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# Stable group 8 metal porphyrin mono- and bis(dialkylcarbene) complexes. Synthesis, characterization, and catalytic activity

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Alkyl-substituted carbene (CHR or CR<sub>2</sub>, R = alkyl) complexes have been extensively studied for alkylcarbene (CHR) ligands coordinated with high-valent early transition metal ions (a.k.a. Schrock carbenes or alkylidenes), yet dialkylcarbene (CR<sub>2</sub>) complexes remain less developed with bis(dialkylcarbene) species being little (if any) explored. Herein, several group 8 metal porphyrin dialkylcarbene complexes, including Fe- and Ru-mono(dialkylcarbene) complexes [M(Por)(Ad)] (**1a,b**, M = Fe, Por = porphyrinato dianion, Ad = 2-adamantylidene; **2a,b**, M = Ru) and Os-bis(dialkylcarbene) complexes [Os(Por)(Ad)<sub>2</sub>] (**3a-c**), are synthesized and crystallographically characterized. Detailed investigations into their electronic structures reveal that these complexes are formally low-valent M(II)-carbene in nature. These complexes display remarkable thermal stability and chemical inertness, which are rationalized by a synergistic effect of strong metal-carbene covalency, hyperconjugation effect, and a rigid diamondoid carbene skeleton. Various spectroscopic techniques and DFT calculations suggest that dialkylcarbene Ad ligand is unique to other common carbene ligands as it acts as both a potent  $\sigma$ -donor and  $\pi$ -acceptor; its unique electronic and structural features, together with the steric effect of porphyrin macrocycle, render its Fe porphyrin complex **1a** an active and robust catalyst for intermolecular diarylcarbene transfer reactions including cyclopropanation (up to 90% yield) and X–H (X = S, N, O, C) insertion (up to 99% yield) reactions.

#### Introduction

Since the discovery of a metal-alkylcarbene (M=CHR) complex, [Ta(CH<sub>2</sub><sup>t</sup>Bu)<sub>3</sub>(CH<sup>t</sup>Bu)], by Schrock,<sup>1</sup> alkyl-substituted carbene ligands (alternative name: alkylidenes), i.e., alkylcarbene (CHR) and dialkylcarbene (CR<sub>2</sub>), herein generally described as (di)alkylcarbenes, have been mainly studied for M=CHR complexes with early transition metals (TMs, Group 4-6), with their roles ranging from reactive synthons in olefin metathesis to supporting ligands (in nucleophilic, dianionic form (CHR)<sup>2-</sup>) that stabilize high-valent metal ions.<sup>2</sup> In contrast, the chemistry of dialkylcarbene complexes of TMs and (di)alkylcarbene complexes of middle/late TMs remains less developed (Fig. 1a), particularly for mononuclear bis((di)alkylcarbene) complexes, examples of which are sparse and belong to bis(alkylcarbene) species.<sup>3</sup> To the best of our knowledge, no mononuclear bis(dialkylcarbene) complexes of TMs have been reported previously.<sup>4</sup>

We are interested in developing novel types of dialkylcarbene complexes of group 8 metals Fe, Ru, and Os. In the literature, Grubbs' Ru-alkylcarbene species have received much attention owing to their essential role in olefin metathesis.<sup>5</sup> Related (di)alkylcarbene species of Fe,<sup>6</sup> Ru,<sup>7</sup> and Os,<sup>3d,8</sup> mostly stabilized by strong-field ligands such as CO/phosphine and Cp (cyclopentadienyl), have also been reported; some Fe-(di)alkylcarbene complexes  $[Cp(CO)(L)Fe(CHR)]^+$  (L = PR<sub>3</sub>, CO)<sup>9</sup> or  $[Cp(CO)_2Fe(CR_2)]^+$  <sup>10</sup> undergo stoichiometric reactions typical of electrophilic carbenes, including cyclopropanation,<sup>9a-g,10</sup> Si-H insertion,<sup>9h</sup> and C–H insertion.9i Interest in the Fe-carbene complexes6a,11 also lies in their potential role as next-generation catalysts for olefin metathesis and mechanistic implication of iron porphyrin carbene complexes for artificial metalloenzyme catalysis involving heme-carbenes as key intermediates.<sup>12</sup> Recently, we developed catalytic dialkylcarbene transfer reactions<sup>13</sup> including sp<sup>3</sup> C–H insertion, cyclopropanation, and Buchner reactions using various metalloporphyrin catalysts including Ru and Fe porphyrins; the active intermediates in these catalytic processes are likely to be the corresponding metalloporphyrin dialkylcarbene complexes [M(Por)(CR<sub>2</sub>)] (Por = porphyrinato dianion) which, however, have not been detected. Unlike the directly above-mentioned  $[Cp(CO)(L)Fe(CHR)]^{\scriptscriptstyle +}$  and  $[Cp(CO)_2Fe(CR_2)]^{\scriptscriptstyle +}$  which bear strong  $\pi$ -acidic CO ligand(s) in favor of low-valent metal centers,

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<sup>&</sup>lt;sup>†</sup> Electronic Supplementary Information (ESI) available: Abbreviations, experimental procedures, characterization of compounds, computational details, Table S1–S8, Fig. S1–S11, NMR spectra of compounds, Cartesian coordinates from DFT calculations, and CIF file for the crystal structure of **1b**, **1a**-Py, **2b**-MeOH, **2az**, and **3a**. See DOI: 10.1039/x00xx00000x

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complexes [M(Por)(CR<sub>2</sub>)] can possibly be formulated as either low-valent  $M^{II} \leftarrow (:CR_2)^0$  or high-valent  $M^{IV} = (CR_2)^{2-}$  species.<sup>14</sup> To clarify this issue, it is highly desirable to isolate and fully characterize stable metalloporphyrin dialkylcarbene complexes for detailed studies on their electronic and molecular structures.

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Up to now, metalloporphyrin dialkylcarbene complexes are extremely rare; the only examples are [Fe(TPP)(CMeR)] (R = "Bu, <sup>n</sup>Pr) prepared by treatment of [Fe(TPP)Cl] with terminal alkynes and NaBH<sub>4</sub>.<sup>15</sup> These [Fe(TPP)(CMeR)] complexes were not structurally characterized by X-ray crystallography and were formulated as Fe(II) species by analogy with the <sup>1</sup>H NMR, UV-vis, and MS spectra of iron porphyrins bearing other types of carbene ligands. The very limited knowledge on metalloporphyrin dialkylcarbene species contrasts with extensive studies on other types of nonheteroatom-stabilized carbene complexes of Fe,11e,16 Ru,<sup>7a,17</sup> and Os<sup>18</sup> porphyrins, which were generally prepared using diazo compounds as carbene sources; such a synthetic method is hardly applicable to dialkylcarbene complexes owing to the short lifetime of dialkyldiazomethanes. Moreover, metalloporphyrin dialkylcarbene species could be prone to undergo 1,2-hydride shift, which is a common side reaction observed in dialkylcarbene transfer catalysis.<sup>13</sup> In addition, non-porphyrin group 8 metal dialkylcarbene complexes reported previously were often prepared with limited choice of ligand sets (e.g., phosphine, Cp, tris(pyrazolyl)borate) and/or under demanding conditions (e.g., strong acid, reducing medium),<sup>5-8</sup> and only a few non-porphyrin Ru-7b-e,19 and Os-dialkylcarbene20 complexes have been structurally characterized by X-ray crystallographic studies and, despite the report of a structurally characterized Fe=CHMe nonporphyrin complex,<sup>21</sup> no crystal structure of Fe-dialkylcarbene complex has been reported so far.

In questing for a highly stable dialkylcarbene complex of metalloporphyrin, we paid attention to the dialkylcarbene ligand 2-adamantylidene (Ad). This was inspired by the studies of Ad as a model of dialkylcarbene in free carbene chemistry, as it can be photochemically generated from the diazirine compound, aziadamantane, under mild conditions and exhibits great resistance against 1,2-hydride shift due to its rigid diamondoid skeleton,<sup>22</sup> coupled with the use of diazirines as carbene sources for the preparation of non-porphyrin metal-C(Ph)X (X = OMe, Br) carbene complexes;<sup>23</sup> there is a literature report on the X-ray crystal structure of [Cp(CO)<sub>2</sub>Mn(Ad)],<sup>24</sup> which is hitherto the only example of a known M<sup>---</sup>Ad complex, although this Mn=Ad complex was prepared from a metal-borylene precursor rather than using aziadamantane as Ad source. We envisaged that diazirines could be a new type of carbene source for synthesizing metal-dialkylcarbene species and Ad may also lead to isolable group 8 metal porphyrin dialkylcarbene complexes by reaction of readily accessible metalloporphyrin precursors with aziadamantane under photolysis.

