

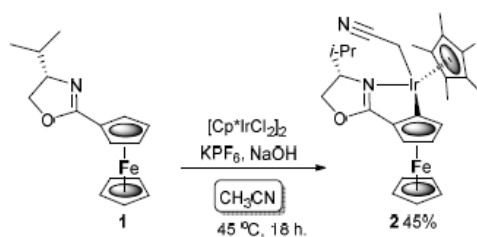
Metalocene to Metalocene Conversion. Synthesis of an Oxazoline-Substituted Pentamethyliridocenium Cation from a Ferrocenyloxazoline

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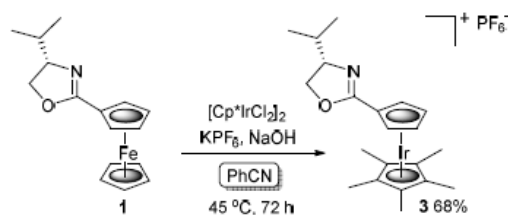
Reaction of (S)-2-ferrocenyl-4-(1-methylethyl)oxazoline with $[\text{Cp}^*\text{IrCl}_2]_2$ in benzonitrile with KPF_6 and NaOH gave $(\eta^5\text{-}(S)\text{-}2\text{-}(4\text{-}(1\text{-methylethyl}))\text{oxazolinylcyclopentadienyl})(\eta^5\text{-pentamethylcyclopentadienyl})\text{iridium(III) hexafluorophosphate}$ (68%). This transformation of an iron-based into an iridium-based metalocene proceeds via the rearrangement, with loss of cyclopentadienyliron, of an intermediate cationic ferrocenylirodacycle.

Metalloenes comprise one of the most important class of compounds in organometallic chemistry. Many catalysts and ligands are based on these complexes that contain an element, usually a transition metal, sandwiched between two η^5 -cyclopentadienyl rings.¹ Homoleptic metalloenes are made typically from the reaction of a cyclopentadiene or a cyclopentadienyl complex with a suitable metal precursor,² and these methodologies have been adapted widely to the synthesis of heteroleptic metalloenes.³ The starting cyclopentadienyl complexes used generally contain an s-block element and are largely ionic in character, with examples including CpLi , CpNa and Cp_2Mg . The use of the latter magnesium complex for the synthesis of ferrocene etc⁴ is a very specific type of transmetalation, a metalocene to metalocene conversion where the two complexes are based on a different metal.⁵ Other examples of this type of transformation appear to be rare,⁶⁻⁸ in particular, the transformation of one air, moisture and thermally stable d-block based complex into another.⁹ In this communication we describe the conversion of substituted ferrocene derivatives into substituted iridocenium cations,¹⁰ reactions that proceed via the intermediacy of planar chiral iridacycles.

We recently reported that reaction of ferrocenyloxazoline **1** with $[\text{Cp}^*\text{IrCl}_2]_2$ in acetonitrile with 4 equivalents of KPF_6 and 4 equivalents of NaOH results in the formation of a single diastereoisomer of neutral iridacycle **2** containing a cyanomethyl ligand (Scheme 1).¹¹



Scheme 1 Highly diastereoselective synthesis of planar chiral and chiral-at-metal iridacycle **2**.¹¹



Scheme 2 Conversion of ferrocenyloxazoline **1** into oxazoline-substituted iridocenium complex **3**.

In an attempt to generate a corresponding nitrile-ligated cationic iridacycle, benzonitrile was employed as the reaction solvent to avoid the deprotonation and rearrangement of acetonitrile that results in the formation of **2**. With 2 equivalents of NaOH this reaction resulted in the isolation of an air and thermally stable new complex, for which the ¹H NMR spectrum contained four diastereotopic cyclopentadienyl hydrogen signals at significantly higher chemical shift than would be expected for a ferrocene derivative (5.77, 5.79, 5.84 and 5.88 ppm in CDCl₃). In addition to signals from the oxazoline moiety, the spectrum contained a Cp* singlet at 2.16 ppm with a relative integration of fifteen. The identity of the product as hexafluorophosphate iridocenium salt **3** was confirmed by X-ray crystallography (Figure 1).¹² Replacement of benzonitrile by trimethylacetone nitrile also resulted in the generation of **3** (47%). No reaction occurred when [Cp*IrCl₂]₂ was replaced by [Cp*RhCl₂]₂ or [Ru(p-cymene)Cl₂]₂ with benzonitrile as solvent under the same conditions that gave **3**.

