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Twist it! The Acid-Dependent Isomerization of Homoleptic Carbenic Iridium(III) Complexes

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The first successful *meridional* to *facial* isomerization of homoleptic carbenic iridium(III) complexes is presented. The Brønsted-acid-mediated procedure allows the conversion of large amounts of material and additionally provides an in situ purification because of precipitation of the target material during the reaction. The pronounced acid-dependency of the reaction yield observed for tris(*N*-phenyl,*N*-methyl-benzimidazol-2-yl)iridium(III) and tris(*N*-phenyl,*N*-benzyl-benzimidazol-2-yl)iridium(III) was investigated by labelling experiments and quantum chemical calculations. The results reveal a subtle balance between the strength of the acid, the coordinating power of the corresponding base and steric effects of the ligand sphere. Based on these findings, general rules are given for a systematic and material-specific modification of the reaction conditions for the *mer-fac* isomerization of homoleptic carbenic Ir(III) complexes.

Interest in iridium chemistry has markedly increased over the last two decades. Cyclometallated Ir(III) complexes have spread into the most diverse scientific fields in medical, catalytic, sensing and optoelectronic applications.[1] One major driving force in this process has been their excellent electro-phosphorescent properties, making them one of the most commonly used class of emissive materials in commercial phosphorescent organic light emitting diodes (PhOLEDs).
Prominent representatives of this compound class are homoleptic tris-cyclometallated d^6-Ir(III) complexes. The use of asymmetric chelate ligands in an octahedral complex leads to two possible geometrical isomers, namely the meridional (*mer*) and the facial (*fac*) isomer (Scheme 1). These configurations often differ in physical and photophysical properties such as long term stability, quantum efficiency or radiative rates.[2] Unfortunately, most synthetic pathways yield a mixture of both isomers so that for certain applications additional purification or transformation of one isomer is necessary. The currently available tools for these transformations can be divided into thermal[3,4] and photoinduced[3,5] isomerizations. So far, none of these methods have been successfully applied to the compound class of homoleptic carbenic Ir(III) complexes.
The particular interest in those Ir(III) complexes featuring a carbenic motif was sparked by the lack of sufficiently stable and highly efficient electrophosphorescent deep blue materials for PhOLEDs.[6] Especially the *fac* isomers, which show a specifically narrow blue electroluminescence (EL) emission band width, are of particular importance for device engineering. Unfortunately, there is no robust route to synthesize the *fac* isomer selectively. According to a recent publication by Thompson and Forrest, the lack of conversion methods for these complexes can be ascribed to the stronger metal-ligand bonds in carbenic Ir(III) compared to the weaker Ir-N bonds in Ir(C^N) complexes.[7]
Addressing the need for reliable *mer-fac* conversion procedures, this work presents an acid-mediated isomerization methodology at the example of the two deep blue phosphorescent Ir(III) complexes tris(*N*-phenyl,*N*-methyl-benzimidazol-2-yl)iridium(III) (**1**) and tris(*N*-phenyl,*N*-benzyl-benzimidazol-2-yl)iridium(III) (**2**). The success of the method is confirmed by X-ray analyses of the *fac*-**1** and *mer*-/*fac*-**2** crystal structures. The overall reaction yields depend on the employed acid. Whereas hydrochloric acid (HCl), as a strong acid, instantaneously leads to degradation of both **1** and **2,** malonic acid (MA) and trifluoroacetic acid (TFA) show a complex-dependent selectivity. In order to gain a deeper understanding of this dependency, a ^{1}H-NMR isotopic labeling experiment and quantum chemical calculations were carried out.

