz), a Bruker Avance III 500 (^1H, 500.1 MHz; ^{13}C, 125.8 MHz; ^{31}P, 202.4 MHz) or a Bruker Avance 400 (^1H, 400.1 MHz; ^{13}C, 100.6 MHz) spectrometer using $CDCl_3$ or CD_2Cl_2 as the solvent. Chemical shifts (ppm) were determined relative to internal residual solvent signals (^1H, ^{13}C)[77] or external 85% H_3PO_4 (^{31}P, δ 0.0 ppm). Cyclic voltammetry was carried out in a nitrogen-filled glovebox using a PalmSens Emstat^{3+} potentiostat, with platinum working electrode, a platinum-plated titanium-wire counter electrode, and a platinum-plated titanium wire pseudoreference electrode, from solutions of the complex (ca. 0.2 mM) in dichloromethane containing 0.1 M NBu_4PF_6 as the electrolyte: ν = 100 mVs^{-1}. The cobaltocene/cobaltocenium couple was used as an internal reference for potential measurements such that $Cp_2Co/[Cp_2Co]^+$ falls at −1.30 V relative to external $Cp_2Fe/[Cp_2Fe]^+$ at 0.00 V.[40] Electron spin resonance (ESR) spectra were recorded on a Bruker EMX-8/2.7 (X-band) spectrometer at 77 K (liquid nitrogen). Spectroelectrochemistry was conducted in an OTTLE cell,[78] using solutions in dichloromethane containing 0.1 M nBu_4NPF_6 as the supporting electrolyte. Spectra were recorded on an Agilent Technologies Cary 660 FT-IR, an Agilent Technologies Cary 5000 UV−vis−NIR, or an Avantes diode array UV−vis−NIR system comprising two light sources (UV−vis, AvaLight-DH-S-Bal; vis−NIR, AvaLight-Hal-S) and two spectrometers (UV−vis, AvaSpec-ULS204−8L-USB2; NIR, AvaSpec-NIR256-2.5TEC) connected to a custom-built sample holder by bifurcated fiber optic cables. The Vis−NIR light source was attenuated with a band-pass filter transparent between ∼900 and 4700 nm. Mass spectrometry was carried out employing ASAP (APCI), ESI, MALDI, or EI ionization techniques. Elemental analyses were performed at the London Metropolitan University.

FcCH=C{1,4-C≡C−C_6H_4−C≡CSiMe$_3$}$_2$ (3). A mixture of FcCH=C{C≡CH}$_2$ (762 mg, 2.93 mmol), 4-(trimethylsilylethynyl)-bromobenzene (1.56 g, 6.15 mmol), Pd(PPh_3)$_4$ (160 mg, 147 μmol), CuI (28.0 mg, 147 μmol), and triethylamine (50 mL) was heated at reflux for 17 h and then cooled to ambient temperature. Following removal of the solvent, the residue was purified by column chromatography (eluent: hexanes/ethyl acetate (98/2 (v/v))) to afford FcCH=C{1,4-C≡C−C_6H_4−C≡CSiMe$_3$}$_2$ as a red solid (661 mg, ∼80% purity by ^1H NMR). Analytically pure FcCH=C{1,4-C≡C−C_6H_4−C≡CSiMe$_3$}$_2$ was obtained following preparative TLC of this solid (eluent: hexanes/ethyl acetate (98/2 (v/v))). which was carried out in small batches immediately prior to its use in further reactions. For a typical preparative TLC purification, 109 mg of crude **3** gave 53 mg of pure product. ^1H NMR (500 MHz, $CDCl_3$): δ 0.26 (s, 9H, Si(CH_3)$_3$), 0.27 (s, 9H, Si(CH_3)$_3$), 4.22 (5H, s, C_5H_5), 4.55 (m, 2H, C_5H_4), 4.88 (m, 2H, C_5H_4), 6.99 (s, 1H, C=CH), 7.41−7.51 (m, 8H, C_6H_4). ^{13}C NMR (125 MHz, $CDCl_3$): δ 0.07 (Si(CH_3)$_3$), 69.9 (C_5H_5), 70.0 (C−H, C_5H_4), 70.9 (C−H, C_5H_4), 79.6 (C−CH=C, C_5H_4), 87.3 (C≡C), 89.8 (C≡C), 91.6 (C=C−H), 93.3 (C≡C), 96.4 (C≡C−Si), 96.7 (C≡C−Si), 98.9 (C≡C), 104.8 (C≡C), 104.9 (C≡C), 122.8 (C−C≡C, C_6H_4), 123.2 (C−C≡C, C_6H_4), 123.5 (C−C≡C, C_6H_4), 123.5 (C−C≡C, C_6H_4), 131.3 (C−H, C_6H_4), 131.4 (C−H, C_6H_4), 132.0 (C−H, C_6H_4), 132.2 (C−H, C_6H_4), 145.6 (C=C−H). FT-IR (CH_2Cl_2): ν 2209 (C≡C), 2156 (C≡C−Si), 1576 cm^{-1} (C=C). ASAP-MS(+): m/z 605.2 $[M + H]^+$. Anal. Calcd for $C_{38}H_{36}Si_2Fe$: C, 75.48; H, 6.00. Found: C, 75.40; H, 6.12.