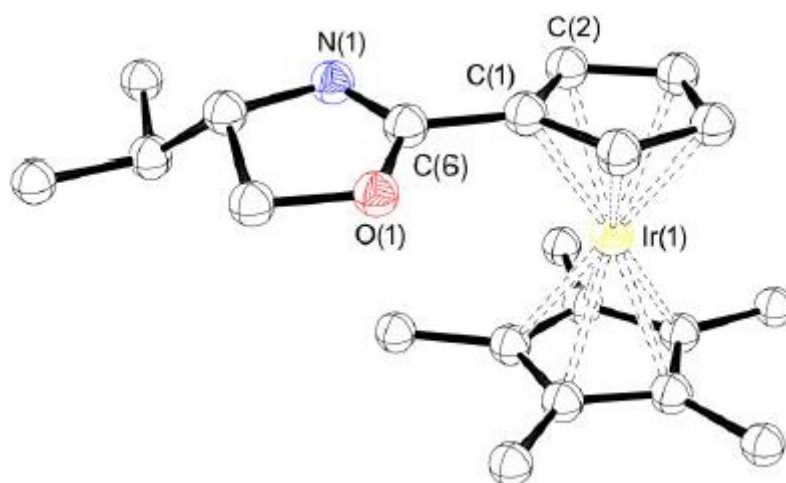
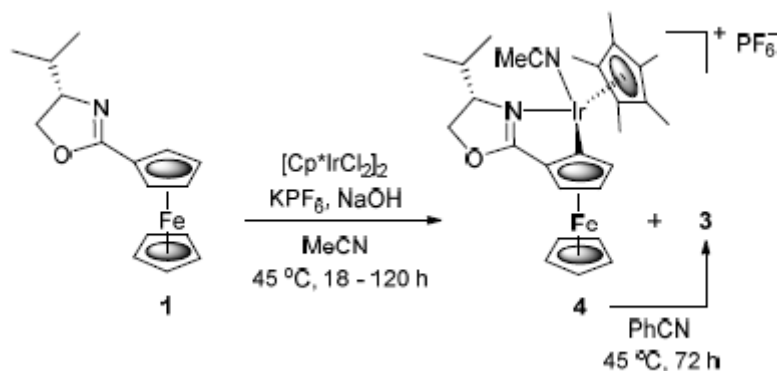


Fig. 1 A representation of the X-ray structure of **3** (hydrogen atoms, disordered atoms (Cp* and Ir) and hexafluorophosphate ion omitted for clarity). Principle bond lengths [Å] include: Ir(1)-Cp* (centre of mass) = 1.817(3), Ir(1)-Cp (centre of mass) = 1.813(3), C(1)-C(6)=1.455(12), C(6)-O(1) = 1.350(9), C(6)-N(1) = 1.272(11). Principle torsion angles (°) include: C(2)-C(1)-C(6)-N(1) = -11.8(13).

The cationic iridacycle **4**, containing a coordinated acetonitrile ligand, is available from **1** by a reduction in the quantity of base employed (either NaOH or KOtBu) to one equivalent on reaction with [Cp*IrCl₂]₂ and KPF₆ for 18 hours (Scheme 3).¹¹ Re-examination of the synthesis of **4** employing NaOH as base, with an increase in the reaction time to 24 h at 45 °C, revealed a 5 : 1 ratio of **4** : **3** following work-up.¹³ With a 5 day reaction time the ratio of **4** : **3** was 1 : 1.

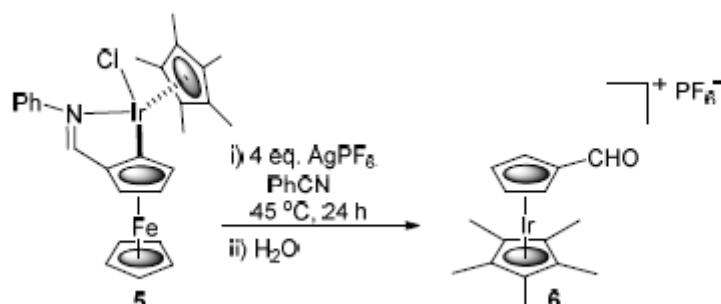


Scheme 3 Synthesis of cationic iridacycle 4 and iridocenium cation 3.

