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Unique Class of Enantiopure *N*-Heterocyclic Carbene Half-Sandwich Ir(III) Complexes With Stable Configurations: Probing Five-membered Versus Six-membered Iridacycles.

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Supporting Information Placeholder

ABSTRACT: A unique class of enantiopure *N*-heterocyclic carbene half-sandwich iridium complexes is reported. These compounds display stable configurations at the metal center as demonstrated by their chiroptical properties. Remarkably, due to the nature of the naphthalimide molecule, two isomers containing five-membered (*R*)-**2a**, (*S*)-**2a** and six-membered (*R*)-**2b**, (*S*)-**2b** iridacycles were obtained. DFT-calculations are advanced to rationalize their relative stability.

Half-sandwich compounds with three-legged piano stool geometry with different substituents are archetypal examples of optically active chirality-at-metal center.¹⁻³ Pioneering work of Brunner *et al.* and Gladysz *et al.* on the preparation of optically active [CpMn(CO)(NO)(PPh₃)] [PF₆] and [CpRe(L)(NO)(PPh₃)] [BF₄] (L = CH₂Cl₂, C₆H₅Cl) complexes gave an impetus to the development of modern chiral organometallic chemistry.^{4, 5} Depending on the metal and the nature of ligands as well, such compounds tend to exhibit labile or stable configuration in solution. For instance, the related chiral Cp*Ir complexes were found to exhibit labile configuration in solution.⁶⁻⁸ More recently, however, the use of strongly coordinating *N*-heterocyclic carbene (NHC) ligands brought some stability to the metal center but only a few examples of enantiopure half-sandwich Cp*Ir complexes were reported by Crassous and Peris.^{9, 10}

On the other hand half-sandwich metal complexes have received considerable attention due to their importance in medicinal chemistry^{11, 12}, materials science^{13, 14} and catalysis.¹⁵⁻¹⁷ Thus we sought to design a novel class of stable half-sandwich Cp*Ir complexes in which the NHC unit is directly attached to a naphthalimide molecule (NI). The latter adopts a planar structure and contains three fused arenes, which should bring strong configurational rigidity around the metal center. Moreover it might also provide an entry to a novel class of luminescent compounds. To demonstrate the viability of our strategy, we first prepared the naphthalimide-imidazolium salt (**1**) according to our described synthetic procedure.¹⁸⁻²⁰ Significantly, treatment of two equivalents of **1** with [Cp*Ir(μ-Cl)Cl]₂ in the presence of Ag₂O and

NBu₄I in CH₃CN for overnight reflux afforded in one-pot reaction the iridium carbene complexes [Cp*Ir(NI-NHC)] (**2a** and **2b**) in 1:1 ratio. The regioisomers **2a** and **2b** were separated by column chromatography and fully characterized. They differ only by the size of the iridacycle, whether five-membered or six-membered, constructed by the carbene and the naphthalimide units (Figure 1). Indeed due to the structure of the naphthalimide molecule, which contains two fused arenes available for metal coordination, the iridacyclization process occurs in two different ways. This phenomenon has not been observed before in the literature for this class of half-sandwich metal carbene complexes.

The ¹H-NMR of **2a** recorded in CDCl₃ presented six multiplets in the range of δ 7.1 ppm and δ 9.2 ppm corresponding to the aromatic protons of the naphthalimide unit and to the diene protons of the NHC moiety. The *n*-Bu group of the naphthalimide unit displayed four multiplets in the range δ 0.9 ppm to δ 4.3 ppm while the methyl group of the carbene unit appeared as a singlet at δ 3.98 ppm. The Cp*Ir moiety gave a singlet at δ 1.96 ppm. The ¹H-NMR of isomer **2b** in CDCl₃ displayed a marked difference with respect to **2a** where the Cp*Ir protons appeared downfield at δ 1.54 ppm and the aromatic protons of the naphthalimide and NHC moiety appeared in the range of δ 7.1 to δ 8.6 ppm and displayed a different pattern. Moreover 2D COSY, ROESY, HSQC and HMBC experiments allowed us to fully characterize both isomers (See supporting information Figures S1-S7). In addition, the molecular structures of isomers *rac*-**2a** and *rac*-**2b** were also ascertained by X-ray crystallography.