FcCH=C{1,4-C≡C−C_6H_4−C≡CH}$_2$ (4). A Schlenk tube was charged with FcCH=C{1,4-C≡C−C_6H_4−C≡CSiMe$_3$}$_2$ (218 mg, 0.36 mmol) and an excess of K_2CO_3 (299 mg, 2.76 mmol, 6 equiv), and the solids were dissolved in 2/1 MeOH/THF (18 mL). The reaction was stirred at room temperature for 4 h, after which the solvents were removed under reduced pressure and the solid residue was extracted with diethyl ether. The extracts were combined, the solvent was removed under reduced pressure, and the resulting red powder was dried in vacuo for 1 h to yield **4**, which was briefly characterized before further use (166 mg, 0.36 mmol, nominally 100%) . ^1H NMR (400 MHz, $CDCl_3$): δ 2.98 (s, 1H, C≡CH), 3.00 (s, 1H, C≡CH), 4.02 (s, 5H, C_5H_5), 4.25 (s, 2H, C_5H_4), 4.69 (s, 2H, C_5H_4), 6.82 (s, 1H, C=CH), 7.06 (s, 2H, C_6H_4), 7.26 (s, 2H, C_6H_4), 7.31 (m, 4H, C_6H_4).

[FcCH=C{1,4-C≡C−C_6H_4−CH=C=Fe(dppe)Cp*}$_2$](PF$_6$)$_2$ (5-(PF$_6$)$_2$). A Schlenk tube was charged with a freshly prepared sample of **4** (149 mg, 0.32 mmol), FeCl(dppe)Cp*·CH_2Cl_2 (477 mg, 0.67 mmol, 2.1 equiv), and NH_4PF_6 (109 mg, 0.67 mmol), before addition of 2/1 MeOH/THF (15 mL). The reaction medium was stirred at room temperature for 48 h, the solvents were removed, and the product was extracted with dichloromethane (2 × 10 mL). The combined extracts were concentrated to 5 mL under vacuum, and addition of methanol (15 mL) caused the precipitation of a red solid that was collected by filtration, washed with methanol (3 × 10 mL), and dried in vacuo to afford **5(PF$_6$)$_2$** (401 mg, 0.208 mmol, 65%), as a red powder. ^1H NMR (400 MHz, $CDCl_3$): δ 1.51 (s, 30H, $C_5(CH_3)_5$), 2.42 (m, 4H, CH_2), 2.98 (m, 4H, CH_2), 4.15 (s, 5H, C_5H_5), 4.40 (s, 2H, C_5H_4), 4.81 (s, 2H, C_5H_4), 5.04 (m, 2H, Fe=C=CH), 6.21 (m, 2H, C_6H_4), 6.51 (m, 2 H, C_6H_4), 6.90 (s, 1 H, C=CH), 7.02 (m, 2 H, C_6H_4), 7.10 (m, 10H, C_6H_4+m-$C_6H_5/_{dppe}$), 7.26 (m, 8H, m-$C_6H_5/_{dppe}$), 7.39 (m, 16H, o-$C_6H_5/_{dppe}$), 7.52 (m, 8H, p-$C_6H_5/_{dppe}$). ^{31}P NMR (162 MHz, $CDCl_3$): δ = 86.5 (s, dppe), 86.6 (s, dppe), −144.5 (septet, $^1J_{P-F}$ = 710 Hz, PF_6). FT-IR (KBr): ν 2184 s (C≡C), 1640 s (Fe=C=C), 831 s (PF_6) cm^{-1}.