In the present work, we report a simple and mild method of synthesizing dialkylcarbene complexes of TMs using diazirine as the carbene source, leading to the isolation of several M<sup>---</sup>Ad complexes of group 8 metal porphyrins including Fe- and Rumono(dialkylcarbene) [M(Por)(Ad)] (M = Fe 1, Ru 2) and Osbis(dialkylcarbene) [Os(Por)(Ad)2] (3) complexes, along with the Xray crystal structures of these complexès): ଶନ୍ତ Wିଶ୍ୱୀ କିନ୍ତି ଦିଶି<sup>କ</sup>ୀଡିଥିନ୍ତି



complexes (mononuclear examples which have been isolated)



Fig. 1 (a) Literature examples of isolated mononuclear (di)alkylcarbene complexes of TMs. Mono- and bis(CHR/CR<sub>2</sub>) complexes are represented by different colors filled. Structurally characterized examples are indicated by . TMs for which no isolated examples were found are left blank. (b) Group 8 metal porphyrin dialkylcarbene complexes reported in this work. M<sup>---</sup>Ad (M = Fe, Ru, Os) represents an Ad $\rightarrow$ M  $\sigma$ bonding (–) and a M $\rightarrow$ Ad  $\pi$ -backbonding (---).

spectroscopic studies including XANES (X-ray absorption near edge structure) spectroscopy and also DFT calculations (Fig. 1b), which all lend evidence for the low-valent M(II)-carbene nature of 1-3. Complexes 3a-c contribute unique examples of a bis(dialkylcarbene) complex of TMs. Surprisingly, the metaldialkylcarbene complexes 1-3 are not reactive toward dialkylcarbene transfer reactions and generally display remarkable stability. Direct comparison is also drawn among dialkylcarbene Ad and other types of carbene ligands, mainly based on the system of group 8 metal porphyrins. Furthermore, a promising role of dialkylcarbene Ad as a supporting ligand is demonstrated by one of its Fe complexes 1a in homogeneous donor-donor carbene transfer catalysis.

#### Results

#### Synthetic procedures

Treatment of [Fe<sup>II</sup>(TPFPP)] and aziadamantane at room temperature under UV irradiation (365 nm) for 15 min afforded 1a in 93% yield as a bright red solid (reaction 1 in Scheme 1a). Alternatively, it could be synthesized directly from the commercially available [FeIII(TPFPP)Cl] at 40 °C with a slightly lower yield (85%, reaction 2 in Scheme 1a; the Fe(III) center was presumably reduced in situ by free Ad). Complex

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[Fe(TTP)(Ad)] (1b) could be prepared by the same two methods yet in much lower isolated yields, probably due to its higher susceptibility toward aerobic oxidation as it decomposed immediately to  $\mu$ -oxo dimer [Fe(TTP)]<sub>2</sub>O at above 60 °C under air (reaction 4 in Scheme 1a). Six-coordinate iron porphyrin carbene species 1a.Py could be easily accessed by adding pyridine into a solution of 1a (reaction 3 in Scheme 1a). Ruthenium analogues [Ru(Por)(Ad)] (Por = TPFPP: 2a; TTP: 2b) could be similarly prepared from [Rull(Por)(CO)] and aziadamantane in high yields (reaction 5 in Scheme 1b). Besides 2a,b, diazirine complexes 2az and 2bz (Scheme 1b), which are a new type of metalloporphyrin complexes, were isolated as minor species. The coordinated diazirine molecules are less photoactive and 2az could only be sluggishly transformed to 2a under UV irradiation and at elevated temperature (reaction 6 in Scheme 1b); we conceive that the coordinated diazirine ligand was either first converted to the corresponding diazo compound which then reacted with Ru porphyrin, or directly decomposed to free carbene that subsequently coordinated to the Ru center. Complexes 2az and 2bz are also slightly air-sensitive and slowly underwent oxidation to give 2-adamantanone.25

Strikingly, by similar treatment of [Os(Por)(CO)] (Por = 4-F-TPP, TPFPP, and TTP) with aziadamantane, bis(dialkylcarbene) product  $[Os(Por)(Ad)_2]$  (Por = 4-F-TPP: **3a**, TPFPP:  $(\mathbf{3b}_{Ar}, \mathbf{TP})$ were observed by <sup>1</sup>H NMR measurements 10786686666757348 Scheme 1c). Monitoring the reaction of [Os(TPFPP)(CO)] and aziadamantane by <sup>1</sup>H NMR showed that **3b** was formed immediately after UV irradiation and no mono(dialkylcarbene) species [Os(Por)(Ad)] was detected. Thus it is likely that the bis(dialkylcarbene) complexes 3a-c were formed directly from the Os carbonyl precursors, different from the pre-formation of an isolable mono(diarylcarbene) analogue [Os(TPFPP)(CPh<sub>2</sub>)] and its conversion to the bis(diarylcarbene) counterpart [Os(TPFPP)(CPh<sub>2</sub>)<sub>2</sub>].<sup>18e</sup> Besides, **3a-c** could all be readily purified by alumina column under air, in contrast to the analogous bis(diarylcarbene) complexes which could not be isolated in pure form when supported by simple porphyrin ligands such as TTP.<sup>18a,d</sup> The lower isolated yields (12-30%) for **3a-c** are attributable to the strong absorptivity of the Os precursors at 365 nm; attempts to improve the yields of **3a-c** by increasing irradiation time were not successful, as prolonged irradiation caused decomposition of the Os-dialkylcarbene products. The bis(dialkylcarbene) complexes 3a-c were found slightly susceptible to aerobic oxidation, as exemplified by the oxidation of 3c to trans-dioxo complex [Os(TTP)O2] and 2adamantanone after standing in aerobic solution for ~1 d 1c). (reaction 8 in Scheme



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(a)

(b)

Scheme 1 Synthesis of Fe (a), Ru (b), and Os (c) dialkylcarbene complexes.

e1 N3



Fig. 2 ORTEP diagrams of 1b (a), 1a·Py (b), 2b·MeOH (c), and 3a (d) with thermal ellipsoids at 50% probability level. Hydrogen atoms, disordered atoms/solvent molecules, and ellipsoids of porphyrin ligands (except for pyrrolic nitrogens) are omitted for clarity.

(M = Fe, Ru, Os)	1b	<b>1a</b> ∙Py	<b>2b</b> ·MeOH	3a <sup>a</sup>
M1-C1	1.770(3)	1.829(9)	1.856(3)	2.061(7)
C1-C2	1.500(4)	1.50(3)	1.511(5)	1.510(7)
C1-C3	1.488(5)	1.50(2)	1.507(5)	1.510(7)
M1-N <sub>pyrrole</sub> <sup>b</sup>	1.978(4)	1.996(8)	2.047(3)	2.065(5)
M1–L <sub>ax</sub> <sup>c</sup>		2.200(8)	2.364(3)	2.061(7)
C2-C1-C3	112.8(3)	111.2(12)	110.7(3)	106.8(7)
C2-C1-M1	124.2(2)	123.2(11)	124.5(2)	126.3(6)
C3-C1-M1	123.1(2)	125.5(11)	124.7(2)	126.7(5)
C1–M1–L <sub>ax</sub> <sup>c</sup>		178.4(7)	176.16(12)	180.0(9)

#### X-ray crystallography

The crystal structures of 1b, 1a·Py, 2b·MeOH, and 3a were determined by X-ray crystallography (Fig. 2), and the selected bond distances and angles are listed in Table 1. The sum of angles around C<sub>carbene</sub> atoms (1b: 360.1°; 1a·Py: 359.9°; 2b·MeOH: 359.9°; 3a: 359.8°) is indicative of sp<sup>2</sup>-hybridization of carbene carbons; the carbene planes are close to bisecting the M-N<sub>pyrrole</sub> bonds (31.6-44.3°) in all four complexes. The Fe-C<sub>carbene</sub> distance in **1b** is 1.770(3) Å, which is typical of fivecoordinate iron porphyrin carbene species.11e,16a The TTP macrocycle suffers from saddled distortion and the mean deviation of 24 atoms from the porphyrin mean plane is 0.268 Å, with the iron atom being displaced from this mean plane for 0.269 Å. Coordination of pyridine at the trans axial site causes elongation of the Fe-C<sub>carbene</sub> distance to 1.829(9) Å in **1a**·Py, yet this distance is still much shorter than Fe-C single bonds;<sup>26</sup> meanwhile, distortion of porphyrin ligand is greatly suppressed

(mean deviation: 0.051 Å) and the iron atom is only marginally deviated (0.074 Å) from the mean porphyrin plane. The crystal structure of 2b·MeOH features a short Ru-Ccarbene distance of 1.856(3) Å, and its porphyrin ring shows a minor doming distortion (mean deviation: 0.037 Å) along with a slightly outof-plane Ru atom (0.172 Å).