Crystals of cyclometalated carbene complex **2a** were obtained from a mixture CH₂Cl₂/Et₂O by slow diffusion. A view of the molecule is given in Figure 2. The structure of **2a** is in accord with the spectroscopic data and confirms the formation of a five-membered iridacycle. As expected, the metal adopts a distorted tetrahedral geometry. The structure packing in the crystal shows the formation of a dimer assembly between two adjacent molecules, which are arranged in a head-to-tail fashion where each complex adopts an opposite configuration at the

metal center (S_{Ir} , R_{Ir}). The dimer assembly arises from weak non-covalent C-H $\cdots\pi$ interactions (CH \cdots C = 3.60(3) Å) between the *n*-Bu group and the naphthalimide moiety (Figure S8).²¹

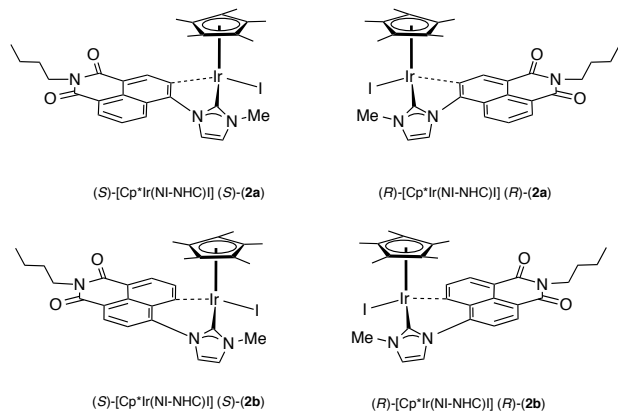


Figure 1. Schematic drawings of enantiopure carbene regioisomeric complexes (**S**)-**2a**, (**R**)-**2a**, and (**S**)-**2b**, (**R**)-**2b** described in this work. Priority sequence of ligands: I > η^5 -C₅ > C-carbene > C-arene.^{22, 23}

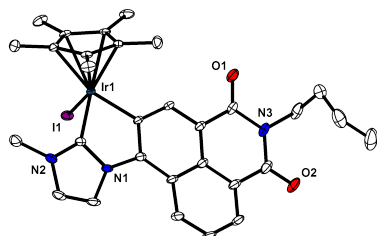


Figure 2. Molecular structure of complex *rac*-**2a**.

In a similar fashion, crystals of [Cp*Ir(NI-NHC)I] (**2b**) were obtained by slow diffusion of diethylether into a saturated CH₂Cl₂ solution of the complex. Details regarding crystal structure determination are given in the ESI. A view of **2b** is shown in Figure 3. The structure of complex **2b** confirms the formation of the target molecule and shows that the iridacycle is composed of a six membered ring. The configuration around the iridium center is a distorted tetrahedral geometry. The crystal structure adheres to a similar head-to-tail dimer assembly as *rac*-**2a**, but with C-H $\cdots\pi$ interaction (C28A \cdots C17 = 3.41(3) Å) between the *n*-Bu group and the Cp*Ir moiety (Figure S9).²¹

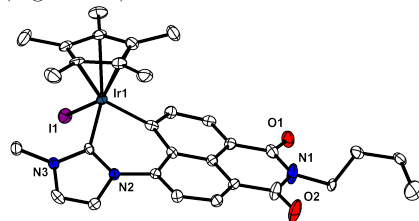


Figure 3. Molecular structure of complex *rac*-**2b**.

To examine their configurational stability we decided to resolve these compounds into their single enantiomers and to investigate their chiroptical properties in solution (vide infra).