These results point to cationic iridacycle 4 being a precursor to iridocenium 3, a hypothesis supported by the clean conversion of 4 into 3 on heating at 45 °C in benzonitrile for 3 days. Following isolation, a solution of 4 is stable in CD₃CN under argon, but heating to 45 °C in this instance resulted only in decomposition.

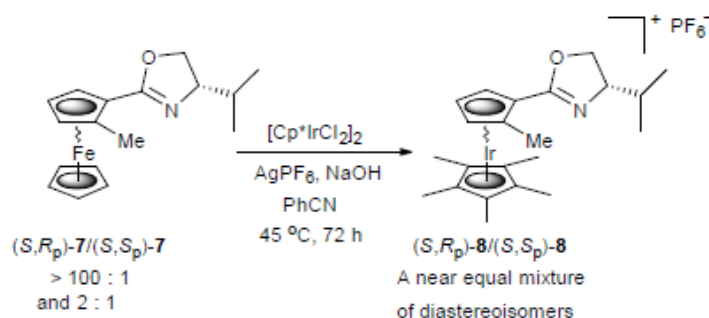
Two further results support the intermediacy of a cationic iridacycle in iridocenium formation. Firstly, reaction of methyl ferrocenecarboxylate with [Cp*IrCl₂]₂ under the same conditions as given in Scheme 2 resulted only in the recovery of the starting ester.

Thus a substrate that is less able to coordinate to iridium, and by extension not able to form an iridacycle, does not result in iridocenium formation. Secondly, and in contrast to the stability of neutral imine-based iridacycle 5,¹¹ the cationic complex that results from chloride abstraction with AgPF₆ transformed over a period of 1 day into iridoceniumcarbaldehyde 6 (Scheme 4). This complex was identified, in part, by the 1 [9.79 (s)] : 2 (6.01 (t, J 2.0)] : 2 [5.76 (t, J 2.0)] : 15 [1.57 (s)] ratio of signals in the 1H NMR spectrum (CD₃CN), the aldehyde moiety arising from facile aldimine hydrolysis under the conditions used for product isolation.

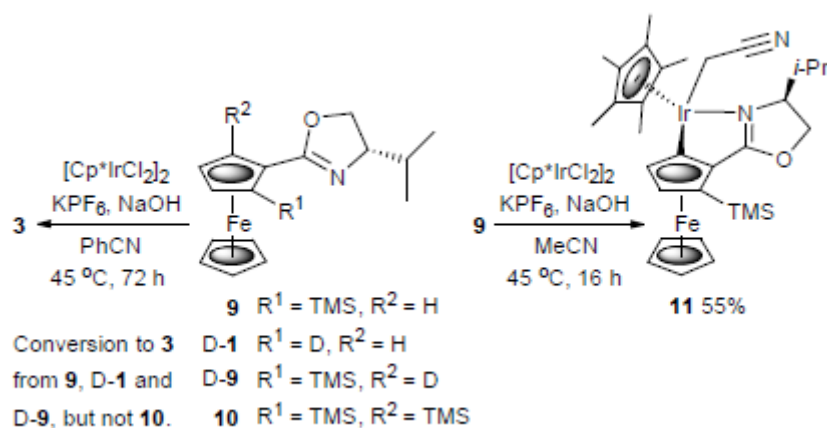


Scheme 4 Synthesis of iridoceniumcarbaldehyde 6

We next investigated the stereochemistry of the ferrocene-iridocenium transformation with planar chiral (*S,R*)-7 synthesised by highly diastereoselective lithiation¹⁴ and addition of MeI.¹⁵ This was transformed into iridocenium complexes (*S,R*)-8 and (*S,S*)-8 as a 1:0.86 ratio of diastereoisomers (assignment impossible), this ratio not changing during the course of the reaction (Scheme 5). The same outcome was observed starting with a (*S,R*)-7/(*S,S*)-7 ratio of 2:1. Thus this iridocenium formation reaction is not stereospecific with respect to planar chirality, and shows little stereoselectivity.