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**Fig. 3** *ORTEP* diagram of **2az** with thermal ellipsoids at 50% probability level. Hydrogen atoms and ellipsoids of porphyrin ligands (except for pyrrolic nitrogens) are omitted for clarity.

Table 2	Carbene	chemical	shifts	$\delta$	(ppm)	)a,t
	00.000	0	0	~	100	

	δ(Fe <sup></sup> C)		δ(Ru==C)
1a	413.57	2a	369.55
1b	394.92	2b	353.72
1a ArNC	444.78		
1a ·CNPy	433.85		δ(Os <sup></sup> C)
<b>1a</b> ·Py	433.58	3a	351.28 <sup>c</sup>
1a·NMe₂Py	433.39	3b	367.04 <sup>c</sup>
<b>1a</b> ·Melm	433.36	3c	350.39

<sup>*a*</sup> Measured in CDCl<sub>3</sub> at 298 K. <sup>*b*</sup> ArNC = 2,6-dimethylphenyl isocyanide, CNPy = 4-cyanopyridine, Py = pyridine, NMe<sub>2</sub>Py = 4-dimethylaminopyridine, MeIm = 1-methylimidazole. <sup>*c*</sup> Measured in C<sub>6</sub>D<sub>6</sub> at 298 K.

The Os-bis(dialkylcarbene) complex **3a** features an Os-C<sub>carbene</sub> bond of 2.061(7) Å, similar to the bis(diphenylcarbene) complex [Os(TPFPP)(CPh<sub>2</sub>)<sub>2</sub>] (~2.03 Å)<sup>18e</sup> yet apparently longer than the Os porphyrin mono(carbene) complexes (1.79–1.87 Å),<sup>18c,e</sup> which is likely due to the strong *trans* influence exerted by the carbene ligands. A 90° disorder is observed for one of the two Ad ligands, making them either orthogonal or parallel to each other. Notably, the porphyrin plane in **3a** is almost planar (mean deviation: 0.025 Å), which is in stark contrast to the strongly ruffled porphyrin ligand observed in [Os(TPFPP)(CPh<sub>2</sub>)<sub>2</sub>] (mean deviation: 0.197 Å).<sup>18e</sup>

Complexes **2az** and **2bz** represent two of rare examples of metal diazirine complexes<sup>25,27</sup> and the X-ray crystal structure of **2az** was obtained (Fig. 3). The two diazirine moieties experience slight  $\pi$ -backbonding from the Ru center, as the N=N bond distance (1.248(9) Å) is longer than those in non-coordinated diazirines (1.228–1.235 Å)<sup>25</sup> while the Ru–N<sub>diazirine</sub> bonds (1.985(6) and 1.996(6) Å) are also shorter than a typical Ru–N single bond (~2.1 Å). Evidence of such  $\pi$ -backbonding further comes from the N=N stretching bands observed in the IR spectrum of **2az** (1518 and 1491 cm<sup>-1</sup>) which appear at appreciably lower frequencies than that of the free ligand (1570 cm<sup>-1</sup>).<sup>28</sup>

#### Spectral features

All the <sup>1</sup>H NMR signals of dialkylcarbene complexes **1–3** are in the diamagnetic region, and no significant spectral change was observed at up to 60 °C under an inert atmosphere. The Ad protons of these M<sup>---</sup>Ad complexes (Scheme 1) are strongly shielded and well separated by the porphyrin ring current, as

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assigned by COSY spectra (see ESI). In the case of ArtiCa NMB spectra, the five-coordinate Fe-dialkylcarbene03complexe321 show characteristic downfield carbene chemical shifts at 394.92–413.57 ppm, and ligation of 1a with an axial ligand such as isocyanide, imidazole, or pyridines results in further downfield shifts of carbene carbons to 433.36-444.78 ppm; less deshielded signals are observed in Rumono(dialkylcarbene) complexes **2** as well as Osbis(dialkylcarbene) complexes 3 (350-370 ppm, Table 2).

Several other spectroscopic techniques were employed to probe the oxidation state of metal centers in these metalloporphyrin dialkylcarbene complexes. Fe K-edge XANES spectrum of **1a** was recorded along with several reference iron porphyrin complexes. The pre-edge peak of 1a (7113.0 eV) is highly similar to that of [Fe<sup>II</sup>(TPFPP)(CPh<sub>2</sub>)] (7113.0 eV) yet appreciably lower in energy than [Fe<sup>III</sup>(TPFPP)Cl] (7114.0 eV), thus suggesting a Fe(II) center in the dialkylcarbene complex (Fig. 4, top). These results are also consistent with those measured previously for Fe porphyrin carbene and related complexes (Table S6).<sup>16a</sup> The <sup>57</sup>Fe isomer shift ( $\delta$  = 0.25 mm s<sup>-1</sup> 1) of 1a in Mössbauer spectroscopy (Fig. 5) fall in the region of low-spin five-coordinate Fe(II) porphyrin complexes (-0.03 to 0.37 mm s<sup>-1</sup>);<sup>16c</sup> the relatively small guadrupole splitting ( $|\Delta E_0|$ = 1.61 mm s<sup>-1</sup>) is possibly related to the unique ligand field posed by the dialkylcarbene ligand.<sup>29</sup> Resonance Raman spectrum of 1a features a 1356 cm<sup>-1</sup> band (Fig. S5) which is comparable to that of [Fe(TPP)(CCl<sub>2</sub>)] (1368 cm<sup>-1</sup>) and indicative of a low spin Fe(II) center (1358–1379 cm<sup>-1</sup>) rather than other higher valent configurations (> 1370 cm<sup>-1</sup> for Fe at +3 to +5 oxidation states).<sup>16a,30</sup> Diamagnetism of **1a** is also suggested by Evans' method where no observable separation of solvent peaks was found. Ruthenium complex 2b displays an oxidation-state marker band at 1009 cm<sup>-1</sup> in its IR spectrum, which is within the normal range of Ru(II) porphyrin carbonyl or carbene complexes (1001–1017 cm<sup>-1</sup>).<sup>17g,31</sup>



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the XANES spectra of 3a (blue), [Os(4-F-TPP)(CO)] (red), and trans-dioxo complex [Os(TTP)O<sub>2</sub>] (green).



Zero-field Mössbauer spectrum of 1a at 298 K. Fig. 5



UV-vis spectra of 1a (black), and 1a ligated with 4-cyanopyridine (blue), pyridine (green), and 4-dimethylaminopyridine (red) in DCM. Inset: titration of pyridine (5×10<sup>-5</sup>-0.01 M) into a DCM solution of 1a (5×10<sup>-5</sup> M).

Previously, the oxidation state of metal center in Os porphyrin carbene complexes remained ambiguous.<sup>18c,e,f</sup> To clarify this issue, we conducted Os L-edge XANES study on 3a and two related Os porphyrins (Fig. 4, bottom). Complex 3a exhibits an L<sub>3</sub>-edge peak at 10879.0 eV in its XANES spectrum, and this was found to be highly similar to that of [Os"(4-F-TPP)(CO)] (10879.0 eV) but different from the high-valent trans-dioxo complex [Os<sup>VI</sup>(TTP)O<sub>2</sub>] (10880.0 eV); these results are supportive of an Os<sup>II</sup>-bis(carbene) electronic structure of **3a** rather than an Os<sup>VI</sup> Schrock alkylidene formulation.