FcCH=C{1,4-C≡C−C_6H_4−C≡C−Fe(dppe)Cp*}$_2$ (1). *Route A.* Potassium fluoride (8.0 mg, 130 μmol) and FeCl(dppe)Cp*·CH_2Cl_2 (98 mg, 138 μmol) were added to a solution of **3** (42 mg, 69 μmol) in tetrahydrofuran (4 mL) and methanol (4 mL), and the mixture was heated at reflux for 20 h. Following cooling to ambient temperature, a solution of potassium *tert*-butoxide in methanol (10 mL, 0.1 M) was added, affording a deep red precipitate. The precipitate was filtered under Schlenk conditions, washed with a solution of potassium *tert*-butoxide in methanol (10 mL, 0.1 M) and hexanes (10 mL), and dried

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under vacuum to afford **1** as a red powder (109 mg, 67 μmol, 97%). The product was transferred directly to a nitrogen-filled glovebox, and all further manipulations were carried out therein.

Route B. A Schlenk tube was charged with the bis-vinylidene complex **5(PF$_6$)$_2$** (400 mg, 0.208 mmol), KOBu^t (58.0 mg, 0.52 mmol, 2.5 equiv), and THF (20 mL). The reaction mixture was stirred at room temperature for 2 h. The solvent was evaporated to dryness under vacuum, and the crude residue was extracted with dichloromethane (2 × 10 mL). After removal of the solvent from the combined extracts under reduced pressure, the solid material was washed with pentane (10 mL) and dried in vacuo to give **1** as a red powder (340 mg, 0.208 mmol, 100% yield). ^{1}H NMR (500 MHz, CD_2Cl_2): δ 1.42 (br s, 30H, $C_5(CH_3)_5$), 2.00 (br s, 4H, CH_2), 2.63 (br s, 4H, CH_2), 4.21 (br s, 5H, C_5H_5), 4.41 (br s, 2H, C_5H_4), 4.90 (br s, 2H, C_5H_4), 6.80−6.89 (m, 5H, C_6H_4 and C═C*H*), 7.17−7.45 (m, 36H, C_6H_4 and C_6H_5), 7.85 (br s, 8H, C_6H_5). ^{31}P NMR (202 MHz, CD_2Cl_2): δ 99.3. FT-IR (CH_2Cl_2): ν 2201 w,sh, 2187 w (C≡C), 2046 s,br (C≡C−Fe), 1591 s cm^{-1} (C═C). Anal. Calcd for $C_{104}H_{96}P_4Fe_3$: C, 76.29; H, 5.91. Found: C, 76.67; H, 5.51. HRMS (ESI$^+$): *m/z* calculated for $C_{104}H_{96}P_4{}^{56}Fe_3$, 1635.43877; calculated for $C_{104}H_{97}P_4{}^{56}Fe_3$ ([M + H]$^+$), 1636.4466; found, 1636.4508 (0 ppm) ([M + H]$^+$).

FcCH═C{1,4-C≡C−C_6H_4−C≡C−Ru(dppe)Cp*}$_2$ (2). Potassium fluoride (10 mg, 175 μmol) and RuCl(dppe)Cp* (117 mg, 175 μmol) were added to a solution of **3** (53.0 mg, 88.0 μmol) in tetrahydrofuran (5 mL) and methanol (5 mL), and the mixture was heated at reflux for 16 h. After the mixture was cooled to ambient temperature, methanol (15 mL) was added, affording an orange precipitate. The precipitate was collected by filtration, washed with methanol (2 × 15 mL) and hexanes (2 × 15 mL), and dried under vacuum to afford **2** as an orange powder (99 mg, 57 μmol, 65%). ^{1}H NMR (600 MHz, CD_2Cl_2): δ 1.57 (s, 15H, $C_5(CH_3)_5$), 1.58 (s, 15H, $C_5(CH_3)_5$), 2.11 (m, 4H, CH_2), 2.69 (m, 4H, CH_2), 4.20 (s, 5H, C_5H_5), 4.41 (m, 2H, C_5H_4), 4.88 (m, 2H, C_5H_4), 6.71 (m, 2H, C_6H_4), 6.76 (m, 2H, C_6H_4), 6.86 (s, 1H, C═C*H*), 7.15 (m, 2H, C_6H_4), 7.21−7.24 (m, 10H, C_6H_4 and C_6H_5), 7.37−7.39 (m, 24H, C_6H_5), 7.77 (m, 8H, C_6H_5). ^{31}P NMR (242 MHz, CD_2Cl_2): δ 80.6. FT-IR (CH_2Cl_2/cm^{-1}): ν(C≡C) 2189 w, ν(RuC≡C) 2062 s,br, ν(C═C) 1592 s. MALDI-MS(+): *m/z* 1729.3 [M + H]$^+$. Anal. Calcd for $C_{104}H_{96}P_4FeRu_2$: C, 72.30; H, 5.60. Found: C, 72.15; H, 5.63.