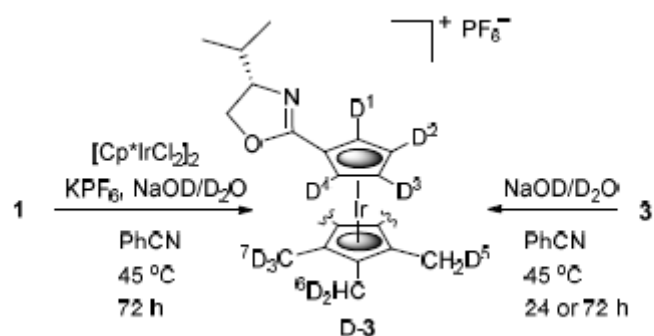
Scheme 5 Investigation into the planar chiral stereochemistry of substituted ferrocene to substituted iridocenium conversion.



Scheme 6 Generation of iridocenium 3 from trimethylsilylated and deuterated precursors, and retention of TMS on iridacycle formation.

Application of the iridocenium synthesis protocol to diastereomerically pure 916 containing a TMS substituent resulted in desilylation and isolation of 3 (Scheme 6). The same outcome was observed with deuterated $D-1$ and trimethylsilyl/deuterated $D-9$. In contrast, doubly silylated 10 was recovered unchanged from the reaction. That desilylation of 9 does not occur on iridacycle formation had been determined previously with the isolation of 11 , 11 hydrogen/deuterium shifts. When the partially deuterated product obtained from run 2 (Table 1) was heated at 45 oC for 48 h in benzonitrile with D_2O , and no NaOD, no change was observed in the $1H$ NMR of the material isolated. This reveals the requirement of deuterioxide in deuterium incorporation, and by extension the role of hydroxide or deuterioxide in iridocenium formation the TMS blocking group resulting in the opposite sense of planar chirality. The absence of reaction with 10 is consistent with the two blocking groups preventing iridacycle formation, and thus generation of an iridocenium cation.

Deuterium incorporation during iridocenium complex formation was investigated by replacement of NaOH with 20 eq. of NaOD (as a 40% wt. solution in D_2O - Scheme 7, Table 1, entry 1). This resulted in the formation of 3 with partial deuterium incorporation into the cyclopentadienyl and pentamethylcyclopentadienyl moieties, and no incorporation into the oxazoline. Starting material 1 recovered from this reaction contained no incorporated deuterium. Iridocenium deuteration was also observed on addition of 10 eq. of NaOD in D_2O to 3 and heating in benzonitrile at 45 oC for 24h (entry 2). On increasing this reaction time to 72 h further deuteration of the Cp and Cp* groups was observed (entry 3).



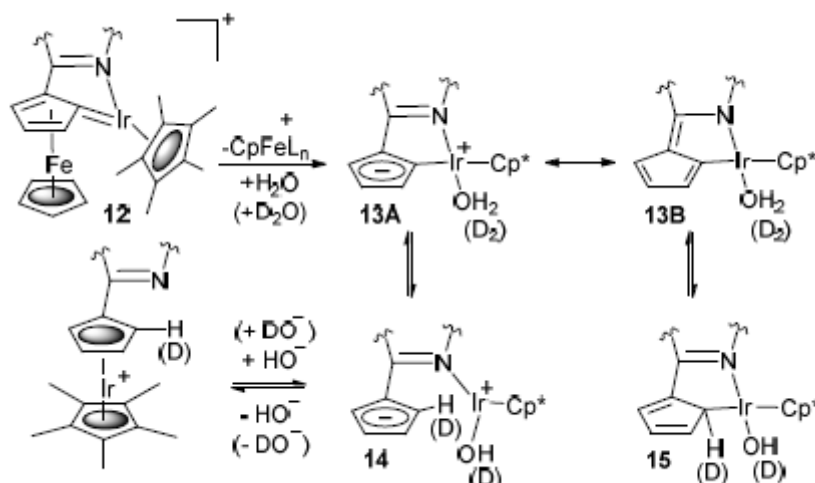
Scheme 7 Formation of deuterated 3 .