UV-vis absorption spectra of Fe complexes 1a,b both exhibit a single Soret band, whereas two separate Soret bands could be observed for the Ru congeners (Fig. S1). Addition of an axial ligand generally leads to red shift of the Soret band(s), and the extent of red-shift is affected by the electronic property of the axial ligand (Fig. 6). The binding constants of pyridine with 1a and 2b were measured to be (9.90 ± 0.48)×10<sup>2</sup> and (2.375 ± 0.144)×10<sup>4</sup> M<sup>-1</sup> respectively (Fig. S2), both being smaller than those of the analogous Fe/Ru porphyrin complexes bearing other carbene ligands (3500 M<sup>-1</sup> for Fe-dichlorocarbene<sup>11a</sup> and 1.13×10<sup>5</sup> M<sup>-1</sup> for Ru-quinoid carbene complex<sup>17l</sup>). Interestingly, no binding between PPh<sub>3</sub> and 1a/2b has been observed according to UV-vis monitoring. The Soret and Q bands of Os-bis(dialkylcarbene) complexes 3 are generally weakened and broadened, with the Q bands of 3b,c markedly blue-shifted (< 500 nm) as compared to 1a,b

and **2a,b** bearing the same porphyrin ligands (Fig., S1); these spectral features are typically found<sup>Ol</sup>fd<sup>p.1</sup>Og/Cporphyrin complexes.32

#### Electrochemistry

Electrochemical studies on these group 8 metal dialkylcarbene complexes were conducted to gain insights into their electronic structures (Fig. 7 and Fig. S3). Complexes 1a,b both show one reversible oxidation wave at -0.18 to 0.01 V (vs Fc<sup>+/0</sup>, same as below) in the cyclic voltammograms (Table 3), falling in the region of Fe<sup>III/II</sup> couple.<sup>33</sup> This assignment complied with the results from XANES, Mössbauer, and resonance Raman spectroscopies (vide supra), and was further verified by the spectroelectrochemical spectrum of 1a in which broadened Soret band and red-shifted Q bands characteristic of Fe(III) porphyrins appeared after oxidation (Fig. 8, top);<sup>34</sup> products derived from porphyrin- or carbene ligand-oxidation could be precluded, since metal-Por+\* species feature a broad band between 630–710 nm while oxidation on axial ligand generally leads to minor changes in electronic spectra of [M(Por)] complexes.<sup>33,35</sup> Although the oxidation is reversible on the cyclic voltammetry timescale, the oxidized Fe(III) species was found unstable and decomposed within minutes. The first reversible oxidation waves of 2a,b (-0.03 to 0.18 V, Table 3) are also ascribed to be Ru-centered according to our previous study.<sup>17g</sup> The Os complexes **3a-c** all show a quasi-reversible oxidation wave (-0.17 to 0.04 V) assignable to the Os<sup>III/II</sup> couple,<sup>36</sup> in agreement with the +2 oxidation state of Os center suggested by XANES spectroscopy (Fig. 4, bottom). The second oxidation waves in 1b, 2b, 3a, and 3c could be attributed to porphyrin-centered oxidation processes. The first reduction waves of the Fe complexes are strongly influenced by the aryl substituents on porphyrin ligands (Table 3) and are therefore assigned to porphyrin-centered reduction. This was also evidenced by the noticeable spectral changes of Soret and Q bands upon reduction of 1a (Fig. 8, bottom). The first reductions of 2a,b and 3a,b are assigned likewise in view of the similarity in potential and reversibility (Table 3); no reduction peaks are observed for 3c and they are possibly beyond the solvent window of DCM.



Cyclic voltammograms of group 8 metal dialkylcarbene complexes supported Fig. 7 by TTP macrocycle, using 0.1 M ( $Bu_4N$ )PF<sub>6</sub> as electrolyte and at a scan rate of 0.1 V s<sup>-1</sup>. Top: **1b** and **2b**, measured in DMF with SCE as reference electrode;  $E(Fc^{+/0}) = 0.49 V$ .

Bottom: **3c**, measured in DCM with Ag/AgCl as reference electrode;  $E(Fc^{+/0}) = 0.40 \text{ V}$ . Dotted lines indicate irreversible redox events.

Table 3	Redox p	ootentials V vs Fc <sup>+/0</sup>	a		
E (	V)	E <sub>01</sub>	E <sub>02</sub>	E <sub>R1</sub>	E <sub>R2</sub>
1	а	0.01		-1.59	-2.07
1	b	-0.18	0.47 <sup>b</sup>	-1.86	-2.38
2	а	0.18		-1.66	-2.10
2	b	-0.03	0.61 <sup>b</sup>	-1.91	-2.50
3	а	-0.10 <sup>d</sup>	0.77 <sup>b</sup>	-2.05 <sup>d</sup>	
3	b	0.04 <sup>d</sup>		-1.71 <sup>d</sup>	
3	с	-0.17 <sup>d</sup>	0.59 <sup>b</sup>		

<sup>*a*</sup>  $E_{1/2}$  values. **1a,b** and **2a,b** were measured in DMF with SCE as reference electrode;  $E(Fc^{+/0}) = 0.49$  V. **3a-c** were measured in DCM with Ag/AgCl as reference electrode;  $E(Fc^{+/0}) = 0.40$  V. <sup>*b*</sup>  $E_{p,a}$ . <sup>*c*</sup>  $E_{p,c}$ . <sup>*d*</sup> Quasi-reversible.



Fig. 8 Spectroelectrochemistry of 1a in DMF. Electrode potentials: 0.6 V (top) and – 1.1 V (bottom) vs Ag/AgCl.



**Fig. 9** Calculated molecular orbitals of [Fe(TTP)(Ad)] (**1b**). LUMO, which is mainly located on TTP ligand, is not shown. The z axis is orthogonal to the porphyrin plane and the x and y axes are on the porphyrin plane and bisecting  $Fe-N_{pyrrole}$  vectors.

#### **DFT** calculations

DFT calculations were performed on 1b and 3a to provide detailed information on the bonding nature of а metalloporphyrin mono(dialkylcarbene) complex and a metalbis(dialkylcarbene) complex. The optimized structure of 1b and **3a** show the M–C<sub>carbene</sub> (M = Fe, Os) bond distances of 1.742 Å and 2.003 Å respectively, which are close to the experimental values (Table 1). A low-spin Fe(II) center with an electronic configuration of  $(d_{x2-y2})^2(d_{yz})^2(d_{zz})^0(d_{zy})^0$  was calculated for 1b (Fig. 9), consistent with the diamagnetism of this complex and also similar to previous experimental and computational results on iron porphyrin complexes ligated with other types of carbene ligands.<sup>16b,37</sup> The Fe-dialkylcarbene  $\pi$ -backbonding interaction is formed between d<sub>yz</sub> of Fe and p<sub>y</sub> orbital of C<sub>carbene</sub>, and the  $\pi$ (Fe<sup>---</sup>C) orbital is mostly Fe d<sub> $\pi$ </sub> in character (H–3, 45%) Fe, 17% C<sub>carbene</sub>) while the  $\pi^*$  (Fe<sup>---</sup>C) orbital is more polarized to the carbene carbon (L+2, 32% Fe, 52% C<sub>carbene</sub>). Therefore, the complex should be best described as a formally Fe<sup>II----</sup>Ad<sup>0</sup> species with decent Fe-to-carbene  $\pi$ -backbonding. Similar to free Ad in which hyperconjugation plays an essential role in stabilizing the carbene center,<sup>22d,e</sup> the  $\pi^*(Fe^{---}C)$  orbital in **1b** is also stabilized by such an effect exerted by the flanking alkyl groups. The LUMO is essentially populated on the porphyrin ligand and the HOMO mostly resides at the Fe center, both of which comply with the electrochemical study (vide supra).

A similar M(II) electronic configuration was calculated for Os-bis(dialkylcarbene) complex **3a** which features a low-spin d<sup>6</sup> Os(II) center and strong metal-carbene covalency (Fig. 10, top). The two perpendicular  $p_{\pi}$  orbitals of the two Ad ligands interact with  $d_{xz}$  and  $d_{yz}$  orbitals of Os, giving rise to two pairs of almost degenerate  $\pi$ (Os<sup>---</sup>C) (H–1 and H–2) and  $\pi^*$ (Os<sup>---</sup>C) (L+2 and L+3) orbitals. Different from **1b**, the  $d_{z2}$  orbital of **3a** is higher in energy than  $d_{xy}$  as a result of the strongly

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coordinating dialkylcarbene ligands. TD-DFT calculations could well reproduce the UV-vis spectrum of 3a which consists of two separate Soret bands at 343-395 nm and a weak and broad Q band at 557 nm (Fig. 10, bottom).