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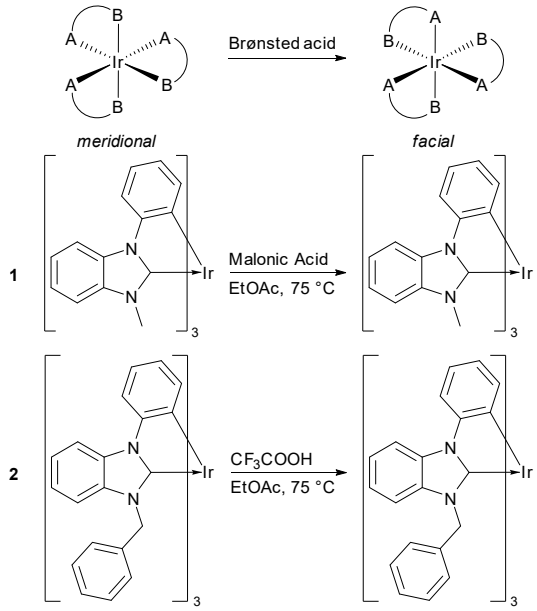


Scheme 1 Overview of the acid-mediated isomerization of tris-(*N*-phenyl,*N*-methyl-benzimidazol-2-yl)iridium(III) (1) and tris-(*N*-phenyl,*N*-benzyl- benzimidazol-2-yl)iridium(III) (2).

The procedure for the geometric isomerization of the Ir(III) complexes can be directly carried out on the isolated isomeric mixtures obtained from the non-selective preparation. The complexes **1** and **2** were obtained as a mixture of the *fac* and the *mer* isomers, whereby the *mer* isomer was formed in both cases predominantly. According to HPLC analysis the *mer* : *fac* ratios for the isomers were 6.1:1.0 for **1** and 7.2:1.0 for **2**.

In agreement with literature, variation of the reaction temperature, time or solvents had little influence on the isomeric ratios.[8] When the mixtures are dissolved in EtOAc with the addition of a dilute Brønsted acid, the *mer* isomer is converted to the *fac* isomer. An essential factor for the successful conversion is the choice of an appropriate acid. While a strong acid, such as HCl, leads to a rapid degradation of the precious complex, a weak acid, as for instance acetic acid, promotes at best a slow *mer* to *fac* conversion (if any) of the respective material.

The optimized conditions for the conversion of the complexes **1** and **2** are depicted in Scheme 1. MA was used for the conversion of **1,** but its acidity was insufficient for the geometric isomerization of **2**, for which a stronger acid, such as TFA, was needed. The progress of the reaction is indicated under optimized conditions by the precipitation of the desired *fac* isomer, while the *mer* isomer remains dissolved. This in situ purification allows facile isolation of the *fac* isomer by filtration (see Supporting Information).

From the four geometric isomers of the two complexes, three single crystals suitable for X-ray structural analysis were obtained (*fac* of **1**, *mer* and *fac* of **2**). The structures are displayed in Figure 1. Crystallographic information are given in the ESI and via the CCDC.

In order to study the practically inaccessible intermediates of the *mer-fac* isomerization complementary quantum chemical calculations have been conducted. By employing **1** as a model