Table 1 Percentage deuterium incorporation into 3.a

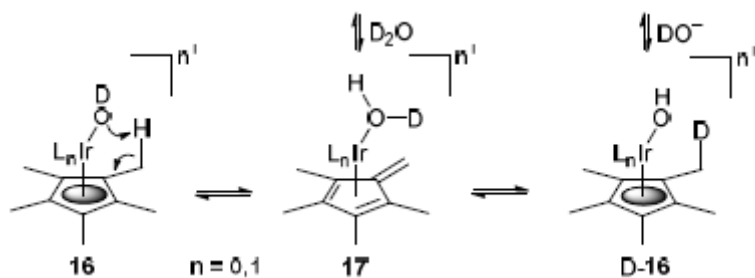
Entry	SM ^b	^c RT	D ¹	D ^{2/3}	D ⁴	^d D ⁵	^e D ⁶	^f D ⁷
1	1	72 h	43	13	39	41	40	6
2	3	24 h	66	19	58	40	32	15
3	3	72 h	78	33	76	21	42	34

^aDetermined by ¹H NMR. ^bStarting material. ^cReaction time. ^dFrom 1:1:1 triplet at 2.09 ppm. ^eFrom 1:2:3:2:1 pentet at 2.08 ppm. ^fCalculated from remaining singlet at 2.11 ppm.

Loss of the exchangeable ligand from iridacycles such as 4 and 5 results in coordinatively-unsaturated iridacycle 12 (Scheme 8). For the cation derived from 5 calculations give an iridium-iron bonding parameter of 1.25, and partial charge delocalisation onto iron.¹¹ A possible mechanism for the loss of CpFe⁺ is via migration of this moiety onto iridium, and iron ligation by the nitrile solvent and/or hydroxide/water.¹⁷ The resulting neutral and resonance-stabilised cyclopentadienyl-iridacycle can coordinate water to give 13 from which can occur reversible proto-deiridation.¹⁸ A related process may account for the desilylation of 9. Subsequent loss of the hydroxide ligand from 14, and non-facially selective η⁵- coordination, completes this suggested pathway for iridocenium formation. That deuterium incorporation was observed when iridocenium 3 was heated with NaOD in D₂O points to the reversible formation of 13. In addition to α-deuteration with respect to the oxazoline substituent (D¹ and D⁴), a lesser degree of β-deuteration was also observed (D^{2/3} - Table 1). Assuming that formation of a β- analogue of 13 is not possible, this suggests the reversible formation of 15, from which scrambling can occur by [1,5]-hydrogen/deuterium shifts. When the partially deuterated product obtained from run 2 (Table 1) was heated at 45 °C for 48 h in benzonitrile with D₂O, and no NaOD, no change was observed in the ¹H NMR of the material isolated. This reveals the requirement of deuteroxide in deuterium incorporation, and by extension the role of hydroxide or deuteroxide in iridocenium formation.

**Scheme 8** Outline pathway for iridacycle to iridocenium conversion.

The intermediacy of an iridium-hydroxide species also accounts for deuterium incorporation into Cp*. First reported by Maitlis,¹⁹ a later study by Macchioni with [Cp*RhCl(PTA)₂]⁺X⁻ (PTA = 7-phospha-1,3,5-triazaadamantane) revealed abstraction of a Cp* methyl proton by a coordinated hydroxide anion.²⁰ By extension, a generalised deuteroxide-iridium(III) coordinated intermediate 16 can reversibly generate Ir(I)-fulvene 17 as the intermediate in the formation of D-16 (Scheme 9).



Scheme 9 Mechanism of Cp* deuterium incorporation.

Conclusions

Heating an oxazoline-substituted ferrocene with $[\text{Cp}^*\text{IrCl}_2]_2$ in benzonitrile with NaOH and KPF₆ results in the formation of an oxazoline-substituted pentamethyliridocenium cation. This transformation of one air, moisture and thermally stable d-block based metallocene previous precedent. A key intermediate in the kinetically accessible pathway is a cationic iridacycle. Deuterium incorporation with NaOD/D₂O occurs at Cp* and at the α/β -cyclopentadienyl positions. These outcomes are compatible with the reversible formation of the pentamethyliridocenium product by η^5 -cyclopentadienyl complexation from a deuterioxide coordinated iridium-Cp* complex. This first report on the synthesis of a chiral non-racemic iridocenium metallocene provides access to novel iridium-based species for future catalytic investigations.