Fig. 10 Top: Calculated molecular orbitals of [Os(4-F-TPP)(Ad)<sub>2</sub>] (3a). The z axis is orthogonal to the porphyrin plane and the x and y axes are on the porphyrin plane and bisecting Os-N<sub>pyrrole</sub> vectors. Bottom: Experimental (black solid line) and TD-DFT simulated (red dashed line) UV-vis spectrum of 3a.

#### Stability and reactivity

Fe(II) porphyrins are usually air-sensitive and could be stabilized by a few  $\pi$ -acceptor ligands (e.g., CS, isocyanides). In this work, the dialkylcarbene Ad ligand was found to confer remarkable stability on Fe(II) porphyrins, especially for 1a bearing the electron-deficient porphyrin ligand TPFPP. No decomposition of 1a could be detected even by treating its benzene solution at 80 °C under air for at least 1 h; its six-coordinate adducts with pyridines and MeIm also stayed intact in solution for at least one week under ambient conditions, which is in sharp contrast to the [Fe(TPFPP)(CPh<sub>2</sub>)(MeIm)].<sup>11e</sup> air-sensitive Surprisingly. thermogravimetric analysis (TGA) revealed that 1a in the solid state is stable at up to ~230 °C under air (Fig. S6; the <sup>1</sup>H NMR spectrum of 1a, after being heated at 230 °C in the solid state for 5 min under air, remained unchanged). The Ru analogue 2a also exhibits great thermal stability under air with onset of decomposition appearing at ~330 °C (Fig. S6). The Osbis(dialkylcarbene) complexes are stable below 60 °C under an inert atmosphere in both solution and solid states.

Although Fe porphyrin CPh<sub>2</sub> and C(Ph)CO<sub>2</sub>Et carbene complexes could react stoichiometrically with alkenes and/or sp<sup>3</sup>

C-H bonds,<sup>11e</sup> 1a was found resistant toward various, organic substrates/nucleophiles (e.g., styrene, 1,4-eyclohexadiene, PhNH2, PPh<sub>3</sub>; see ESI for details), even in the presence of trans axial ligand (pyridine, Melm) and at high temperature (80 °C); nor was it reactive under UV irradiation, which has been reported to trigger the reactions between [Fe(TPP)(CX<sub>2</sub>)] (X = halogens) and alkenes.<sup>38</sup> Remarkable stability was also found with the Ru congener 2a which was unreactive under the above conditions. When 1a was treated with anionic nucleophiles such as NaXMe (X = S, O) at 80 °C,  $S_NAr$  reactions on the TPFPP *meso*- $C_6F_5$  groups slowly took place to afford 1c and 1d respectively (reaction 9 in Scheme 2), which could be traced by the changes in <sup>1</sup>H and <sup>19</sup>F NMR spectra; the carbene carbons kept intact and still resonated at ~410 ppm in their <sup>13</sup>C NMR spectra, demonstrating the remarkable kinetic inertness of Ad ligand.

Previously, the Os-bis(CPh<sub>2</sub>) complex has been shown to display stoichiometric diarylcarbene transfer reactivity.18e However, no dialkylcarbene transfer product was detected when treating nucleophilic organic substrates (e.g., styrene, 1,4-cyclohexadiene, PhNH<sub>2</sub>, PhNO, PPh<sub>3</sub>, and PhSH) with the bis(dialkylcarbene) complex 3a at up to 60 °C; further heating up the reaction mixture to 80 °C only caused decomposition of 3a to complicated mixtures, which was similarly observed in a control experiment without the presence of substrate. Surprisingly, 3a was also stable against MeLi at -78 °C to room temperature, although MeLi was known to undergo nucleophilic addition or  $\alpha$ -deprotonation of metal-carbene complexes. Addition of pyridine into a DCM solution of 3a at room temperature slowly led to carbene ligand dissociation and formation of 2-adamantanone, yet neither dialkylcarbene transfer product nor Os-mono(dialkylcarbene) complex could



Intermolecular reactions of 1a with anionic nucleophiles Scheme 2



Scheme 3 Carbene substitution experiments

be observed.<sup>18f,g</sup> In view of the relatively labilized Ad ligands in the Os-bis(dialkylcarbene) complexes **3**, we wondered whether **3a** would exhibit partial nucleophilic free dialkylcarbene character;<sup>22f</sup> however, it was found unreactive toward electrophiles such as ethyl acrylate or bis(pinacolato)diboron.

While the studies described above revealed that the dialkylcarbene Ad ligand coordinated to group 8 metal porphyrins is less reactive than the diarylcarbene CPh<sub>2</sub>, their relative thermodynamic stability was further probed by carbene substitution experiments (Scheme 3). It was found that [Fe(TPFPP)(CPh<sub>2</sub>)] and [Os(TPFPP)(CPh<sub>2</sub>)<sub>2</sub>] could readily react with free Ad, generated from photolysis of aziadamantane, to afford **1a** and **3b**, respectively (reactions 10 and 12 in Scheme 3), yet treatment of **1a** or **3b** with excess diazo compound Ph<sub>2</sub>CN<sub>2</sub> was not able to result in replacement of the Ad ligand(s) in the Fe or Os complex by CPh<sub>2</sub> even under more forcing conditions (reactions 11 and 13 in Scheme 3). For the reaction of **1a** with Ph<sub>2</sub>CN<sub>2</sub> (reaction 11 in Scheme 3), the azine product Ph<sub>2</sub>C=N-N=CPh<sub>2</sub> was obtained in 90% yield.

# Catalytic intermolecular donor-donor carbene transfer reactions catalyzed by 1a

Given the remarkable stability of Ad ligand, we examined the possibility of using 1a as a robust Fe(II) catalyst for some challenging transformations. Diarylcarbene (CAr<sub>2</sub>) transfer reactions remain less developed in the literature, which is mainly owing to the intrinsic low reactivity of CAr<sub>2</sub> carbenes since they are known to form isolable adducts even with the most active catalysts such as Rh<sup>39</sup> and Cu.<sup>40</sup> Inspired by the carbene substitution experiments (reaction 11 in Scheme 3) revealing the formation of an azine product, we envisioned that 1a might serve as an efficient catalyst for diarylcarbene transfer reactions, since the observed azine product possibly resulted from reaction of Ph<sub>2</sub>CN<sub>2</sub> with a reactive Fe-bis(carbene) intermediate [Fe(TPFPP)(Ad)(CPh<sub>2</sub>)] (4a, Scheme 3; by drawing analogy from Os-bis(carbene) analogues), in which the CPh<sub>2</sub> ligand was activated by the trans-Ad ligand. Gratifyingly, cyclopropanation of styrene with Ph<sub>2</sub>CN<sub>2</sub> could be catalyzed by 2 mol% of 1a in excellent yield (90%, entry 1 in Table 4). Time course plot of this reaction showed that product 5a was smoothly produced with very short induction period, and catalyst 1a remained rather stable in the reaction mixture (85% recovery, Fig. 11). Employing [Fe<sup>II</sup>(TPFPP)] as catalyst led to poorer yield of 5a (entry 2 in Table 4), which suggests the important role played by the Ad ligand in 1a in this reaction. Complex 1a showed superior catalytic performance and chemoselectivity to other commonly used carbene transfer catalysts (e.g., Rh and Cu catalysts, entry 4-6 in Table 4; see also Table S7) under the same reaction conditions since the latter catalysts afforded mainly the azine product; the Ru-dialkylcarbene complex 2a gave slightly better results than 1a (entry 3). By using 1a as catalyst, the scope of alkene was extended to styrenes bearing electron-donating (5b,c) and withdrawing (5d) substituents with good to high product yields (Scheme 4). Conjugated alkene was selectively cyclopropanated at the less hindered site in moderate yield (5e). However, alkylsubstituted alkene such as 1-octene resulted in low yield of 5f and mainly the azine by-product. Besides CPh2 carbene, electrondeficient (5g) and -rich (5h,i) diarylcarbenes were also converted to the desired cyclopropanes in high yields.<sup>DOI: 10.1039/C9SC05432D</sup>

 Table 4
 Comparison of catalytic performance among 1a, 2a, and other common carbene transfer catalysts<sup>a</sup>

Entry	Catalyst	Yield of <b>5a</b> (%) <sup>b</sup>
1	1a	90
2	[Fe <sup>II</sup> (TPFPP)]	48
3	2a	92
4	[Rh <sub>2</sub> (esp) <sub>2</sub> ]	10
5	Cul	1
6	[Ru(TTP)(CO)]	56

 $^o$  Conditions: Ph\_2CN<sub>2</sub> (0.2 mmol), styrene (2 mmol), catalyst (0.004 mmol), DCM (1 mL), 40 °C, 12 h, under Ar.  $^b$  Yield determined by <sup>1</sup>H NMR with PhTMS as internal standard.



