Aromatic Iridacycles

JOHN R. BLEEKE*

Department of Chemistry, Washington University, One Brookings Drive, St. Louis, Missouri 63130

Received March 22, 2007

ABSTRACT

The first example of a *family* of related aromatic metallacycles has been synthesized, and the physical and chemical properties of its individual members have been investigated. The metallacyclic rings in these compounds are, in general, constructed from pentadienyl- or heteropentadienyliridium precursors via C–H bond activation processes. The molecules display the structural and spectroscopic features of aromaticity, including ring planarity, π-bond delocalization, and diamagnetic ring current effects. The reactivity profile of the molecules is complex, reflecting the simultaneous presence of an aromatic ring and a reactive metal center.

Introduction

Ever since August Kekulé[1] proposed the cyclic structure of benzene, "aromaticity" has been one of the most vexing and yet one of the most fascinating topics in chemistry. For more than 140 years, theorists and synthesists have struggled with the elusive essence of aromaticity, and the field has historically provided one of the most fruitful interplays of theory and experiment in chemistry.[2] As evidenced by the recent thematic issue of *Chemical Reviews*,[3] interest in aromaticity shows no signs of abating.

One class of aromatic molecules that has received increasing attention over the past several decades is *aromatic metallacycles*, i.e., transition metal-containing ring systems that exhibit aromatic properties. While much of this attention has been focused on metallabenzenes,[4] which are the archetypical aromatic metallacycles, progress has also been made in synthesizing and studying the properties of heteroatom-containing systems, including metallafurans, metallapyrroles, metallathiophenes, metallapyryliums, metallapyridines, and metallathiabenzenes. Even stable metallabenzynes have recently joined the menagerie of aromatic metallacycles.[5]

The history of this field can be traced back to a seminal paper by Thorn and Hoffmann[6] in which five-carbon delocalized metallacycles (metallabenzenes) were first examined theoretically. Three hypothetical classes of compounds were identified as good candidates for exhibiting the delocalized bonding characteristics of aromatic species. Shortly thereafter, in 1982, the first example of a

stable isolable metallabenzene was reported by Roper.[7] Roper's "osmabenzene" was synthesized by a cyclization reaction involving a thiocarbonyl ligand and two ethyne molecules. The X-ray structural analysis showed an essentially planar metallacycle and delocalized bonding within the ring.

Following Roper's 1982 communication, there was a hiatus in the field until the late 1980s when we succeeded in synthesizing a stable iridabenzene,[8] using a pentadienide reagent as the source of ring carbon atoms, and C–H bond activation as the key ring-forming reaction. The initially formed six-membered ring was an iridacyclohexadiene, which was "dehydrogenated" to the iridabenzene in two steps. One attractive feature of this synthetic approach was that it allowed for a side-by-side comparison of the nonaromatic iridacyclohexadiene with the aromatic iridabenzene ring system.

In subsequent work, we adapted the iridabenzene synthetic approach to produce a whole family of related five- and six-membered iridacycles. In each case, a heteropentadienide reagent supplied the ring carbons and heteroatom, while C–H bond activation closed the ring. As in the iridabenzene system, nonaromatic precursors provided important points of comparison for the ultimate aromatic products.

In this Account, we describe the scientific journey that led to this fascinating class of molecules, a journey which has now lasted more than 20 years. While the focus of this story is on synthesis and reactivity, special attention is paid to the structure and spectroscopy of these metallacycles, which provide strong evidence of their aromatic character.

Iridabenzene

In 1986, we discovered that treatment of $(Cl)Ir(PEt_3)_3$ with potassium 2,4-dimethylpentadienide leads to the high-yield production of the iridacyclohexadiene complex, **1** (Scheme 1), via an iridium-mediated C1–H1 bond activation process.[9] "Dehydrogenation" of compound **1** can then be carried out in two steps: (a) removal of the iridium hydride using methyl triflate to generate cationic **2** followed by (b) deprotonation of the α-carbon with lithium diisopropylamide in acetone.[8] The resulting iridabenzene product, **3**, is a deep red crystalline solid whose X-ray crystal structure is presented in Figure 1. The metallacyclic ring in **3** exhibits a slight puckering, with the iridium atom lying 0.24 Å out of the plane of the five carbon atoms. This displacement of the iridium atom from the ring probably results, at least in part, from steric interactions involving the ethyl groups of phosphine ligands P1 and P2 and the ring carbons,[10] but subtle electronic factors may also contribute.[11] Bonding within the ring is highly delocalized, as expected for an aromatic species. The C–C bonds in **3** range from 1.369(10) Å in length to 1.402(11) Å, while the Ir–C bond distances [2.024(8) and 1.985(8) Å]

John R. Bleeke was born in Port Washington, WI, in 1954. After receiving his B.A. degree from Carthage College (Kenosha, WI) in 1976, he began graduate studies as a NSF Predoctoral Fellow at Cornell University (Ithaca, NY) under the direction of the late E. L. Muetterties. At Cornell and later at the University of California (Berkeley, CA), he probed the mechanism of transition metal-catalyzed arene hydrogenation. In 1981, he took a faculty position at Washington University in St. Louis, where he is currently Associate Professor and Vice Chair of the Chemistry Department. Dr. Bleeke's work has centered on the synthesis and reactivity of organometallic compounds, particularly those containing pentadienyl and heteropentadienyl ligands. In addition, he has a long-standing research interest in metallabenzenes and other aromatic metallacycles.

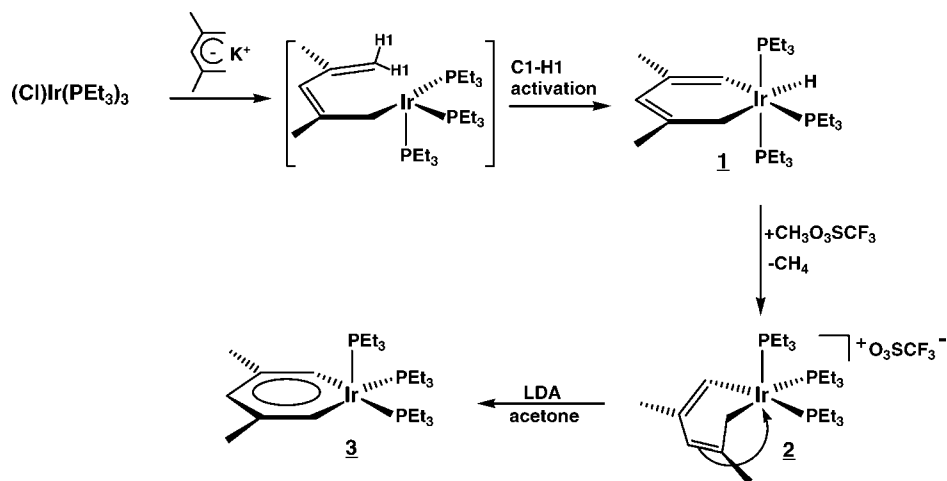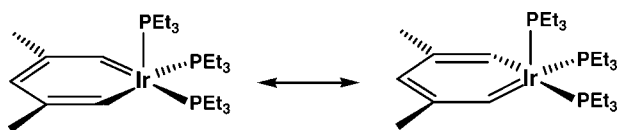* Telephone: (314)935-6809. Fax: (314) 935-4481. E-mail: bleeke@wustl.edu.

Scheme 1

Chart 1

are intermediate in length between normal Ir–C single and double bonds, signaling participation of the iridium atom in ring π-bonding.

The delocalized bonding within the iridabenzene ring can be ascribed to the contributions from the two equivalent metal–carbene resonance structures shown in Chart 1. The iridium center uses several d orbitals to interact with the p-π system of the carbon framework.[12]

The aromaticity of **3** is also indicated by the downfield ^{1}H NMR chemical shifts of the ring protons. The H1/H5 and H3 protons in **3** resonate at δ 10.91 and 7.18, respectively, while those in the nonaromatic precursor **1** appear at δ 7.00 (H1) and δ 5.93 (H3). Iridabenzene **3** adopts a square pyramidal coordination geometry in the solid state (Figure 1), but all of the phosphines appear to be equivalent as determined by solution-phase NMR,
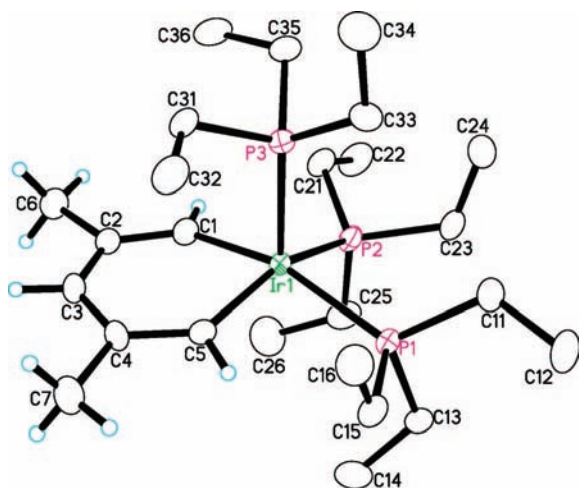

FIGURE 1. ORTEP drawing of iridabenzene, **3**. Selected bond distances in angstroms: Ir1–C1, 2.024(8); Ir1–C5, 1.985(8); C1–C2, 1.369(10); C2–C3, 1.402(11); C2–C6, 1.523(11); C3–C4, 1.370(11); C4–C5, 1.392(10); C4–C7, 1.503(12).

even at -90 °C, because of a facile intramolecular exchange process. As a result of this fluxional process, the ^{1}H NMR signal at δ 10.91 (H1/H5) appears as a characteristic phosphorus-coupled binomial quartet ($J_{H-P} = 7.2$ Hz).