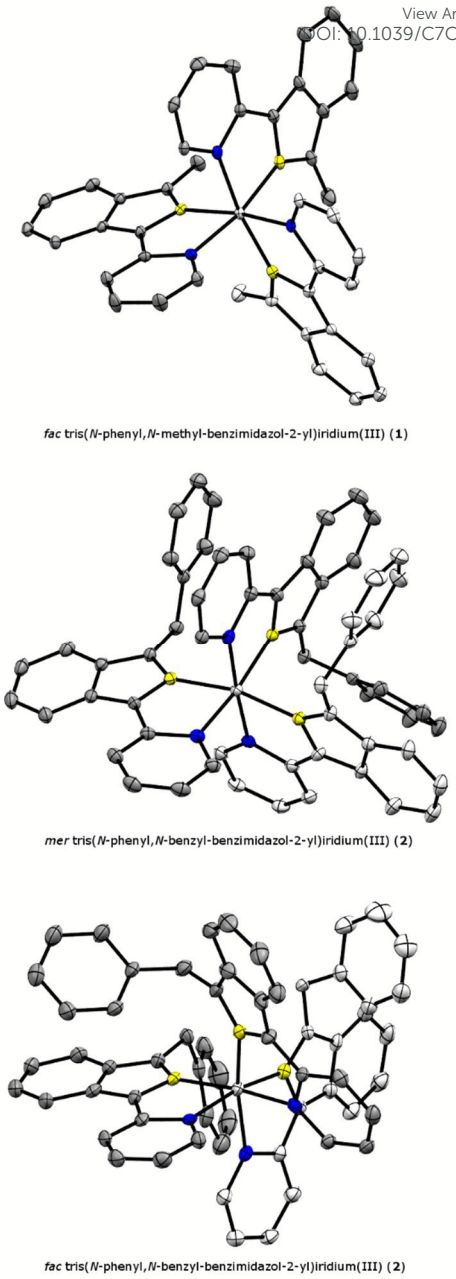


Fig. 1. ORTEP plots of *fac* (**1**) and *mer*/*fac* (**2**). Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms and co-crystallized solvent molecules were omitted for clarity.

system to study the key mechanistic features, conformational issues caused by ligands with larger substituents than the methyl group of **1** can be excluded. TFA was chosen as an isomerization agent in the computations, because of its ambiguous behavior, it enables the geometric conversion of **1** while partially leading to its degradation.

The initial protonation of **I** (*mer*-**1**)**,** which triggers the isomerization, was studied by a systematic sampling of the protonation sites, which showed that a protic Ir-ligand bond cleavage most probably yields two energetically similar intermediates (*G = -4.3 kJ/mol and G = 5.0 kJ/mol),* both of which have a characteristic protonation at the phenyl moiety in

common (see Supp. Info. SI-Fig. 6). A protonation at the carbene is unlikely as all resulting intermediates exhibit high energies (*G ≥ 106.0 kJ/mol*).

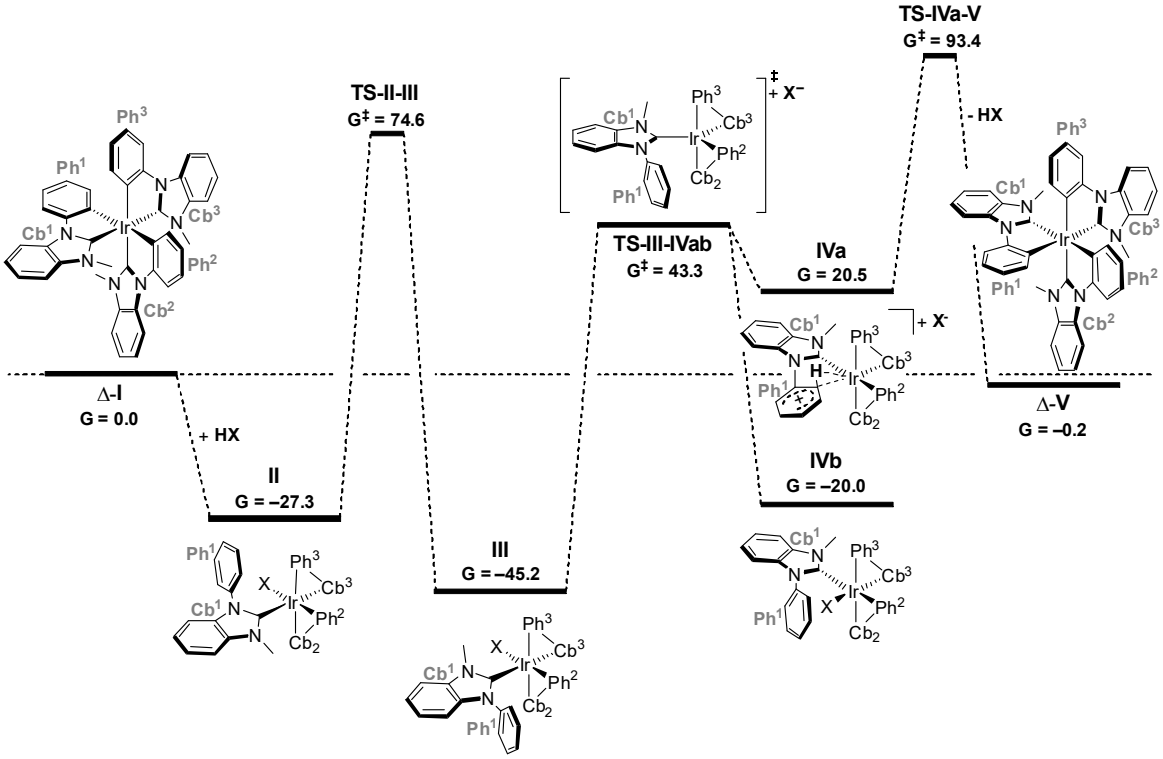
To justify the neglect of conformational influences caused by different substituents of the ligand, a deuteration experiment of *mer*-**2** was conducted using CF_3COOD. The ^{1}H-NMR results show a protonation of the phenylic and also of the benzylic moieties (see Supp. Info. SI-Fig. 1). A comparison of the computed energies of all possible constitutional isomers relative to *mer*-**2** (*ΔG = 0.0 kJ/mol*) rules out the benzyl moiety as a reasonable participant. Species with at least one benzyl-iridium(III) linkage are energetically disadvantageous (*ΔG = 44.7 kJ/mol*) compared to Ir(III)-phenyl linked isomers (*fac*-**2**: *ΔG = -3.8 kJ/mol*). Therefore, substitution-dependent byproducts or intermediates can be excluded. Consequently, an initial phenyl-carbon-iridium(III) bond-breakage is a reasonable starting point to initiate the geometric transformation.