Fig. 11 Time course plot of the reaction among  $Ph_2CN_2$ , styrene, and 1a according to <sup>1</sup>H NMR monitoring.

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Intermolecular diarylcarbene transfer reactions catalyzed by 1a. Product Scheme 4 yields in red and recovery of 1a (blue) in parentheses. <sup>a</sup> Conditions: Ph<sub>2</sub>CN<sub>2</sub> (0.2 mmol), substrate (2 mmol), catalyst (0.004 mmol), DCM (1 mL), 40 °C, 12 h, under Ar. <sup>b</sup> Conditions:  $Ph_2CN_2$  (0.2 mmol, added over 3 h), substrate (2 mmol), catalyst (0.004 mmol). DCE (1 mL). 80 °C. 12 h. under Ar.



Fig. 12 DFT-optimized structure of model complex 4b (left) and its LUMO (middle) and L+3 orbitals (right).

Complex 1a could also catalyze intermolecular S-H, N-H, and O-H insertion reactions, thereby introducing benzhydryl

#### activated by aryl (6a-c) and 2-pyridyPgroups3%6d) Createrly underwent carbene insertion in 88-99% yields; alkylsubstituted thiol such as ethanethiol also afforded the desired sulfide product albeit in lower yield (6e, 33%). Catalytic N-H insertion could be furnished in high yields by using electronrich N-heterocycles such as carbazole (7a) and imidazole (7b), as well as secondary alkyl amine such as morpholine (7c); primary amines, aryl (7d) and aliphatic (7e), resulted in only moderate product yields. Aryl alcohols including phenols (8a,b) and 2-naphthol (8d) were transformed into the O-H insertion products in 75-92% yields, yet electron-poor phenol (8c) and aliphatic alcohol (8e) showed appreciably lower reactivity. Notably, catalytic C(sp<sup>3</sup>)–H insertion of CPh<sub>2</sub> carbene was furnished under more demanding conditions (80 °C and dropwise addition of Ph<sub>2</sub>CN<sub>2</sub>), and previously such catalytic transformations were largely confined to the intramolecular versions using Rh catalysts.<sup>41</sup> C–H insertion of doubly-activated substrates including 1,4-cyclohexadiene (9a) and fluorene (9b) were achieved in moderate yields, while low yield was observed with the less reactive indane (9c). Moreover, the

above (Scheme 4). Attempts to isolate or directly detect the proposed Febis(carbene) intermediate 4a have not been successful. We performed DFT calculations on a model complex 4b (Fig. 12), which is identical to 4a except that the meso-aryl groups in 4a were replaced by hydrogen for simplicity.37,42 The calculated structure of **4b** features a rather lengthened Fe-C<sub>CPh2</sub> bond (1.96 Å) as compared to the Fe– $C_{Ad}$  bond (1.89 Å); the LUMO was mainly localized on the  $p_{\pi}$  of  $C_{CPh2}$  while the  $p_{\pi}$  of  $C_{Ad}$  was higher in energy (L+3); these could account for the relatively high reactivity of CAr<sub>2</sub> ligands as well as the stability of **1a** and its Ad ligand during catalytic turnover.

robustness of catalyst 1a could be demonstrated by the high

 
 Table 5
 Intermolecular cyclopropanation reactions between other diazo compounds
 and styrene catalyzed by 1a



(In situ generated) diazo compound

Entry	Diazo compound	Yield of cyclopropane (dr) <sup>b</sup>	By-product	Recovery of <b>1a</b>
1	Ph CF3	71% (2.4 : 1)		90%
<b>2</b> <sup>c</sup>	Ph CH <sub>3</sub>	45% (2.0 : 1)	Azine	88%
3 <sup><i>d</i></sup>	N <sub>2</sub>	0%	N=N Ph	81%

<sup>a</sup> See ESI for detailed reaction conditions. <sup>b</sup> Yield and diastereomeric ratio (dr)

determined by <sup>1</sup>H NMR with PhTMS as internal standard. <sup>c</sup> In situ generated diazo compound from acetophenone hydrazone and Ag<sub>2</sub>O.  $^{\it d}$  In situ generated diazo

compound from 2-adamantanone hydrazone and PhIO.

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Catalytic intermolecular cyclopropanation reactions of other donor-donor (phenyl/alkyl- and dialkyl-) carbenes were also tested by using freshly prepared or in situ generated diazo compounds.43 Complex 1a could catalyze the reactions of  $N_2C(Ph)CF_3$  and  $N_2C(Ph)Me$  (the latter was generated in situ from acetophenone hydrazone and Ag<sub>2</sub>O) with styrene to afford the corresponding cyclopropanation products in moderate to good yields albeit with low diastereomeric ratios (entries 1-2 in Table 5); however, similar treatment of diazoadamantane (in situ generated from AdNNH<sub>2</sub> and PhIO) with styrene using catalyst 1a did not give cyclopropanation product, and [3+2] cycloaddition between styrene and the diazo compound to give 10 was the major reaction observed (entry 3 in Table 5).43c Worthy of note is the high recovery of 1a in all these reactions as this complex showed decent stability toward PhIO which is known to generate Fe-oxo species with common Fe porphyrin complexes.44

#### Discussion

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Middle/late transition metal (TM) (di)alkylcarbene species are key intermediates related to olefin metathesis<sup>5</sup> and (di)alkylcarbene transfer catalysis,<sup>13,45</sup> yet the electronic property of dialkylcarbene as a ligand, especially in comparison with the common carbene ligands including "stable" (NHC, CAAC) and "reactive" (phenyl-/ester-substituted) carbenes, still remains less understood. In this work, by choosing 2adamantylidene (Ad) as a rigid model, we have is wathesized several terminal group 8 metal dialkylcarbene complexes from easily accessible precursors and by a simple and mild method. We have also demonstrated that, different from the well documented reactive features, dialkylcarbene ligand such as Ad can be highly stable upon coordination to TMs including Fe and even act as a robust ancillary ligand for catalytic applications. To gain deeper knowledge, the following aspects of the dialkylcarbene ligand Ad coordinated to TMs are discussed in this section.

#### Dialkylcarbene vs common carbene ligands

Although both stable and reactive carbene ligands feature an sp<sup>2</sup>-hybridized carbene center with a vacant  $p_{\pi}$  orbital, they have scarcely been linked or discussed together due to the drastic differences in molecular structure, stability, and/or electronic properties of their metal complexes.46 The uniqueness of dialkylcarbene lies in the fact that it possesses mutual characters from the above two types of carbenes: on the one hand, its carbene transfer reactivity has been well documented in the literature; 10,13,45 on the other hand, we have discovered in this work that it confers remarkable thermodynamic and kinetic stability on group 8 metal porphyrin complexes and in particular, it leads to great stabilization of an Fe(II) porphyrin species and several Osbis(carbene) complexes. These findings prompt us to make a closer comparison between dialkylcarbene and stable/reactive carbenes with the aid of theoretical calculations.



Fig. 13 (a) Comparison of calculated carbene frontier orbitals of free NHC, CAAC, Ad, and CPh<sub>2</sub> carbenes in their singlet states. (b) Comparison of calculated Fe–C<sub>carbene</sub> orbitals in [Fe(Por)(Ad)], [Fe(Por)(CPh<sub>2</sub>)], and [Fe(Por)(C(Ph)CO<sub>2</sub>Et)].