The reaction chemistry of iridabenzene **3** has been extensively investigated and is described in detail elsewhere.[13] Among the most pervasive reactions is 4+2 cycloaddition with a wide variety of unsaturated substrates (see Scheme 2). These cycloaddition reactions are a consequence of two important factors: (a) the five-coordinate geometry of **3** which causes a reactive face of the iridabenzene ring to be exposed to incoming substrates and (b) the shape of the HOMO, which displays opposite phases on Ir and C3.[12] The symmetry match between the HOMO of **3** and the LUMO of the unsaturated reactant molecules allows concerted 4+2 cycloadditions to occur. Interestingly, CO_2 cycloadds to iridabenzene **3** in a 2+2 fashion, probably because the short C=O bond cannot "stretch" across the Ir–C3 ring diagonal.[14] Compound **3** also engages in several reactions in which the aromatic ring is retained. For example, treatment of **3** with excess PMe_3 produces the tris(PMe_3) analogue (**4**, Scheme 3), while reaction with I_2 or Br_2 generates oxidized iridabenzenes (**5**, Scheme 3). Treatment with (η^6-*p*-xylene)-$Mo(CO)_3$ leads to clean arene exchange and formation of (η^6-iridabenzene)$Mo(CO)_3$ (**6**, Scheme 3).

In recent years, there has been a flurry of activity in the area of iridabenzene chemistry, involving various groups worldwide. The first alternative synthetic approach, developed by Haley in 1999,[15] involves treatment of a suitable iridium precursor with a lithiated 3-vinylcyclopropene. With some precursors, an iridabenzvalene isomer is initially formed, and this then rearranges upon heating to the more stable iridabenzene.[16] Paneque has developed another alternative synthesis that involves cyclotrimerization of dimethylacetylene dicarboxylate molecules at an iridium center. The resulting iridacycloheptatriene is then oxidized, causing ring contraction to the iridabenzene.[17] Significantly, the method can be adapted to produce iridanaphthalene, the first example of a fused ring metallabenzenoid compound. Finally, both Chin[18]
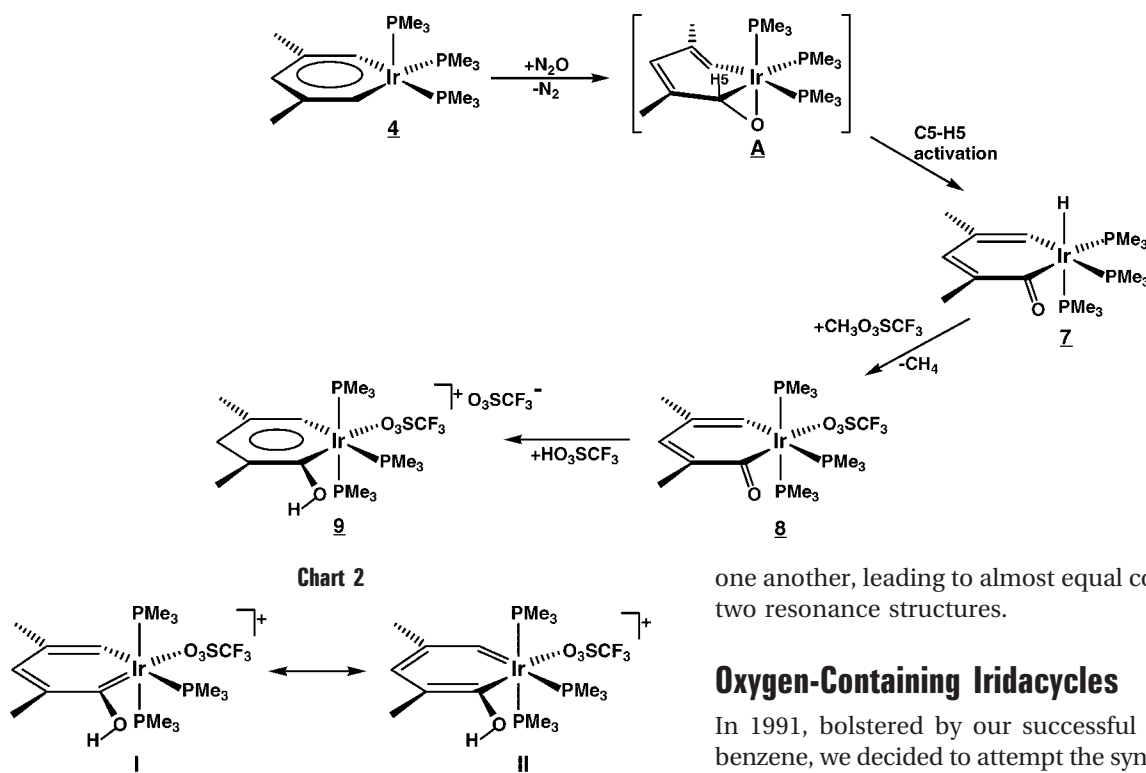
Scheme 2
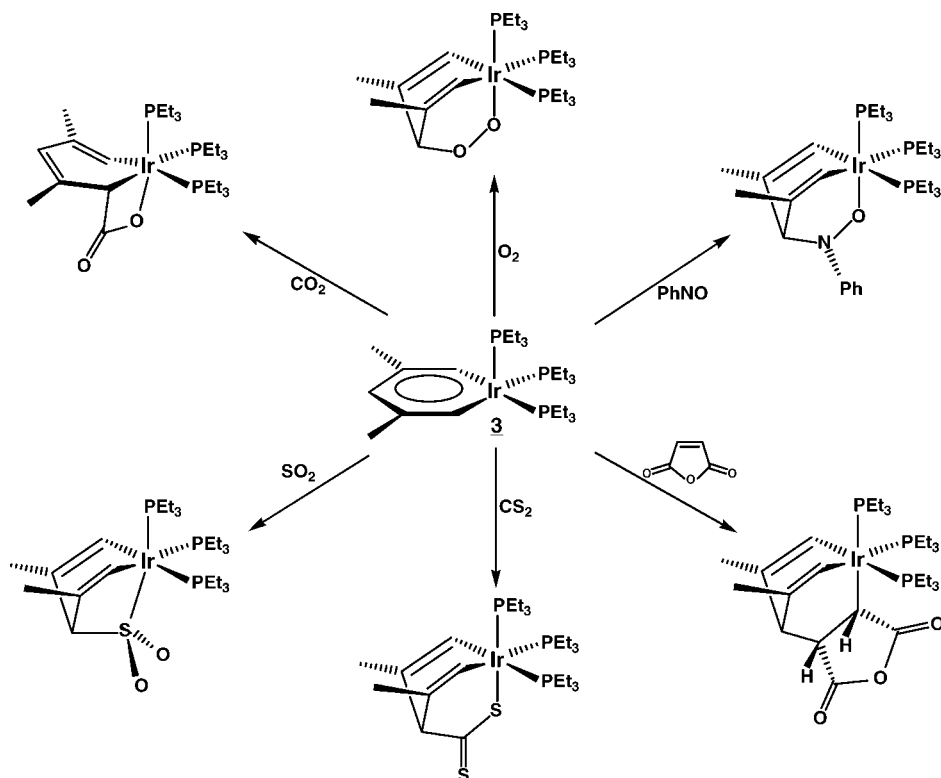
Scheme 3
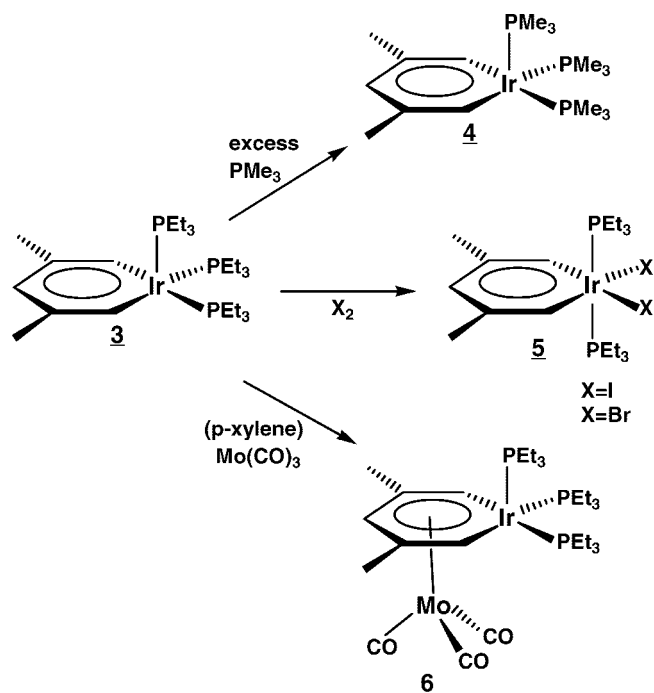
and Paneque[19] have independently produced iridabenzenes from iridacyclopentadiene precursors, while Roper and Wright[20] have recently synthesized an iridabenzene from iridacyclobutadiene precursors. The diversity of these synthetic approaches not only illustrates the vitality of the field but also is a testament to the stability of the iridabenzene structure, providing strong evidence for its aromaticity.

Iridaphenol

The synthesis of the first example of an iridaphenol resulted directly from our reactivity studies of the tris(PMe$_3$) version of iridabenzene (**4**). We found that treatment of **4** with nitrous oxide (N$_2$O) leads cleanly to the production of an iridacyclohexadienone (**7**, Scheme 4), probably through the intermediacy of a metallaepoxide (**A**, Scheme 4).[21] Note that **A** can also be viewed as an (η^2-aldehyde)metal complex. Activation of the C5–H5 bond in **A** by the iridium center leads to the observed product, **7**. Treatment of **7** with methyl triflate then removes the hydride ligand, generating the new iridacyclohexadienone (**8**, Scheme 4). Finally, protonation of yellow **8** with triflic acid occurs at the carbonyl oxygen, producing dark red-orange iridaphenol **9**.[21]

The aromatization of the ring in **9** is indicated by the downfield shifting of ring protons H1 and H3 to δ 10.54 and 7.49, respectively, from their positions of δ 9.25 and 6.66, respectively, in precursor **8**. The X-ray crystal structure of **9** (see Figure 2) further supports its aromatic character. The metallacyclic ring is planar, and the carbon–carbon bond lengths have moved toward equalization. In addition, the Ir–C bonds have been shortened from their values in precursor **8**, indicating significant metal participation in ring π-bonding. However, there are small differences in the ring bond distances (see the legend of Figure 2), suggesting that of the two resonance structures shown in Chart 2, structure **I** contributes more strongly than **II** to the overall bonding. This may result, in part, from the fact that the triflate ligand (*trans* to C5) exerts a weaker *trans* influence than the phosphine ligand (*trans* to C1). In addition, resonance structure **I** may

Scheme 4

Chart 2

benefit from heteroatom (oxygen) stabilization of the metal carbene.