Enantiopure [Cp*Ir(NI-NHC)I] complexes (**S**)-**2a**, (**R**)-**2a**, and (**S**)-**2b**, (**R**)-**2b**

The optically active compounds (**S**)-**2a**, (**R**)-**2a**, and (**S**)-**2b**, (**R**)-**2b** were obtained by resolving the racemic samples using chiral column chromatography techniques. Full experimental details are given in the supporting information. Gratifyingly all of our enantiopure compounds were found to display stable configuration in strongly coordinated CH₃CN solution and did not epimerize upon standing for several days in solution as demonstrated by their CD curves (vide infra). The same behavior is observed in CH₂Cl₂ (Figures S15-S16).

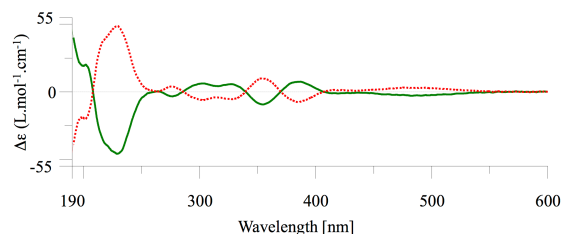


Figure 4. CD traces of **S**-**2a** and **R**-**2a** showing perfect mirror image. Recorded in CH₃CN at C = 0.24mM

The CD traces recorded in CH₃CN show an excellent mirror-image relationship for the two enantiomers of **2a** (Figure 4). In both cases, several peaks (with opposite signs for the two enantiomers) are visible at 240, 260, 290 and 320 nm, associated with the polarized π - π^* transition of the naphthalimide unit. Moreover, bands of weak intensity attributed principally to MLCT electronic transitions are also visible at 350, 390 and 480 nm.

We then investigated the chiroptical properties of the other isomer **2b** to see whether the presence of a six membered cycle might affect the Cotton transitions (Figure 5).

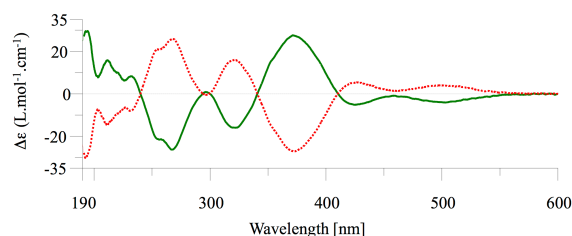


Figure 5. CD traces of **S**-**2b** and **R**-**2b** showing perfect mirror image. Recorded in CH₃CN at C = 0.24mM.

Again the CD curves recorded in CH₃CN show an excellent mirror-image relationship for the two enantiomers of **2b**. We also notice that several peaks (with opposite signs for the two enantiomers) are visible at 240, 260, 290 and 320 nm, associated with the polarized π - π^* transition of the naphthalimide unit. Moreover, bands of more pronounced intensity relative to **2a** attributed to MLCT electronic transitions are also visible at 370, 420 and 520 nm. These bands extend more into the visible red region compared to the five membered isomer **2a**. We then attempted to obtain crystals of the enantiopure compounds in order to compare it to the racemic analogues. After many attempts, gratifyingly we were able to obtain convenient crystals of isomer (**R**)-**2b** for an X-ray determination (vide infra).

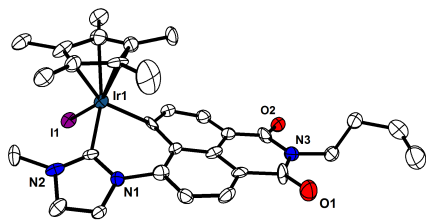


Figure 6. Molecular structure of complex (*R*)-**2b**.