(i) Dialkylcarbene vs stable carbenes (NHC/CAAC). The carbene substituents for dialkylcarbene and stable carbenes show an interesting pattern ranging from diamino (NHC), amino/alkyl (CAAC) to dialkyl (Ad), and such a variation can directly influence their carbene frontier orbitals, i.e., the  $\sigma$  orbital and  $p_{\pi}$  orbital, through inductive and mesomeric effects.<sup>47</sup> By performing DFT calculations on these free

carbenes, we found that the most striking feature of dialkylcarbene is its much lower-lying  $p_{\pi}$  orbital than NHC and CAAC ( $\Delta E > 1.8 \text{ eV}$ , Fig. 13a), likely due to the absence of  $\pi$ -donating atoms adjacent to the carbene center;<sup>48</sup> its  $\sigma$  orbital is also slightly higher in energy ( $\Delta E = 0.10-0.52 \text{ eV}$ ). Therefore, dialkylcarbene acts as a much stronger  $\pi$ -acceptor and a

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slightly better  $\sigma$ -donor, and thus a stronger-field ligand than these conventional stable carbenes.



**Fig. 14** First oxidation potential (*E*<sub>01</sub>) range of group 8 metal porphyrin carbene complexes.

The variation in  $\pi$ -character could account for the distinct differences in the Fe/Ru– $C_{carbene}$  distances, as the Fe/Ru– $C_{Ad}$ bonds are all within double bond regions (Table 1) and are apparently shorter than those in NHC/CAAC complexes (1.87-2.15 Å for Fe and 1.93–2.15 Å for Ru).49 Redox potential of metalloporphyrin carbene complexes, especially the first oxidation potential  $(E_{O1})$ , is a good indicator for the electronic property of carbene ligands,  $^{\rm 17l}$  and the greater  $\pi\text{-acidity}$  of Ad ligand is also noted by the increased  $E_{O1}$  values of **2a**,**b** as compared to their NHC congeners (Fig. 14 and Table S8). In addition, NHC often gives bis(carbene) complexes with Fe and Ru porphyrins<sup>49d,j</sup> yet only mono(dialkylcarbene) complexes of Fe and Ru porphyrins [M<sub>Fe/Ru</sub>(Por)(Ad)] are isolable, which is likely caused by the prominent trans influence of Ad ligand. Stronger trans influence of Ad than NHC is also inferred by comparing the solid-state structures of [Ru(TTP)(Ad)(MeOH)] (2b·MeOH) with [Ru(TPP)(IMe<sub>2</sub>)(THF)] where the axial Ru-O bond is longer in the former (2.36 Å) than in the latter complex (2.22 Å, Fig. S7).

**Table 6** First oxidation potentials ( $E_{01}$ , V vs Fc<sup>+/0</sup>) of group 8 metal carbene complexes supported by TPFPP macrocycle

Complex	$E_{O1}(V)^{\alpha}$	Ref <sup>b</sup>		
Fe-mono(carbene) com	plexes			
[Fe(TPFPP)(Ad)] ( <b>1a</b> )	0.01	TW		
[Fe(TPFPP)(CPh <sub>2</sub> )]	0.35	17g		
Ru-mono(carbene) com	plexes			
[Ru(TPFPP)(Ad)] ( <b>2a</b> )	0.18	TW		
[Ru(TPFPP)(CPh <sub>2</sub> )]	0.46	17g		
[Ru(TPFPP)(C(Ph)CO <sub>2</sub> Me)(MeOH)]	0.65	17g		
Os-bis(carbene) complexes				
[Os(TPFPP)(Ad) <sub>2</sub> ] ( <b>3b</b> )	0.04 <sup>c</sup>	TW		
[Os(TPFPP)(CPh <sub>2</sub> ) <sub>2</sub> ]	0.30	TW		

 $^a$   $E_{\rm 1/2}$  values of reversible oxidation processes.  $^b$  TW = this work.  $^c$  Quasi-reversible.

(ii) Dialkylcarbene vs reactive carbenes (phenyl-/estersubstituted carbenes). Besides all being related /for carbe transfer catalysis, dialkylcarbene also bears some other resemblance to the reactive carbenes. For instance, their complexes of Fe/Ru porphyrins are all mono(carbene) species diaplaying M–C<sub>carbene</sub> double bond character (1.77–1.83 Å for Fe and 1.81–1.88 Å for Ru);<sup>16a,17g,i</sup> these complexes share similar features in their NMR, UV-vis, and IR spectra and cyclic voltammograms. To further compare their electronic properties, we conducted DFT calculations on Fe-carbene complexes bearing Ad, CPh<sub>2</sub>, and C(Ph)CO<sub>2</sub>Et ligands since they have all been isolated in this work or in the previous report;<sup>11e</sup> the porphyrin mesosubstituents are again replaced by hydrogen atoms for simplicity. The most notable difference between dialkylcarbene Ad and reactive carbenes lies in the  $\sigma$ -property, as the Fe d<sub>12</sub> orbital in the Ad complex is calculated at a much higher energy level ( $\Delta E \ge 0.78$ eV) together with a relatively large energy splitting between  $\sigma$  and  $\sigma^*$  orbitals (Fig. 13b), which is attributable to the electrondonating alkyl substituents. Meanwhile, its Fe  $d_{\pi}$  orbital is also slightly destabilized than CPh<sub>2</sub> and C(Ph)CO<sub>2</sub>Et carbene complexes  $(\Delta E = 0.25 - 0.35 \text{ eV})$ . Therefore, dialkylcarbene Ad is a much stronger  $\sigma$ -donor and slightly weaker  $\pi$ -acceptor, and thus a more electron-donating ligand than the other reactive carbenes.

These computational results are supported by a handful of spectroscopic and experimental data. Electron-donating feature of dialkylcarbene can be demonstrated by electrochemical studies where the  $E_{O1}$  values of Ad complexes of group 8 metal porphyrins are appreciably smaller than those of phenyl-/ester-substituted carbene congeners (Table 6 and Fig. 14);<sup>17g</sup> additionally, a larger isomer shift in the Mössbauer spectrum of 1a (0.25 mm s<sup>-1</sup>) than the analogous CPh<sub>2</sub> (0.03–0.19 mm s<sup>-1</sup>) and CCl<sub>2</sub> complexes (0.02–0.10 mm s<sup>-1</sup> 1) also reveals a more electron-rich Fe center in the former complex. The much enhanced  $\sigma$ -bonding interaction improves the trans influence, as revealed by smaller binding constants of 1a and 2b (see the Results section), as well as the thermodynamic stability of dialkylcarbene Ad relative to other reactive carbene complexes, which has been demonstrated by the carbene substitution experiments (Scheme 3). The higher carbene  $p_{\pi}$  orbital in dialkylcarbene complex is accountable for the kinetic stability of 1a and 3a since they were observed to be unreactive towards stoichiometric carbene transfer reactions while the analogous CPh<sub>2</sub> and/or C(Ph)CO<sub>2</sub>R carbene complexes have been reported to be reactive.<sup>11e,18e</sup>

#### Ad vs other dialkylcarbene ligands

In this work, Ad is used as a model to study the features of dialkylcarbene ligands. To examine the effect of alkyl substituents of dialkylcarbene on the frontier orbitals of the carbene carbon, we performed DFT calculations on two *in silico* complexes [Fe(Por)(CMe<sub>2</sub>)] and [Fe(Por)(C'Pr<sub>2</sub>)]; the two calculated complexes show almost identical Fe-carbene bonding structures to the Ad complex (Fig. S8). However, M<sup>----</sup>Ad complexes (especially the Fe and Ru complexes) are uniquely stable as compared to other examples of Fe/Ru-dialkylcarbene



Fig. 15 (a) Resistance of  $M^{---}Ad$  complexes toward 1,2-hydride shift. (b) Calculated potential energy curves for [Fe(Por)(Ad)] and [Fe(Por)(CMe<sub>2</sub>)] by changing the angle  $\theta$ .

complexes which could undergo 1,2-hydride/alkyl shift and/or carbene transfer reaction.<sup>7e,h,10,19b,20b,50</sup> Such a striking difference is attributable to the rigid structure of Ad. On the one hand, its diamondoid skeleton suppresses the innersphere 1,2-hydride shift both thermodynamically and kinetically (Fig. 15a).<sup>22c</sup> On the other hand, the angle at carbene carbon is relatively fixed in Ad complexes while it is more flexible in other dialkylcarbene such as CMe<sub>2</sub>, as revealed by DFT calculations (Fig. 15b). Such an angle is closely related to the reactivity of carbene species<sup>47</sup> as the energy level of CMe<sub>2</sub>  $p_{\pi}$  orbital decreases significantly upon increasing this angle (Fig. S9); in contrast, the Ad complex stays preferentially around the local minimum of its potential energy curve which is apparently steeper than that of CMe<sub>2</sub> complex, thus making it less susceptible towards outer-sphere nucleophilic attack.