In accordance with existing literature, four different mechanistic scenarios featuring three different key transition states were studied.[9,10] The pathway having the lowest overall energy barrier of all four mechanisms is shown in Scheme 2. Gibbs free energies are given in kJ/mol relative to **I** + TFA (*G = 0.0 kJ/mol*).

The initial protonation of Δ-**I** leads to **II** (*G = -27.3 kJ/mol*). Considering the preference of this system for electron-rich species and a fast ligand exchange rate, the vacant coordination site is probably occupied by the electron-rich acid anion CF_3COO^- (**X**$^-$) yielding a significant energy sink. Subsequently, the dangling ligand of **II** rotates around the Cb^1-Cb^3 axis in an anti-clockwise manner giving **TS-II-III** (*G‡ = 74.6 kJ/mol*) while **X**$^-$ still occupies the vacant coordination site. This reaction step, requiring *G = 101.9 kJ/mol*, marks the highest overall reaction barrier during the geometric conversion. The actual *mer-fac* conversion occurs between **III** (*G = -45.2 kJ/mol*) and **IVa**/**IVb** *via* **TS-III-IVab** (*G‡ = 43.3 kJ/mol*). During this step the complex loses its octahedral geometry and forms the trigonal bipyramidal transition state **TS-III-IVab**. This step is initiated by replacement of **X**$^-$ with Cb^1, which moves in *trans* position to Ph^2. Similar transition states can be found in the literature for geometrically comparable systems.[9–11] Returning to the energetically favourable octahedral complex geometry, two intermediates can be identified: **IVa** (*G = 20.5 kJ/mol*) and **IVb** (*G = -20.0 kJ/mol*). In **IVa** the vacant coordination site is shielded by agostic interactions between Ph^1-H and Ir(III) while **X**$^-$ acts as a spectator.[12] However, in **IVb** an **X**$^-$ occupies the free Ir(III) coordination site yielding a thermodynamic sink. Finally, the thermodynamically favoured product **V** (Δ-*fac*-**1**) (*G = -0.2 kJ/mol*) is reached by the energetically preferred cyclometallation step from **IVa** *via* **TS-IVa-V** (*G‡ = 93.4 kJ/mol*) where **X**$^-$ attacks from above the Cb^1-Cb^3-Ph^2-Ph^1 plane and abstracts the proton as an external base.

On closer inspection of the quantum chemical results, the crucial role of the thermodynamic sinks (**II**, **III** and **IVb**), connected with the coordination strength of the corresponding base becomes apparent. If those sinks were too deep to be reversibly overcome during the reaction, the isomerization might stop or potential decomposition reactions might take place.