Complex (*R*)-**2b** crystallizes in the Sohncke space group $P2_1$. A view of the complex is shown in Figure 6. The absolute structure was determined by refinement of the Flack x parameter equal to 0.033(10).²⁴⁻²⁶ The structure confirmed the formation of the six-membered cycloiridated carbene isomer with (*R*)-configuration. The iridium center adopts a pseudotetrahedral geometry and is bound symmetrically to η -Cp*, the NI carbon centers, NHC unit and to the iodide halogen. The Ir---carbene bond distance is 2.03(2) Å similar to 1.97(1) Å reported for the analogous racemic compound. The solid-state packing, on the other hand, shows a completely different arrangement from that observed for the racemic complex **2b**. Indeed in the enantiopure complex (*R*)-**2b** the individual molecules adopt the same configuration and form 1D supramolecular assemblies though non-covalent C-H--- π interactions (C17---C22) = 3.42(5) Å between the NI unit and the Cp*Ir moiety (Figure S10).²¹

We then investigated the solution behavior of both regioisomers in order to see whether a conversion of one regioisomer to the other might occur. Thus, refluxing isomer **2a** in CD₃CN for 24h resulted in no alteration and the starting material remained unchanged. Moreover when isomer **2b** was heated under similar conditions no formation of **2a** was observed. These results suggest that both compounds are stable in solution even at high temperature. This stability arises from the nature of the NI-carbene ligand that acts as a clamp and strongly chelates the metal center.

To shed light on their relative stability and mechanism of their formation, relative energies and other properties both complexes were calculated by density functional theory (DFT). The free energies of **2a** and **2b** were found to be remarkably similar, differing by less than 2.2 kcal/mol in all our calculations, employing different combinations of DFT method, basis set, and solvation model. Indeed, at the highest quality calculations employed Truhlar's M06²⁷ DFT method and a mixed pc-2/cc-pVDZ-pp basis^{28, 29}, the two compounds were found to have equal free energies within 0.1 kcal/mol. These differences are well within the expected error of these calculations, a result that is consistent with the observation of both species in solution. There appears to be a balance of destabilizing ring strains in the two isomers, with the **2a** iradacycle suffering from small bond angles (C-Ir-C=76°, compared to 86° in **2b**; sp² bond angles = 111.5° and 114.5°) whereas the conjugation of the arene system in **2b** is disrupted by a 25° twist of the imidazole unit relative to the neighboring naphthyl ring (compared to an 8° twist in **2a**). Surprisingly, alt-

hough **2a** has the more constrained ring system, frequency corrections consistently improve the relative stability of **2a** by about 0.5 kcal/mol. This primarily results from small shifts to higher arene stretching frequencies in **2b**, because the partial loss of naphthyl-imidazolyl conjugation strengthens the force constants within each ring. The calculations have been carried out only on the monomers, so we are not able to directly compare lattice energies. However, we note that the same 1-D chain assembly observed for **2b** is not available to **2a**, because the *n*-Bu axis is perpendicular to the Ir-Cp axis in **2a**. Computed CD and UV/vis spectra are also found to be consistent with experiment (ESI Figures S17-S18). The supporting information includes details of the computational methods, including predicted UV spectra and a brief MO analysis of the principal electronic transitions.

CONCLUSION

In this paper we reported a unique class of enantiopure N-heterocyclic carbene complexes displaying five- and six-membered iridacycles not reported before. Remarkably these regioisomeric compounds display stable configuration in solution thanks to the naphthalimide-C-NHC-chelate as demonstrated by their chiroptical properties. The use and future applications of these compounds are currently under investigation.

ASSOCIATED CONTENT

The Supporting Information is available free of charge on the ACS Publications website. The synthesis and separation of complexes *S*-**2a**, *R*-**2a** and *S*-**2b**, *R*-**2b**. ¹H, ¹³C and 2D ROESY Spectra of complexes **2a** and **2b** (Figures S1-S7). X-ray molecular structures (Figures S8-S10) UV and ECD spectra are given (Figures S11-S16). DFT calculations (Figures S17-S18). CCDC reference numbers 1880113-1880115 contain crystallographic data for complexes *rac*-**2a**, *rac*-**2b** and *R*-**2b** presented in this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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SYNOPSIS: A unique class of enantiopure *N*-heterocyclic carbene half-sandwich iridium complexes obtained under two regioisomeric forms, not observed before, is described. These compounds display stable configuration at metal center and their molecular structures, chiroptical properties and DFT calculations are presented and discussed.