Treatment of iridacyclohexadienone **8** with trifluoro-acetic acid leads to the production of a second iridaphenol (**10**, Scheme 5).[21] This reaction is accompanied by exchange of the triflate ligand for a trifluoroacetate ligand, which coordinates *cis* to C5 (*trans* to C1), allowing intramolecular hydrogen bonding to occur between the phenol oxygen and the carbonyl oxygen of the trifluoroacetate group. The bonding within the metallacycle in **10** is more highly delocalized than in **9**;[21] hence, it appears that the two structural effects discussed above for **9** offset
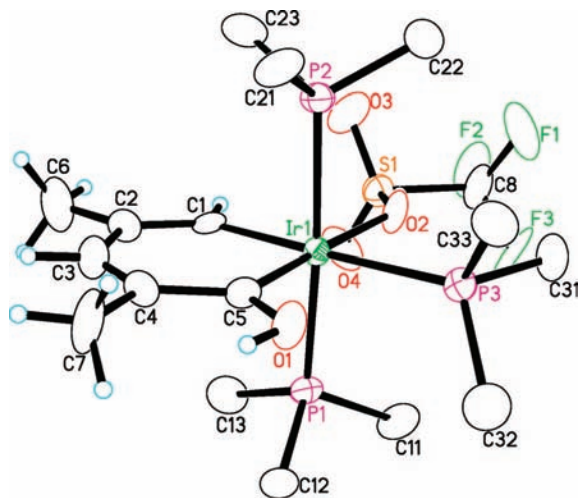

FIGURE 2. ORTEP drawing of cationic iridaphenol, **9**. Selected bond distances in angstroms: Ir1–C1, 2.031(16); Ir1–C5, 1.916(16); O1–C5, 1.331(20); C1–C2, 1.352(25); C2–C3, 1.406(26); C2–C6, 1.523(28); C3–C4, 1.355(26); C4–C5, 1.464(25); C4–C7, 1.532(28).

one another, leading to almost equal contributions by the two resonance structures.

Oxygen-Containing Iridacycles

In 1991, bolstered by our successful synthesis of irida-benzene, we decided to attempt the synthesis of analogous oxygen-containing ring systems using oxapentadienide reagents as the source of ring carbon and oxygen. A quick search of the literature revealed that Kloosterziel had synthesized potassium oxapentadienide in 1967.[22] We repeated his synthesis and reacted the oxapentadienide with $(Cl)Ir(PEt_3)_3$. As expected, the initial product of this reaction was the iridapyran (**11**, Scheme 6), formed from a 16-e$^-$ (η^1-oxapentadienyl)Ir intermediate (**B**) via C1–H1 bond activation.[23] However, when the mixture was stirred in tetrahydrofuran at room temperature, **11** gradually isomerized to an iridacyclopentenone (**12**, Scheme 6).[23] The mechanism of this transformation, outlined in Scheme 6, involves migration of hydride back to C1 to regenerate oxygen-bound η^1-oxapentadienyl intermediate **B**. Isomerization to carbon-bound η^1-oxapentadienyl species **C**, followed by oxidative addition of the aldehydic C–H bond (C4–H4), yields the observed iridacycle (**12**).

At this point, we decided to attempt to block the formation of the iridacyclopentenone by placing a methyl group at the C4 position. Synthesis of potassium 4-methyl-5-oxapentadienide went smoothly, and reaction with $(Cl)Ir(PEt_3)_3$ resulted in production of the desired 4-methyliridapyran (**13**, Scheme 7).[24] Interestingly, this compound also gradually isomerized in solution to a five-membered metallacyclic product, iridaoxacyclopentene (**14**, Scheme 7).[24] As outlined in Scheme 7, the mechanism of this transformation involves migration of hydride back to C1, generating the oxygen-bound η^1-4-methyl-5-oxa-pentadienyl species **D**. Rotation about the C2–C3 bond then places the C2–H2 bond into a position where it is activated by the iridium center.

As described in Iridafuran below, iridaoxacyclopentene **14** provides a convenient entry point to the synthesis of
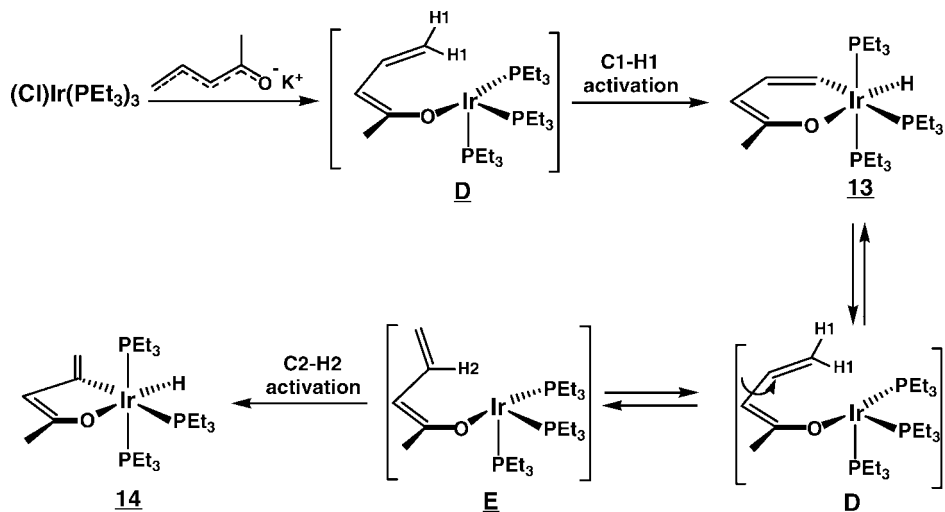
Scheme 5
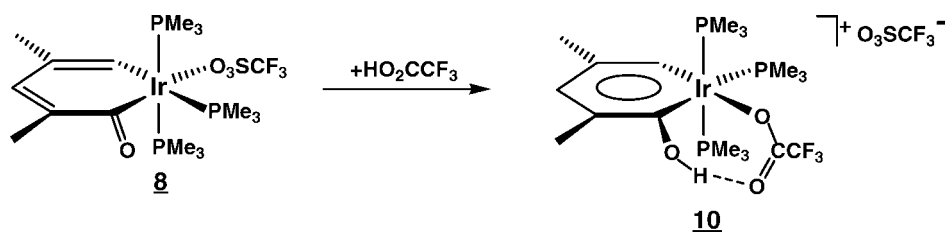
Scheme 6
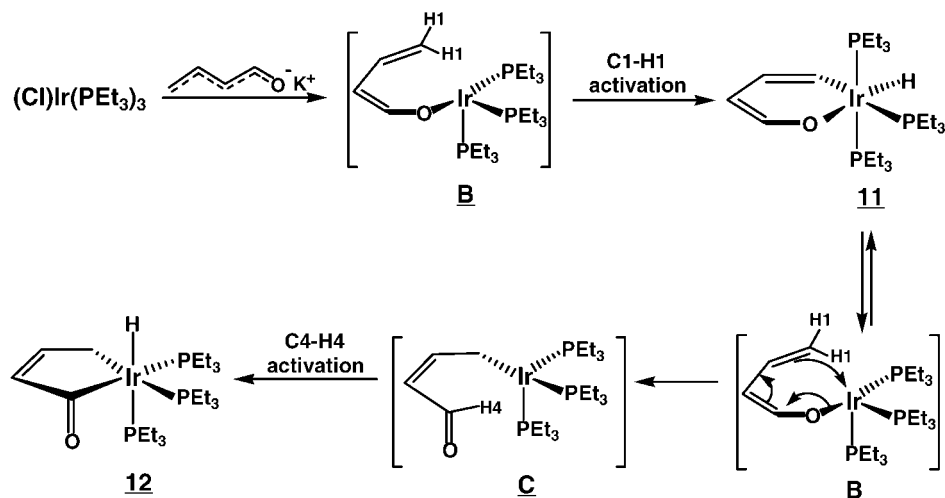
Scheme 7

iridafurans. However, our immediate goal was the synthesis of a thermodynamically stable iridapyran that could be carried on to aromatic iridapyrylium. To prevent C–H bond activation at both the 4- and 2-positions, we synthesized potassium 2,4-dimethyl-5-oxapentadienide and reacted it with (Cl)Ir(PEt₃)₃. To our great relief (!), the 2,4-dimethyliridapyran (**15**) was obtained cleanly and no further rearrangements, even upon refluxing in tetrahydrofuran, were observed.[24]

The observed thermodynamic preference for five-membered iridacyclic rings over their six-membered counterparts can be understood by considering the ring strain in each class of metallacycles. In a planar five-membered ring, the sum of the internal angles must equal

540°, and this requirement can be met without introducing any serious ring strain. In a planar six-membered ring, on the other hand, the sum of the internal angles must equal 720°, and in octahedral iridapyran complexes such as **11**, **13**, and **15** where the C–Ir–O angle is constrained to be approximately 90°, the other ring angles are forced to expand well beyond 120°. This, in turn, introduces substantial ring strain.

Iridapyrylium

With the stable 2,4-dimethyliridapyran (**15**) in hand, it was time to attempt conversion to the aromatic iridapyrylium.