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Notes and references

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† General procedure for the preparation of (η^5 -(S)-2-(4-(1-methylethyl)oxazoliny)cyclopentadienyl)(η^5 -pentamethylcyclopentadienyl)iridium(III) hexafluorophosphate. (S)-2-Ferrocenyl-4-(1-methylethyl)oxazoline (0.019 g, 0.06 mmol), (pentamethylcyclopentadienyl)iridium(III) chloride dimer (0.025 g, 0.03 mmol), NaOH (0.005 g, 0.13 mmol) and potassium hexafluorophosphate (0.047 g, 0.26 mmol) were added to a flame dried Schlenk tube under an inert atmosphere. After the addition of benzonitrile (5 mL) the mixture was stirred at 45 °C for 3 days. Once cooled to room temperature hexane was added and the reaction mixture stirred vigorously for 5 mins. The resulting suspension was filtered through Celite using hexane as the eluent and the column flushed with hexane twice to remove any remaining benzonitrile. Once all the benzonitrile had been removed, acetonitrile was used to flush the brown precipitate from the top of the Celite, and the resulting solution was collected and concentrated in vacuo. Purification was achieved by filtration through a pad of neutral alumina, using acetonitrile as the eluent, and collecting the first bright yellow fractions (subsequent pale yellow fractions contained small amounts of starting material). Removal of the solvent in vacuo yielded the product as a mustard yellow crystalline solid (0.0278 g, 68%): mp 189.7 - 191.2 °C (Found: C, 38.77; H, 4.46; N, 2.22. C₂₁H₂₉F₆IrNOP Requires C, 38.89; H, 4.51; N, 2.16%), HRMS (ES) [cation]⁺ C₂₁H₂₉IrNO⁺, Calc. 502.1850, Obs. 502.1843; 23.0°C = -41.8 (c = 0.22, acetonitrile); ν (film)/cm⁻¹ 2962, 2970, 1666 (C=N), 841; ¹H NMR (500 MHz, CDCl₃) 5.88 (1H, bs, Cp-H), 5.84 (1H, bs, Cp-H), 5.79 (1H, bs, Cp-H), 5.77 (1H, bs, Cp-H), 4.41 (1H, dd, J = 9.1, 8.5 Hz, CHH), 4.06 (1H, t, J = 8.5 Hz, CHH), 4.03 - 3.97 (1H, m, CH), 2.16 (15H, s, Cp*), 1.77 - 1.69 (1H, m, CH(CH₃)₂), 1.03 (3H, d, J = 6.7 Hz, CH₃), 0.92 (3H, d, J = 6.7 Hz, CH₃); ¹³C NMR (125 MHz, CDCl₃) δ 157.02, 95.84, 84.79, 83.22, 83.12, 80.74, 80.64, 73.61, 71.43, 33.46, 19.28, 18.69, 10.05.

Electronic Supplementary Information (ESI) available: Experimental methods and characterisation data. CCDC1442801 contains supplementary X-ray crystallographic data for 3. This data can be obtained free of charge via <http://www.ccdc.cam.ac.uk/conts/retrieving.html>, or from the Cambridge Crystallographic Data Centre, Union Road, Cambridge, CB2 1EZ; fax (+44) 1223-336-033 or email: deposit@ccdc.cam.ac.uk.

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12 Crystal data for 3: $C_{21}H_{29}F_6IrNOP$, $M = 648.62$, pale yellow needle, $a = 7.0929(2)$, $b = 15.6774(4)$, $c = 20.8647(5)$ Å, $V = 2320.12(10)$ Å³, $T = 100(2)$ K, space group $P2_12_12_1$, $Z = 4$, $\mu = 1.857$ mm⁻¹, reflections collected = 15356, independent reflections = 5262, $R_{int} = 0.0298$, Flack parameter = $-0.007(6)$, $R_1 = 0.0281$, $wR_2 = 0.0590$ [$F_2 > 2\sigma(F_2)$], $R_1 = 0.0333$, $wR_2 = 0.0606$ (all data). There is disorder of the Cp^* and hexafluorophosphate ion. For this various geometrical (SAME) and displacement (RIGU) restraints have been used. The Cp and Cp^* rings form infinite alternating stacks. A small percentage (about 2.5%) effectively stack in the opposite direction with the Ir ion lying in the gap. Although it is offset, only the second Ir ion is modelled.

13 Complex 4 was isolated previously by chromatography on neutral Al_2O_3 with acetonitrile as the eluent.¹¹ The ratio of 4 to 3 was determined by 1H NMR following non-separative filtration through neutral Al_2O_3 .

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