In Situ Preparation of [FcCH═C{1,4-C≡C−C_6H_4−C≡C−Fe(dppe)Cp*}$_2$](PF$_6$)$_n$ (1(PF$_6$)$_n$, *n* = 0−2). A Schlenk tube was charged with **1** (0.030 g, 0.018 mmol) and THF (7 mL). The solution was cooled to −60 °C prior to adding ferrocenium hexafluorophosphate (0.0050 g, 0.018 mmol, 1 equiv) in a single portion. The reaction mixture was warmed to room temperature overnight before adding 10 mL of pentane with vigorous stirring. The resulting precipitate was collected by filtration, washed with pentane (2 × 5 mL), and dried in vaccuo to yield 0.014 g of a comproportionated mixture of **1**, **1(PF$_6$)**, and **1(PF$_6$)$_2$** as a red powder (0.0078 mmol, 40%). For ESR measurements, the low-temperature-generated red solution was directly transferred via cannula into an ESR tube conserved at liquid nitrogen temperature.

In Situ Generation of [FcCH═C{1,4-C≡C−C_6H_4−C≡C−Fe(dppe)Cp*}$_2$](PF$_6$)$_2$ (1(PF$_6$)$_2$). The dioxidized product **1(PF$_6$)$_2$** was synthesized in a manner similar to that described above, from **1** (0.050 g, 0.030 mmol) and ferrocenium hexafluorophosphate (0.020 g, 0.060 mmol, 2.0 equiv). Yield: 0.03 g (0.015 mmol, 52%) of a red powder. The same procedure as above was carried out to prepare the ESR samples.

Computational Details. Density functional theory (DFT) calculations were performed using the Gaussian09 program package.[79] Full geometry optimizations were carried out without any symmetry constraint using the PBE0 functional[80] within the LANL2DZ ECP basis set,[81−84] augmented by a polarization function for all atoms except H. Vibrational frequency calculations were computed for all optimized geometries to ensure they were true minima on the potential energy surface (PES). A scaling factor of 0.95 was applied on computed vibrational frequencies discussed in the text.[85] Molecular structures, orbitals, and spin densities were plotted using the GaussView program.[86] Orbital compositions were obtained using the AOMix program.[87,88]

The Amsterdam Density Functional (ADF) program[89−91] was employed to compute the EPR properties of the cationic species using geometries optimized via Gaussian09. Electron correlation was treated within the local density approximation (LDA) in the Vosko−Wilk−Nusair parametrization.[92] Nonlocal corrections were added to the exchange and correlation energies using the PBE0 functional.[80] Calculations were performed using the standard ADF triple-ζ quality basis set. The ESR procedure developed by van Lenthe and co-workers was used.[93−95] The **g**-tensor components were obtained using self-consistent spin-unrestricted DFT calculations after incorporating the relativistic spin−orbit coupling by first-order perturbation theory from a ZORA Hamiltonian.[89,90]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.8b00740.

> Plots of the UV−vis spectra of **1** and **2**, plots of the intermediate NIR spectra collected during the spectroelectrochemical oxidation of **1**, revised synthetic procedure for the synthesis of 4-(trimethylsilylethynyl)-bromobenzene, and plots of NMR spectra (PDF)
>
> Cartesian coordinates for all calculated geometries (MOL)

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Notes

The authors declare no competing financial interest.

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