Scheme 8
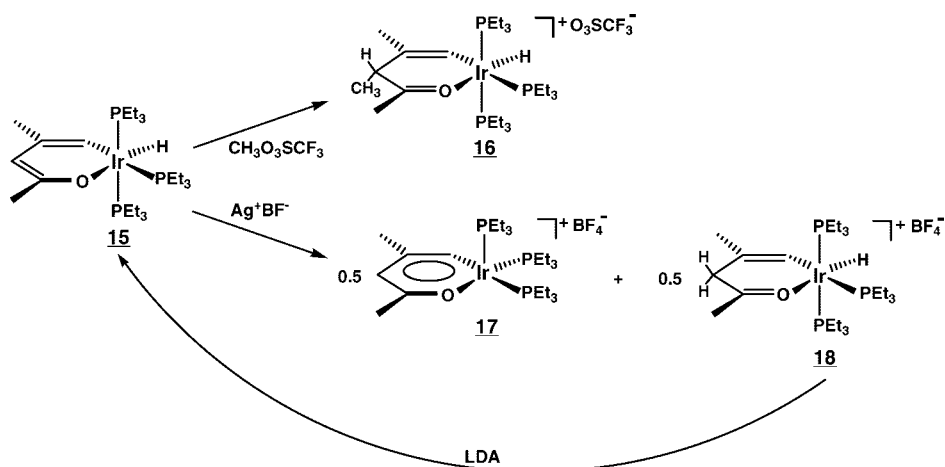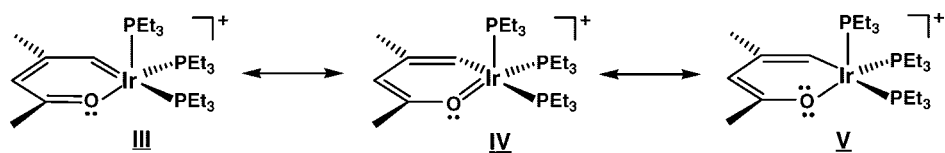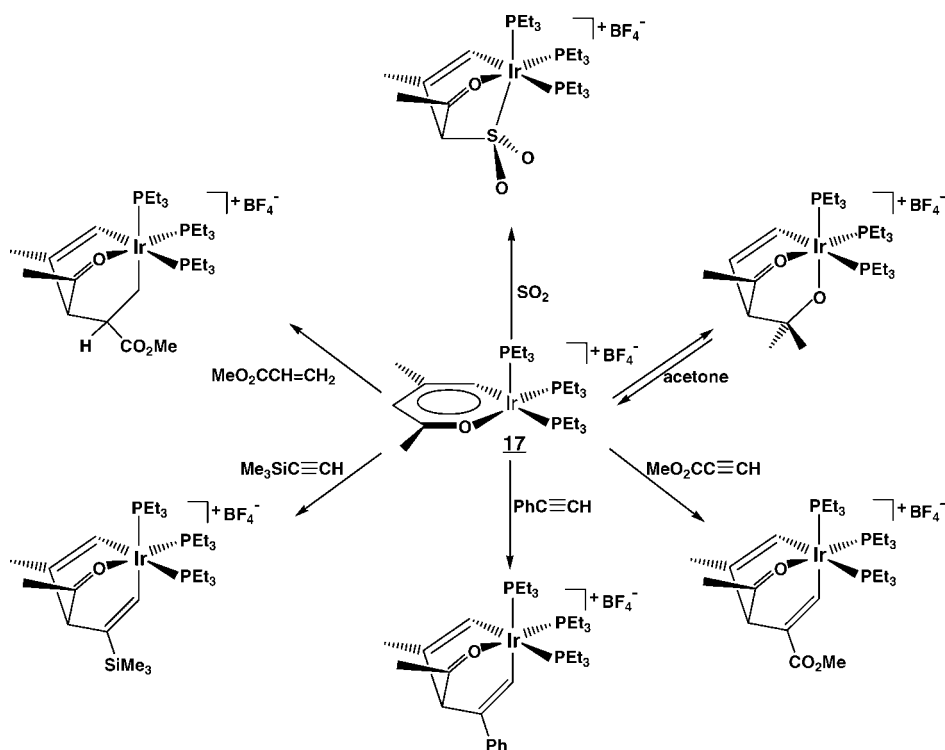

Chart 3

Scheme 9

Recalling the synthesis of iridabenzene (cf. Scheme 1), we reasoned that removal of the metal hydride would allow an oxygen lone pair to form a π-bond to the iridium center, aromatizing the ring system. Unfortunately, the reagent used to remove the hydride ligand in the iridabenzene synthesis, methyl triflate, did not react with iridapyran **15** in the same way. Instead, as shown in Scheme 8, it methylated the iridapyran ring at C3, generating an iridaoxacyclohexa-1,4-diene product, **16**.

Eventually, we discovered that treatment of iridapyran **15** with oxidizing agents such as $Ag^+BF_4^-$ leads to removal of the metal hydride and production of the desired iridapyrylium **17**, the first (and, to date, only) example of a stable metallapyrylium.[25] As shown in Scheme 8, this oxidation reaction actually generates a clean 1:1 mixture of the iridapyrylium **17** with the C3-protonated ring compound **18**. In this reaction, one-half of the iridapyran molecules are doubly oxidized and transfer their metal

Scheme 10
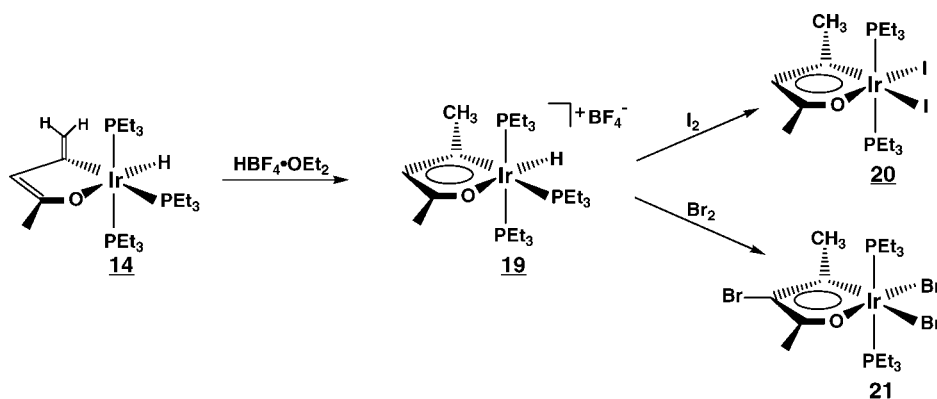
"hydrides" *as protons* to the other half of the iridapyran molecules. The doubly oxidized proton donor molecules become iridapyryliums (**17**), while the proton acceptor molecules become the protonated rings (**18**). Although the yield of **17** is only 50%, the situation is not as dire as it seems because **18** can be cleanly deprotonated with lithium diisopropylamide and, in this way, converted back to **15** for re-use.

In its ^{1}H NMR spectrum, ring protons H1 and H3 of iridapyrylium **17** are shifted downfield to δ 9.35 and 6.45 from their positions of δ 5.76 and 4.02, respectively, in iridapyran precursor **15**. This downfield shifting indicates the participation of metal orbital in ring π-bonding and the establishment of a ring current. As with iridabenzene, the H1 signal is split into a characteristic binomial quartet (J_{H-P} = 6.0 Hz) by the ^{31}P nuclei of the three rapidly exchanging phosphine ligands.

One can write three reasonable resonance structures for iridapyrylium **17** (**III–V**, Chart 3). In structures **III** and **IV**, the iridium center possesses 18 valence electrons while in **V** it possesses 16 electrons. Structures **IV** and **V** differ only in the position of an oxygen electron pair. In **IV**, it resides between oxygen and iridium, forming the π-bond, while in **V**, it resides on the oxygen. Because of the contribution from 16-e⁻ resonance structure **V**, compound **17** is reactive toward a variety of 2-e⁻ donor reagents, L, including hydride, methyllithium, chloride, and trimethylphosphine.[25] The products of these reactions are all octahedral iridapyran compounds in which L has been added to the iridium center. As shown in Scheme 9, compound **17** also undergoes 4+2 cycloaddition reactions similar to those described previously for iridabenzene.[25] Among the reactive unsaturated substrates are terminal alkynes, including phenylacetylene, trimethylsilylacetylene, and methylpropiolate, which generate novel iridaoxabarrelene frameworks. We had hoped that these compounds might be induced to release propyne and produce new iridapyryliums, but alas, they proved to be highly stable. Also noteworthy is the reversible reaction with acetone, which we discovered accidentally while cooling a sample of **17** in d_6-acetone during a variable-temperature NMR experiment. At low temperatures, the yellow acetone adduct is stable, but when the mixture is

warmed to room temperature, compound **17** is regenerated as evidenced by the reappearance of its deep violet color.[26]

Iridafuran[27]

As mentioned above, iridaoxacyclopentene **14** (see Scheme 7) serves as a convenient precursor for the synthesis of an iridafuran. Treatment of this species with acids such as $HBF_4 \cdot OEt_2$ leads to immediate protonation at the exocyclic double bond and production of the dimethylated iridafuran (**19**, Scheme 10).[28] The ^{1}H NMR spectrum of **19** provides strong evidence for its aromatic character. In particular, the signal for ring proton H3 is shifted downfield to δ 7.15 from δ 4.80 in precursor **14**, consistent with the presence of a ring current. In the X-ray crystal structure of the PF_6^- salt of **19**, the ring is planar and exhibits the expected delocalized bonding (see Figure 3 and its legend). Ir1–C2 and C4–O1 ring bonds have both been shortened significantly (with respect to their distances in **14**) to values intermediate between those of
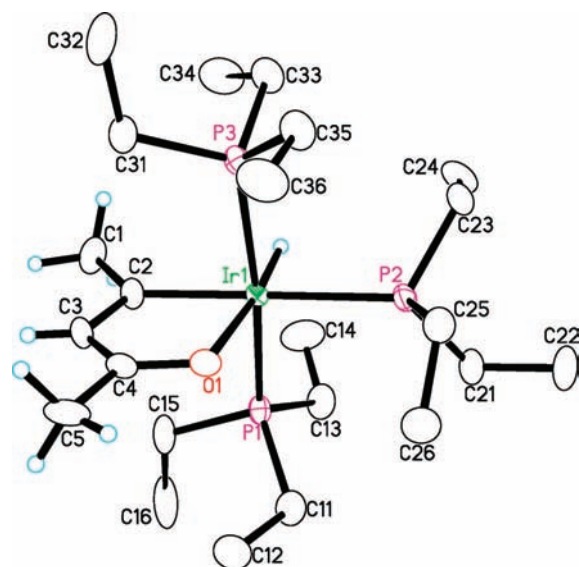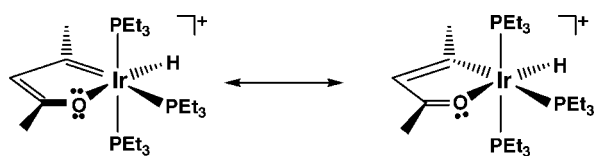

FIGURE 3. ORTEP drawing of cationic iridafuran, **19**. Selected bond distances in angstroms: Ir1–O1, 2.206(4); Ir1–C2, 2.029(6); O1–C4, 1.258(8); C1–C2, 1.516(9); C2–C3, 1.348(9); C3–C4, 1.408(10); C4–C5, 1.505(12).