For the initial reaction step Δ-**I** + HX → **II** the influence of three different acids (**HX** = MA, TFA or HCl) was tested. The corresponding energies obtained for **II** clearly depend on the coordinating power of the acid's anion. Therefore, the use



Scheme 2 Energetic isomerization sequence starting from **I** (Δ-*mer*-**1**) to finally produce **V** (Δ-*fac*-**1**).

of two different MA conformers only yields very modest thermodynamic sinks (*ΔG*(twisted) = *-7.7 kJ/mol*, *ΔG*(planar) = *-15.7 kJ/mol*) (see SI-Fig. 3), while the sink for TFA is almost twice as deep (*ΔG = -27.3 kJ/mol*). Finally, HCl leads to an iridium-chloro-complex that is stabilized by *ΔG = -45.7 kJ/mol* (see SI-Fig. 4). Therefore, the coordinating power of the corresponding base directly correlates with the depth of the resulting energy sinks.

Besides the influence of different acids, a further comparison of **IVa** and **IVb** shows that the complex, depending on its structure, can intrinsically prevent these sinks by agostic interactions (*G* = 20.5 *kJ/mol* vs. *G* = -20.0 *kJ/mol*). In this case the Ph^1-H group in **IVa** can weakly bind to Ir(III) by electrostatic interactions and prevent $\mathbf{X}^-$ from coordinating to the vacant metal center. On the other hand, for **III** the vacant coordination site is completely exposed, because the small methyl group points in the direction of $\mathbf{X}^-$. In conclusion, it can be assumed that thermodynamic sinks are highly unfavourable but sometimes inevitable (see **III**). Deep energy sinks can cause the *mer-fac* conversion to stop or even lead to further degradation cascades. This finding is in excellent agreement with the experimental observations for the geometric conversion of *mer*-**1** (**I**): While MA gives the best reaction yield, TFA already leads to partial decomposition whereas HCl does not produce any *fac*-**1** (**V**).

On the other hand, a successful *mer*-**2** to *fac*-**2** isomerization was only achieved using TFA, while MA did not yield any product. Both complexes essentially differ only in their substitution pattern at the benzimidazole. The replacement of all methyl groups by bulkier benzyl groups in **III** (Scheme 1) reduces the available space for the coordination of acid anions and in this way shields the vacant site of the Ir(III) complex. Consequently, the crowded ligand sphere would hamper the coordination of relatively large anions such as MA^- and TFA^-, while small anions such as Cl^- were still compact enough to overcome this protection. Even with the crowded ligand sphere lowering the influential impact of thermodynamic sinks in the *mer-/fac*-**2** conversion, it is puzzling why the experimental results prove that this conversion requires the use of TFA. However, this necessity can be explained by a difference in the rotational barrier for the *mer-/fac*-**2** conversion compared to **1**. Preliminary results indicate that it is significantly higher for *mer-/fac*-**2** than for the *mer-/fac*-**1** conversion. Therefore, the rate of the *mer-/fac*-**2** conversion is not only determined by thermodynamic sinks but also by a kinetic energy barrier. Employing the weaker and incompletely dissociated MA, only a small portion of protonated educt molecules is generated, and has to overcome the reaction energy barrier to finally recover the acid. Thereby, the reaction rate approaches practically zero. Consequently, not only the coordinating power of the corresponding base but also the strength of the acid are key criteria that determine the successful outcome of the *mer-fac* isomerization.

In summary, a new and efficient acid-mediated *mer-fac* isomerization, featuring an in situ purification, is presented for homoleptic carbenic Ir(III) complexes and is confirmed by X-ray analysis of the single crystal structures. The pronounced acid-dependency of the reaction yields was found to be influenced by a subtle interplay of the acid strength and the coordinating power of its corresponding base. Based on the presented results general guidelines for synthetic planning can be devised: (1) The acid strength generally determines whether or not the reaction is *kinetically* inhibited, whereas very strong acids instantaneously result in material decomposition; (2) The coordinating power of the corresponding base controls the *thermodynamic* barriers by means of energy sinks resulting in unwanted side reactions or material degradation; (3) Agostic interactions between the ligand sphere and a vacant Ir(III) site help to prevent thermodynamic sinks by repelling free coordinating agents.

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