Chart 4

normal single and double bonds. Similarly, the C–C bonds within the ring have moved toward equalization. The spectroscopic and structural data suggest that the two resonance structures shown in Chart 4 both contribute to the overall bonding picture in **19**.

Ring halogenation is one of the characteristic reactions of aromatic compounds. Therefore, we have explored the reactivity of iridafuran **19** toward I_2 and Br_2. As shown in Scheme 10, excess I_2 reacts exclusively *at the metal center* to produce the neutral dihalide compound **20**. This reaction involves formal loss of PEt_3 and H^+ from the iridium center. Excess Br_2, on the other hand, adds to **19** at the metal center *and* at C3 of the ring to form the electrophilic aromatic substitution product **21**. X-ray crystal structures of both **20** and **21** have been obtained, confirming that the delocalized iridafuran rings remain intact.[28]

Sulfur-Containing Iridacycles

While studying the chemistry of oxygen-containing iridacycles, we began to concurrently investigate the analogous sulfur systems with the goal of synthesizing aromatic iridathiabenzene and iridathiophene. Our initial experiments explored the reaction of potassium thiapentadienide, first made by Kloosterziel,[29] with $(Cl)Ir(PEt_3)_3$. As shown in Scheme 11, this reaction produces $(1,2,5\text{-}\eta\text{-}5\text{-thiapentadienyl})Ir(PEt_3)_3$ (**22**), which when stirred in tetrahydrofuran converts to a mixture of iridathiacyclohexadiene **23** (via C1–H1 bond activation) and iridathiacyclopentene **24** (via C2–H2 bond activation). Gradually, all of the six-membered ring converts to the five-membered ring, and compound **24** can be isolated cleanly.[30] It is interesting that in the sulfur system, unlike the analogous oxygen system described earlier, C–H bond activation does *not* occur at the C4–H4 bond to produce a five-membered ring with an exocyclic C=S bond, a result that reflects the relative weakness of C–S double bonds as compared to C–O double bonds. However, in both systems, five-membered rings are thermodynamically preferred over six-membered rings for the reasons outlined earlier.

As described in Iridathiophene below, iridathiacyclopentene **24** provides a good precursor for iridathiophene synthesis, but to produce a *stable* six-membered iridathiacycle, we synthesized lithium 2,3-dimethyl-5-thiapentadienide and reacted it with $(Cl)Ir(PEt_3)_3$. As expected, the methyl group at C2 blocked the formation of the five-membered iridathiacyclopentene and afforded stable iridathiacyclohexadiene **25** (Scheme 12).[31]
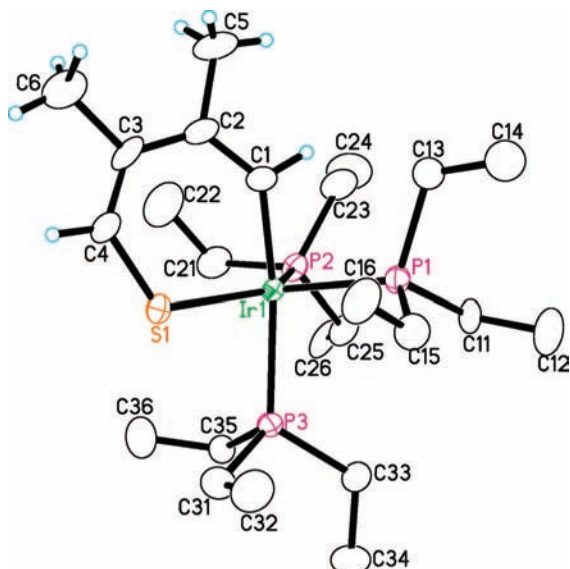
Scheme 11
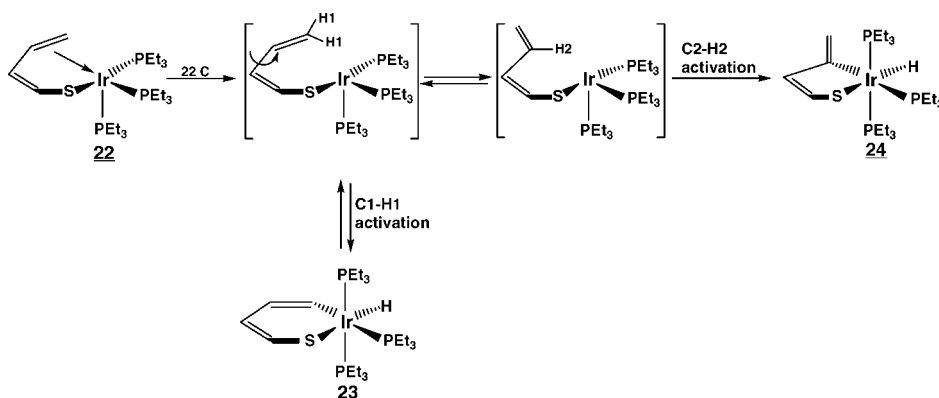
Scheme 12
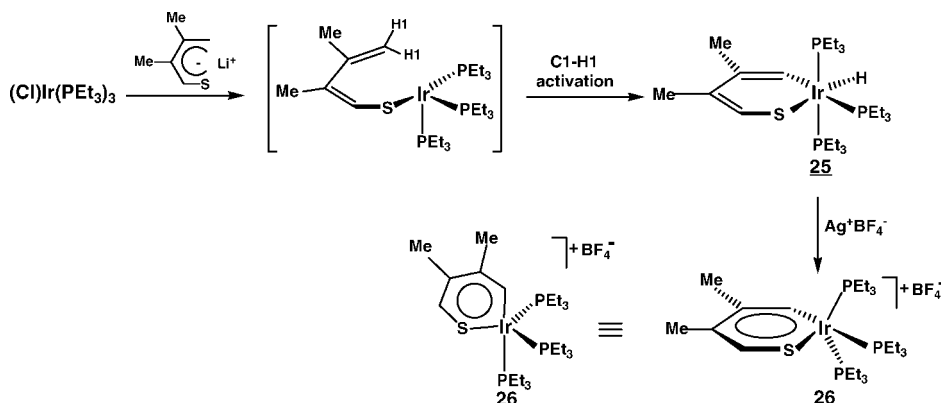
FIGURE 4. ORTEP drawing of cationic iridathiabenzene, **26**. Selected bond distances in angstroms: Ir1–S1, 2.249(3); Ir1–C1, 2.019(10); S1–C4, 1.713(12); C1–C2, 1.396(16); C2–C3, 1.415(15); C2–C5, 1.534(15); C3–C4, 1.361(16); C3–C6, 1.552(19).

Iridathiabenzene[32]

With stable iridathiacyclohexadiene **25** in hand, we applied the same synthetic strategy that had worked earlier for the synthesis of iridapyrylium. To our delight, treatment of yellow-orange **25** with $Ag^+BF_4^-$ in tetrahydrofuran led to the immediate production of deep red iridathia-

benzene (**26**, Scheme 12).[31] The ^1H NMR spectrum of **26** confirms its aromaticity, with H1 resonating at δ 10.36 (as compared to δ 7.05 in **25**) and H4 resonating at δ 8.61 (vs δ 5.78 in **25**).

The X-ray crystal structure of **26** (Figure 4) shows delocalized bonding within the metallacycle, consistent with an aromatic system. The carbon–carbon ring bonds in **26** have moved toward equalization, while Ir1–C1 and Ir1–S1 bonds [2.019(10) and 2.249(3) Å, respectively] have both been shortened substantially from their values in **25** [2.093(10) and 2.433(3) Å, respectively], indicating significant metal participation in ring π-bonding. Like the ring in iridabenzene **3**, the ring in **26** is slightly puckered, with the iridium center lying 0.18 Å out of the plane of the non-metal ring atoms. The coordination geometry of **26** approximates a trigonal bipyramid with ring C1 and phosphine P3 occupying the axial sites, and ring S1 and phosphines P1 and P2 occupying the equatorial sites. This contrasts with the solid state structure of iridabenzene (**3**), which adopts a square pyramidal coordination geometry. As with iridabenzene and iridapyrylium (**17**), the phosphines in **26** are exchanging rapidly in solution at room temperature and appear to be equivalent when assessed by ^{31}P NMR. This phosphine exchange process also causes the H1 signal to appear as a characteristic binomial quartet (J_{H-P} = 8.4 Hz) due to coupling to the equivalent ^{31}P nuclei. However, unlike the case with iridabenzene and iridapyrylium, cooling to −90 °C causes the ^{31}P NMR signal to resolve into two resonances with an intensity ratio of 2 (equatorial) to 1 (axial). From line shape analysis,
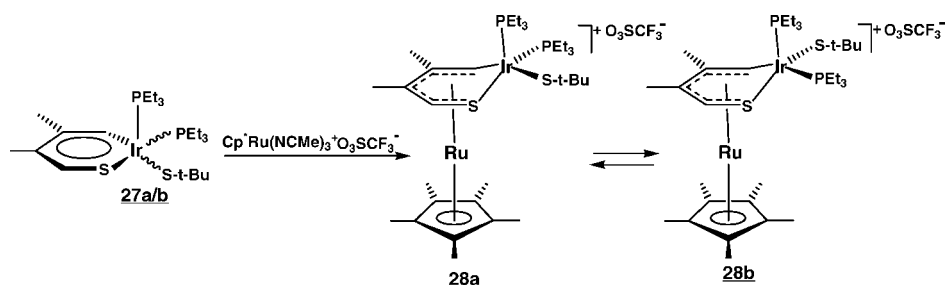
Scheme 13
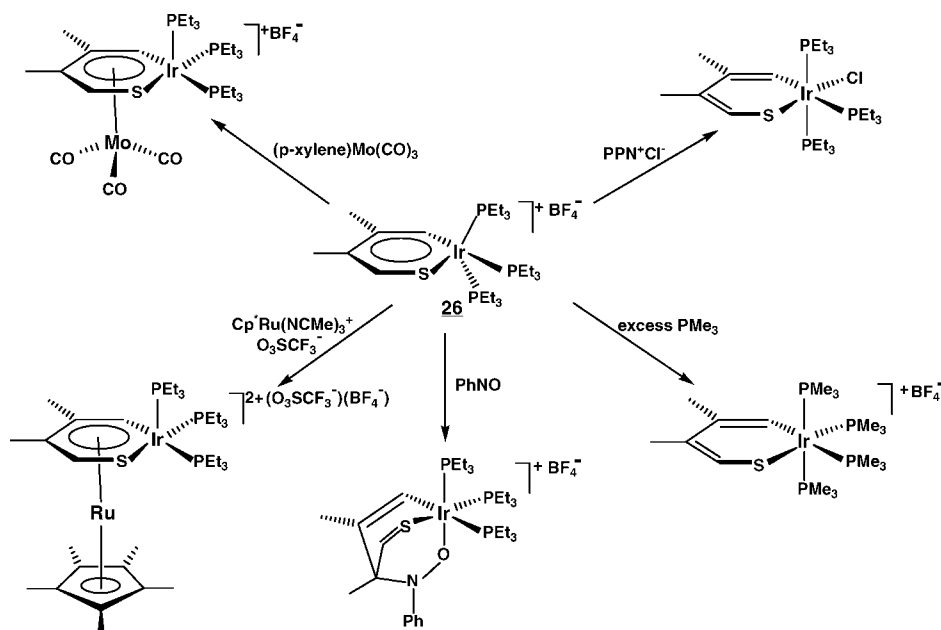
Scheme 14
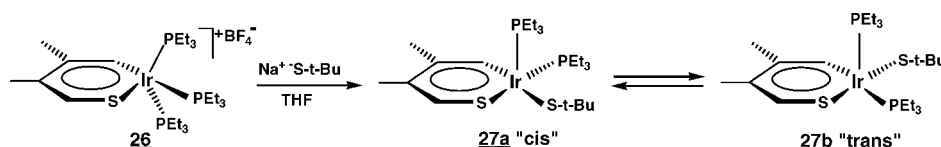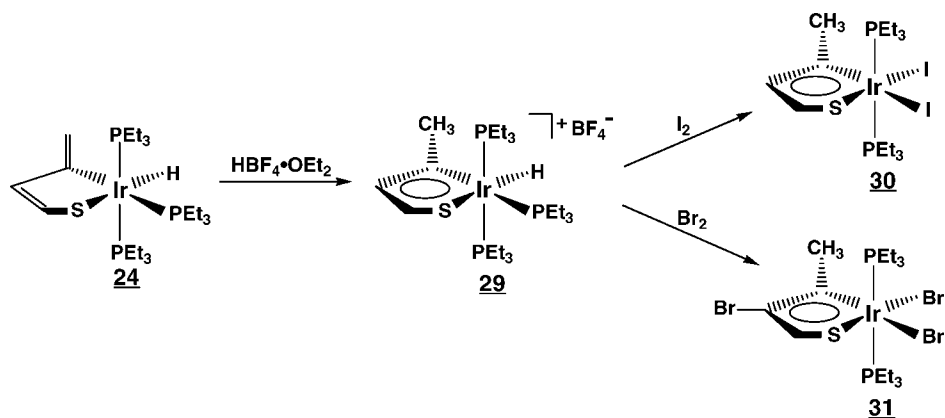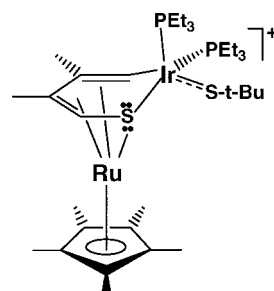
Scheme 15

Scheme 16

Chart 5

the $\Delta G^{\ddagger}$ value for this intramolecular phosphine exchange process has been calculated to be 9.5 (0.2) kcal/mol.

As shown in Scheme 13, the reaction chemistry of **26** is similar to that described previously for iridapyrylium **17**.[31] Two-electron donor ligands L (e.g., Cl⁻ and PMe₃) add to the iridium center to produce iridathiacyclohexa-1,3-diene rings, while unsaturated substrates (e.g., nitrosobenzene) undergo 4+2 cycloaddition. Iridathiabenzene **26** can be coordinated to other metal fragments. For example, treatment with (η^6-*p*-xylene)Mo(CO)₃ leads to formation of [(η^6-iridathiabenzene)Mo(CO)₃]⁺(BF₄⁻), while treatment with [Cp*Ru(NCMe)₃]⁺(O₃SCF₃⁻) produces the sandwich compound, [(η^6-iridathiabenzene)RuCp*]²⁺-(O₃SCF₃⁻)(BF₄⁻).

While we were studying the reaction of **26** with chloride, we observed the transient existence of neutral "(iridathiabenzene)(PEt₃)₂(Cl)" in polar solvents. We reasoned that if the chloride were replaced with a bulkier anionic ligand, a stable neutral iridathiabenzene should result. When we treated **26** with sodium *tert*-butylthiolate, that is exactly what happened, and iridathiabenzene **27** (Scheme 14) was isolated as an equilibrium mixture of square pyramidal *cis* and *trans* isomers.[33] The reactivity of **27** is similar to that of **26** in many ways, but the reaction with [Cp*Ru(NCMe)₃]⁺(O₃SCF₃⁻) is unique. As shown in Scheme 15, a sandwich compound, **28**, is formed (as a mixture of *cis* and *trans* isomers), but the X-ray crystal structure of **28a** reveals that the ruthenium atom is not bonded to iridium! Instead, C1, C2, C3, C4, and S1 of the metallacycle are bonded to ruthenium in an η^5-fashion, while the Ir atom is pushed up and out of the plane by 0.71 Å. The best description of the bonding in **28a** appears

to be the resonance structure shown in Chart 5. By using two carbon–carbon double bonds and a sulfur lone pair, the iridacycle serves as a 6-e⁻ neutral ligand for the ruthenium center. While the Ir–S1(ring) interaction has lost most of its π-character, some new double bond character has developed between Ir and S2 (thiolate) to stabilize the otherwise 16-e⁻ iridium center. This view is supported by the observation that the Ir–S2 bond in **28a** has been shortened significantly (by 0.074 Å) as compared to its length in **27a**. It is noteworthy that isomers **28a** and **28b** interconvert readily at room temperature. This interconversion is possible only because the iridium center is *not* coordinated to ruthenium and, hence, retains its five-coordinate (fluxional) character.

Iridathiophene

Recall from Scheme 11 that iridathiacyclopentene **24** is the final product from the reaction of unmethylated thiapentadienide with (Cl)Ir(PEt₃)₃. Treatment of **24** with H⁺BF₄⁻·OEt₂ leads cleanly to production of the first
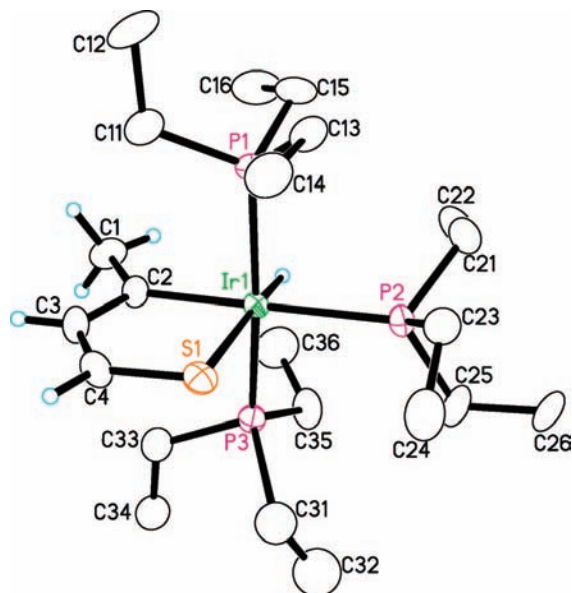
FIGURE 5. ORTEP drawing of cationic iridathiophene, **29**. Selected bond distances in angstroms: Ir1–S1, 2.383(2); Ir1–C2, 2.042(10); S1–C4, 1.647(11); C1–C2, 1.500(15); C2–C3, 1.362(15); C3–C4, 1.399(16).

FIGURE 6. ORTEP drawing of cationic iridaisoindole, **33**. Selected bond distances in angstroms: Ir1–N1, 2.113(3); Ir1–C1, 2.072(3); N1–C7, 1.285(4); C1–C6, 1.413(5); C6–C7, 1.472(5); C7–C8, 1.496(5); C1–C2, 1.399(5); C2–C3, 1.378(4); C3–C4, 1.388(5); C4–C5, 1.374(5); C5–C6, 1.397(4).

example of a metallathiophene (**29**, Scheme 16).[34,35] Aromatic character is confirmed by the downfield shifting of the ^{1}H NMR signals for ring protons H3 and H4 to δ 7.58 and 10.08, respectively, versus δ 5.84 and 6.14, respectively, in precursor **24**. Similarly, the X-ray crystal structure of **29** exhibits the planar ring and delocalized bonding of an aromatic ring system (see Figure 5 and its legend).

The reactivity of iridathiophene **29** toward halogens mirrors that of iridafuran **19**. I$_2$ reacts exclusively at the iridium center, producing the sulfur analogue of **20**. Excess Br$_2$, on the other hand, adds at the metal center *and* at ring C3 to form an electrophilic aromatic substitution product analogous to iridafuran **21**.[36] The regiochemistry of the electrophilic substitution reflects the fact that ring C3 in **29** is a more negative center than C4 due in part to resonance effects involving the sulfur lone pairs.
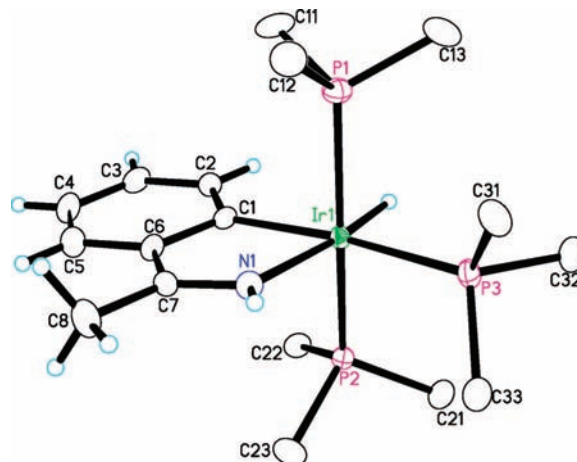
Iridapyrrole[37] Derivatives

To date, we have not succeeded in using azapentadienide reagents to construct nitrogen-containing iridacycles. This lack of success stems from the fact that azapentadienide reagents generally require bulky N-groups for stability, and this, in turn, destabilizes Ir–N bonding. For example, treatment of "(Cl)Ir(PMe$_3$)$_3$" with potassium *tert*-butylazapentadienide results in the production of (1,2,3-η-5-azapentadienyl)Ir(PMe$_3$)$_3$, where the *carbon* end of the azapentadienyl chain is bound to iridium in an η^3-allyl fashion.[38] No N-bound products are observed.

Recently, we have begun to develop an alternative synthetic strategy for the construction of five-membered nitrogen-containing iridacycles and have succeeded in converting them to iridapyrrole derivatives.[39] The approach is illustrated in Scheme 17. Treatment of benzonitrile with methyllithium produces the N-lithiated imine reagent **F**, which reacts with "(Cl)Ir(PMe$_3$)$_3$" to produce 16-e$^-$ intermediate **G**. Ortho metallation of the phenyl ring generates stable fused ring system **32**, which when pro-

Scheme 17
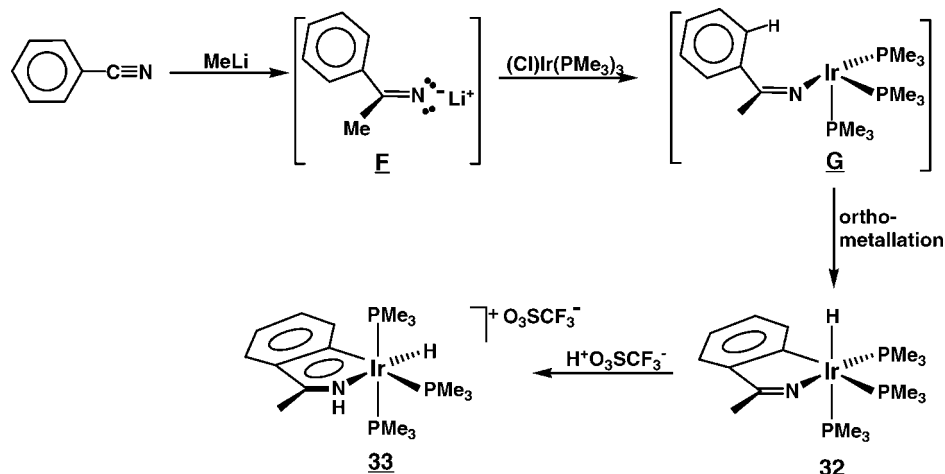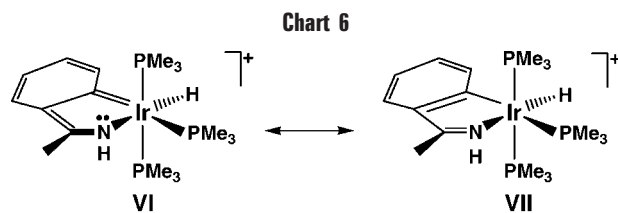
Chart 6

tonated with $H^+O_3SCF_3^-$, generates iridaisoindole **33**. The X-ray crystal structure of **33** has been obtained and is presented in Figure 6. The bonding in this species can be described by the two resonance structures shown in Chart 6. From the bond distances reported in the legend of Figure 6, it appears that resonance form **VII** dominates. This is expected, because in **VI** the resonance energy of the fused six-membered ring is diminished. While this work is still in its early stages, we are hopeful that it can be adapted to produce a variety of aromatic five- and perhaps six-membered ring systems.

Summary

The iridacycles described in this Account represent the first family of closely related aromatic metallacycles, a family that currently includes iridabenzene, iridaphenol, iridapyrylium, iridafuran, iridathiabenzene, iridathiophene, and iridaisoindole. Like their familiar organic namesakes, these organometallic molecules exhibit the structural and spectroscopic hallmarks of aromaticity, including ring planarity, π-bond delocalization, and diamagnetic ring current effects. On the other hand, the reactivity of aromatic metallacycles is quite distinct from that of organic aromatic molecules. While some reaction types are shared (e.g., electrophilic substitution and coordination to metal–ligand fragments), others (e.g., cycloaddition and ligand addition) are unique to the metallacycles. This complex reactivity profile is a direct consequence of having both an aromatic ring and a reactive metal center in the same molecule.

One hundred forty years after Kekulé's celebrated dream, aromatic chemistry continues to be a fascinating and provocative research topic. Aromatic metallacycles represent one of the "new frontiers" that promises to keep aromatic chemistry vibrant well into the 21st century. Our group is continuing to explore the synthesis of new aromatic iridacycles with the immediate goals of adding iridapyridine,[40] iridasilabenzene, and a variety of fused ring systems[41] to the family. We hope to be able to report progress toward these goals in the years to come.

References

(1) Kekulé, A. Sur la constitution des substances aromatiques. *Bull. Soc. Chim.* **1865**, *3*, 98–111.

(2) (a) Badger, C. M. *Aromatic Character and Aromaticity*; Cambridge University Press: London, 1969. (b) Bergmann, D. E., Pullman, B., Eds. *Aromaticity, Pseudoaromaticity, Anti-Aromaticity*; Academic Press: New York, 1971. (c) Garratt, P. J. *Aromaticity*; John Wiley and Sons: New York, 1986. (d) Lloyd, D. *The Chemistry of Conjugated Cyclic Compounds*; John Wiley and Sons: Chichester, U.K., 1989.

(3) Schleyer, P. v. R., Guest Editor. Aromaticity. *Chem. Rev.* **2001**, *101*, 1115–1566.

(4) (a) Bleeke, J. R. Metallabenzenes. *Chem. Rev.* **2001**, *101*, 1205–1227. (b) He, G.; Xia, H.; Jia, G. Progress in the Synthesis and Reactivity of Metallabenzenes. *Chin. Sci. Bull.* **2004**, *49*, 1543–1553. (c) Wright, L. J. Metallabenzenes and Metallabenzenoids. *J. Chem. Soc., Dalton Trans.* **2006**, 1821–1827. (d) Landorf, C. W.; Haley, M. M. Recent Advances in Metallabenzene Chemistry. *Angew. Chem., Int. Ed.* **2006**, *45*, 3914–3936.

(5) Jia, G. Progress in the Chemistry of Metallabenzynes. *Acc. Chem. Res.* **2004**, *37*, 479–486.

(6) Thorn, D. L.; Hoffmann, R. Delocalization in Metallocycles. *Nouv. J. Chim.* **1979**, *3*, 39–45.

(7) Elliott, G. P.; Roper, W. R.; Waters, J. M. Metallacyclohexatrienes or Metallabenzenes. Synthesis of Osmabenzene Derivatives and X-ray Crystal Structure of [Os(CSCHCHCHCH)(CO)(PPh₃)₂]. *J. Chem. Soc., Chem. Commun.* **1982**, 811–813.

(8) (a) Bleeke, J. R.; Xie, Y.-F.; Peng, W.-J.; Chiang, M. Metallabenzene: Synthesis, Structure, and Spectroscopy of a 1-Irida-3,5-dimethyl-benzene Complex. *J. Am. Chem. Soc.* **1989**, *111*, 4118–4120. (b) Bleeke, J. R. Metallabenzene Chemistry. *Acc. Chem. Res.* **1991**, *24*, 271–277.

(9) Bleeke, J. R.; Peng, W.-J. Synthesis, Structure, and Spectroscopy of Iridacyclohexadiene Complexes. *Organometallics* **1987**, *6*, 1576–1578.

(10) This argument is supported by the observation that replacement of the bulky PEt₃ ligands with smaller PMe₃'s causes the iridaben-zene ring to become significantly more planar (see ref 13).

(11) Zhu, J.; Jia, G.; Lin, Z. Understanding Nonplanarity in Metallaben-zene Complexes. *Organometallics* **2007**, *26*, 1986–1995.

(12) For DFT calculations and a detailed analysis of the bonding, see: Iron, M. A.; Lucassen, A. C. B.; Cohen, H.; van der Boom, M. E.; Martin, J. M. L. A Computational Foray into the Formation and Reactivity of Metallabenzenes. *J. Am. Chem. Soc.* **2004**, *126*, 11699–11710.

(13) Bleeke, J. R.; Behm, R.; Xie, Y.-F.; Chiang, M. Y.; Robinson, K. D.; Beatty, A. M. Synthesis, Structure, Spectroscopy, and Reactivity of a Metallabenzene. *Organometallics* **1997**, *16*, 606–623.

(14) Iron, M. A.; Martin, J. M. L.; van der Boom, M. E. Cycloaddition Reactions of Metalloaromatic Complexes of Iridium and Rhodium: A Mechanistic DFT Investigation. *J. Am. Chem. Soc.* **2003**, *125*, 11702–11709.

(15) Gilbertson, R. D.; Weakley, T. J. R.; Haley, M. M. Direct Synthesis of an Iridabenzene from a Nucleophilic 3-Vinyl-1-cyclopropene. *J. Am. Chem. Soc.* **1999**, *121*, 2597–2598.

(16) Gilbertson, R. D.; Weakley, T. J. R.; Haley, M. M. Synthesis, Characterization, and Isomerization of an Iridabenzvalene. *Chem.—Eur. J.* **2000**, *6*, 437–441.

(17) Paneque, M.; Posadas, C. M.; Poveda, M. L.; Rendon, N.; Salazar, V.; Oñate, E.; Mereiter, K. Formation of Unusual Iridabenzene and Metallanaphthalene Containing Electron-Withdrawing Substi-tutents. *J. Am. Chem. Soc.* **2003**, *125*, 9898–9899.

(18) Chin, C. S.; Lee, H.; Eum, M.-S. Iridabenzenes from Iridacyclopen-tadienes: Unusual C-C Bond Formation between Unsaturated Hydrocarbyl Ligands. *Organometallics* **2005**, *24*, 4849–4852.

(19) Álvarez, E.; Paneque, M.; Poveda, M. L.; Rendon, N. Formation of Iridabenzenes by Coupling of Iridacyclopentadienes and Alkenes. *Angew. Chem., Int. Ed.* **2006**, *45*, 474–477.

(20) Clark, G. R.; Lu, G.-L.; Roper, W. R.; Wright, L. J. Stepwise Reactions of Acetylenes with Iridium Thiocarbonyl Complexes to Produce Isolable Iridacyclobutadienes and Conversion of These to Either Cyclopentadienyliridium or Tethered Iridabenzene Complexes. *Organometallics* **2007**, *26*, 2167–2177.

(21) Bleeke, J. R.; Behm, R. Synthesis, Structure, and Reactivity of Iridacyclohexadienone and Iridaphenol Complexes. *J. Am. Chem. Soc.* **1997**, *119*, 8503–8511.

(22) Heiszwolf, G. J.; Kloosterziel, H. The Distribution of Charge in Ambident Anions. *Recl. Trav. Chim. Pays-Bas* **1967**, *86*, 807–808.

(23) Bleeke, J. R.; Haile, T.; Chiang, M. Y. Synthesis of Iridaoxacyclo-hexadiene and Iridacyclopentenone Complexes via C-H Bond Activation. *Organometallics* **1991**, *10*, 19–21.

(24) Bleeke, J. R.; Haile, T.; New, P. R.; Chiang, M. Y. Oxapentadienyl-Iridium-Phosphine Chemistry. Synthesis of Oxygen-Containing Iridacycles via C-H Bond Activation. *Organometallics* **1993**, *12*, 517–528.

(25) (a) Bleeke, J. R.; Blanchard, J. M. B. Synthesis and Reactivity of a Metallapyrylium. *J. Am. Chem. Soc.* **1997**, *119*, 5443–5444. (b) Bleeke, J. R.; Blanchard, J. M. B.; Donnay, E. Synthesis, Spectros-copy, and Reactivity of a Metallapyrylium. *Organometallics* **2001**, *20*, 324–336.

(26) The mechanism of this reaction has been explored using DFT calculations. Unlike the cycloaddition reactions of **3**, the acetone reacts with **17** in a stepwise manner involving prior coordination

of an oxygen lone pair to the iridium center. See: Iron, M. A.; Martin, J. M. L.; van der Boom, M. E. Mechanistic Aspects of Acetone Addition to Metalloaromatic Complexes of Iridium: A DFT Investigation. *Chem. Commun.* **2003**, 132–133.

(27) Metallafurans are the most common aromatic metallacycles, and numerous examples can be found throughout the periodic table. Two examples of *iridafurans* preceded our work. In each case, the five-membered ring was constructed via C–H bond activation on an α,β-unsaturated acid or ester. See: (a) Werner, H.; Dirnberger, T.; Schulz, M. Synthesis of Octahedral Hydrido(vinyl)iridium(III) Complexes by C-H Activation: An Example of a Thermodynamically Favored Rearrangement [M(CHR=CHX)→[M(H)(CR=CHX)]. *Angew. Chem., Int. Ed.* **1998**, *27*, 948–949. (b) Sunley, G. J.; Menanteau, P. d. C.; Adams, H.; Bailey, N. A.; Maitlis, P. M. Cyclometallation of Unsaturated Carboxylic Acids by Pentamethylcyclopentadienyl-rhodium and -iridium Complexes. Crystal Structures of [(C₅Me₅)Ir(CPh=CHCO-O)(Me₂SO)] and [(C₅Me₅)Ir(CPh=CHCO-OMe)I]. *J. Chem. Soc., Dalton Trans.* **1989**, 2415–2421. For recent examples of metallafurans and a survey of major synthetic routes, see: Bierstedt, A.; Clark, G. R.; Roper, W. R.; Wright, L. J. A 2-Iridafuran from Reaction between a 1-Iridaindene and Methyl Propiolate. *J. Organomet. Chem.* **2006**, *691*, 3846–3852.

(28) Bleeke, J. R.; New, P. R.; Blanchard, J. M. B.; Haile, T.; Beatty, A. M. Synthesis of a New Family of Metallafurans from (Oxapentadienyl)Metal Precursors. *Organometallics* **1995**, *14*, 5127–5137.

(29) Kloosterziel, H.; Van Drunen, J. A. A.; Galama, P. Base-induced Electrocyclic Opening of Some Heterocyclic Compounds. *J. Chem. Soc., Chem. Commun.* **1969**, 885.

(30) Bleeke, J. R.; Ortwerth, M. F.; Chiang, M. Y. Thiapentadienyl-Iridium-Phosphine Chemistry. Synthesis of Sulfur-Containing Iridacycles via C-H Bond Activation. *Organometallics* **1992**, *11*, 2740–2743.

(31) (a) Bleeke, J. R.; Hinkle, P. V.; Rath, N. P. Synthesis, Structure, Spectroscopy and Reactivity of a Metallathiabenzene. *J. Am. Chem. Soc.* **1999**, *121*, 595–596. (b) Bleeke, J. R.; Hinkle, P. V.; Rath, N. P. Synthesis, Structure, Spectroscopy, and Reactivity of a Metallathiabenzene. *Organometallics* **2001**, *20*, 1939–1951.

(32) Prior to our work, stable iridathiabenzenes were reported independently by Angelici and by Bianchini. In addition, Bianchini reported an iridabenzothiabenzene containing a fused benzene ring. These previous syntheses differed from our approach in that they involved thiophene C–S bond activation as the key ring-forming step. See: (a) Chen, J.; Daniels, L. M.; Angelici, R. J. New Modes of Thiophene Coordination and Reactivity: Structures of Cp*Ir(η²-thiophene), an Iridathiabenzene, and Cp*Ir(η⁴-thiophene)·BH₃). *J. Am. Chem. Soc.* **1990**, *112*, 199–204. (b) Bianchini, C.; Meli, A.; Peruzzini, M.; Vizza, F.; Frediani, P.; Herrera, V.; Sánchez-Delgado, R. A. Opening, Desulfurization, and Hydrogenation of Thiophene at Iridium. An Experimental Study in a Homo-

geneous Phase. *J. Am. Chem. Soc.* **1993**, *115*, 2731–2742. (c) Bianchini, C.; Meli, A.; Peruzzini, M.; Vizza, F.; Moneti, S.; Herrera, V.; Sánchez-Delgado, R. A. HDS Model Systems. Coordination, Opening, and Hydrogenation of Benzo[b]thiophene at Iridium. *J. Am. Chem. Soc.* **1994**, *116*, 4370–4381.

(33) Bleeke, J. R.; Hinkle, P. V.; Shokeen, M. Synthesis, Structure, Spectroscopy, and Reactivity of a Neutral Iridathiabenzene. *Organometallics* **2004**, *23*, 4139–4149.

(34) Bleeke, J. R.; Ortwerth, M. F.; Chiang, M. Y. Electrophilic Addition to an Iridathiacyclopentene Complex. Synthesis of the First Metallathiophene. *Organometallics* **1993**, *12*, 985–987.

(35) The second example of a metallathiophene, also an iridium complex and closely related to ours, was recently reported: Lu, G.-L.; Roper, W. R.; Wright, L. J.; Clark, G. R. A 2-Iridathiophene from Reaction between IrCl(CS)(PPh₃)₂ and Hg(CH=CHPh)₂. *J. Organomet. Chem.* **2005**, *690*, 972–981.

(36) Bleeke, J. R.; Ortwerth, M. F.; Rohde, A. M. Thiapentadienyl-Iridium-Phosphine Chemistry. *Organometallics* **1995**, *14*, 2813–2826.

(37) Metallapyrroles are still relatively uncommon, at least as compared to the ubiquitous metallafurans. The first examples of *iridapyrroles* were reported by Carmona and Poveda: (a) Alvarado, Y.; Duff, P. J.; Pérez, P. J.; Poveda, M. L.; Sánchez-Delgado, R.; Carmona, E. Iridapyrrole Complexes via Formal 3+2 Cycloaddition of Iridium Alkenyls to Acetonitrile. *Organometallics* **1996**, *15*, 2192–2194. (b) Alías, F. M.; Duff, P. J.; Paneque, M.; Poveda, M. L.; Carmona, E.; Pérez, P. J.; Salazar, V.; Alvarado, Y.; Atencio, R.; Sánchez-Delgado, R. C-C Bond-Forming Reactions of Ir(III)-Alkenyls and Nitriles or Aldehydes: Generation of Reactive Hydride- and Alkyl-Alkylidene Compounds and Observation of a Reversible 1,2-H Shift in Stable Hydride-Ir(III) Alkylidene Complexes. *Chem.—Eur. J.* **2002**, *8*, 5132–5146.

(38) Bleeke, J. R.; Luaders, S. T.; Robinson, K. D. tert-Butylazapentadienyl-Iridium-Phosphine Chemistry. *Organometallics* **1994**, *13*, 1592–1600.

(39) Bleeke, J. R.; Putprasert, P. Unpublished observations.

(40) To date, just one example of a "metallapyridine" has been reported. However, the bonding within the tantalapyridine ring is not delocalized: Weller, K. J.; Filippov, I.; Briggs, P. M.; Wigley, D. E. Pyridine Degradation Intermediates as Models for Hydrodenitrogenation Catalysis: Preparation and Properties of a Metallapyridine Complex. *Organometallics* **1998**, *17*, 322–329.

(41) For a recently reported example of a fused aromatic metallacycle, see: Clark, G. R.; Johns, P. M.; Roper, W. R.; Wright, L. J. An Osmabenzofuran from Reaction between Os(diphenylacetylene)(C-S)(PPh₃)₂ and Methyl Propiolate and the C-Protonation of this Compound to Form a Tethered Osmabenzene. *Organometallics* **2006**, *25*, 1771–1777.

AR700071P