#### Ad vs $\pi$ -acceptor ligands for Fe(II) porphyrins

Some useful comparisons can also be made among dialkylcarbene Ad and common  $\pi$ -acceptor ligands which are important in stabilizing Fe(II) porphyrins.<sup>16b</sup> While Ad only forms mono-adduct with the Fe center, bis-adducts of NO,<sup>51</sup> CO,<sup>52</sup> pyridine,<sup>34b</sup> and isocyanide<sup>53</sup> have all been reported, which implies a stronger ligand field of Ad than other  $\pi$ -acids. Electrochemistry revealed larger  $E_{01}$  values for CS and NO complexes ( $\geq 0.6 \ V \ vs \ SCE$ )<sup>33,51,54</sup> than the Ad counterparts (0.29–0.50 V vs SCE) and thus suggested less electron-donating properties of the diatomic ligands; this is consistent with the larger isomer shift of **1a** (0.25 mm s<sup>-1</sup>) in Mössbauer spectroscopy as compared to CS and CO complexes measured at similar temperatures (–0.03 to 0.18 mm s<sup>-1</sup>).<sup>16c</sup>

#### Catalytic diarylcarbene transfer reactivity

Previously, intermolecular diarylcarbene transfer reactions have only been achieved by a limited number of catalytic systems and some of them suffered from low yield, narrow ARTICLE

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substrate scope, and/or high catalyst loading.  $\frac{18e}{5}$  Theoremeter dialkylcarbene complex **1a** is, to the best of our knowledge, the first Fe catalyst that mediates the transfer of diarylcarbene to a panel of substrates with moderate to high yields while remains largely intact during turnover. Based on a few reports on the stoichiometric reactivity of Fe-diarylcarbene species with organic substrates, 11e,f,h we envision that the plausible intermediates, [Fe(TPFPP)(Ad)(CAr<sub>2</sub>)], are key to the success in our methodology and thus merit further discussion.

We have not been able to detect the presence of [Fe(TPFPP)(Ad)(CPh<sub>2</sub>)] species. Nonetheless, according to our calculated structure of 4b (Fig. 12), the CPh<sub>2</sub> carbene group is rather labile as noted by the elongated Fe–C<sub>CPh2</sub> bond (1.96 Å), which also parallels with the high reactivity of 1a involving 4a as a proposed reactive intermediate; meanwhile the Fe-C<sub>Ad</sub> bond is appreciably shorter (1.89 Å) and could account for the stability of the catalyst. However, such a large difference in Fecarbene distances is in contrast to those found in the corresponding fiveor six-coordinate mono(carbene) complexes, i.e., [Fe(Por)(CPh<sub>2</sub>)] vs [Fe(Por)(Ad)] or [Fe(Por)(CPh<sub>2</sub>)(L)] vs [Fe(Por)(Ad)(L)],<sup>11e,16a,c</sup> where both pairs of complexes display negligible differences in the Fe-carbene bond distances (< 0.02 Å). We attribute this phenomenon to both trans effect of Ad and steric effect of CPh2 carbene ligands. The steric repulsion between the bulky CPh<sub>2</sub> group and porphyrin ligand has been well documented in the literature, especially in six-coordinate complexes where a strong distortion of porphyrin ligand has been observed,<sup>11e</sup> which is distinctly different from the nearly planar porphyrins found in six-coordinate Ad and CCl<sub>2</sub> carbene complexes.<sup>11a</sup> In previous examples with imidazoles as trans-axial ligands, the strong trans effect of CPh<sub>2</sub> carbene and the highly distorted porphyrin plane significantly weaken the Fe-imidazole interaction.<sup>16c</sup> In model complex 4b, however, where the ligand field of Ad is comparable to that of CPh<sub>2</sub>, the Ad group tends to stay closer to the Fe center and reduce the distortion of porphyrin toward itself; consequently, steric effect (or Pauli repulsion) between porphyrin and CPh<sub>2</sub> is expected to increase, as their distance is as close as 2.4 Å (Fig. 16a) which is well within the normal region for  $\pi$ - $\pi$  interaction,<sup>56</sup> and the electrostatic repulsion is also enhanced since both CPh<sub>2</sub> and porphyrin carry partial negative charge (Fig. 16b). Elongation of Fe-C<sub>CPh2</sub> bond is thus resulted in order to offset these repulsive interactions. It should be noted that such a steric effect is unique to metalloporphyrin systems,



Fig. 16 (a) Spatial separation between  $CPh_2$  and Por ligands in the optimized structure of 4b. (b) Calculated electrostatic map of 4b.

since in other common catalysts, such as Rh and Cu catalysts, the coordination environment around  $CAr_2$  is much less congested and the aryl ring(s) on  $CAr_2$  can even be coplanar with the carbene plane according to their crystal structures.<sup>39-40</sup>

Besides being spatially accessible due to the elongated Fecarbene distance, CPh<sub>2</sub> carbene is also energetically favorable to be transferred to organic substrates in the bis(carbene) intermediate. While carbene  $p_\pi$  orbitals of  $\text{CPh}_2$  and Ad ligands in their mono(carbene) porphyrin complexes are both calculated at L+2 (Fig. 13b), in the bis(carbene) complex 4b the  $p_{\pi}$  orbital of CPh<sub>2</sub> is markedly lowered to LUMO while that of Ad slightly increases to L+3 (Fig. 12). This is likely caused by the intrinsic  $\pi$ -characters of the two carbene ligands as the  $p_{\pi}$ orbital of free Ad lies higher in energy than CPh<sub>2</sub> (in their singlet states) due to hyperconjugation effect (Fig. 13a), yet the presence of two  $\pi$ -acceptor ligands on the Fe center decreases the metal-to-carbene backbonding and renders the carbene orbital of CPh<sub>2</sub> shifting to lower energy levels. Meanwhile, the  $\sigma$  orbital of CPh<sub>2</sub> is also strongly destabilized, as it is mainly located at H-17 in the mono(carbene) complex (Fig. 13b), yet in 4b it exists at H–5 and even partially at HOMO (Fig. S10). To briefly summarize, the elongated Fe-C<sub>CPh2</sub> bond as well as reorganized CPh2 carbene frontier orbitals concomitantly lead to great destabilization of the CPh<sub>2</sub> group in the putative bis(carbene) [Fe(Por)(Ad)(CPh<sub>2</sub>)] intermediate, which could in turn account for the high catalytic activity of 1a in these diarylcarbene transfer reactions.

#### Conclusions

In this work we have conducted a detailed study on a series of group 8 metal porphyrin dialkylcarbene complexes. With aziadamantane as carbene source, a novel synthetic method is developed toward Feand Ru-mono(dialkylcarbene) complexes, and also Os-bis(dialkylcarbene) complexes which, to the best of our knowledge, represent the first examples of transition metal-bis(dialkylcarbene) complexes. Spectroscopic investigations including XANES, NMR, electrochemistry, UV-vis, Mössbauer, resonance Raman, and IR, combined with DFT and TD-DFT calculations, reveal that the electronic structures of these dialkylcarbene complexes are all low-valent d<sup>6</sup> metalcarbene (M<sup>II</sup>—Ad<sup>0</sup>) in nature instead of the high-valent Schrock alkylidene formalism. These dialkylcarbene complexes generally exhibit much improved thermodynamic and kinetic stability than other analogous group 8 metal porphyrins bearing nonheteroatom-stabilized carbene ligands such as diphenylcarbene; further comparison with other types of carbene ligands shows that, dialkylcarbene Ad is a borderline species in between the common "stable" and "reactive" carbenes and it displays strong  $\sigma$ -donating as well as  $\pi$ accepting characters. The unique electronic property and stable feature make dialkylcarbene Ad a promising candidate for ligand design in organometallic catalysis, and it has been demonstrated in this work that the Fe(II) complex 1a is highly active and robust in some donor-donor carbene, especially diarylcarbene, transfer reactions where the strong-field transAd ligand is believed to play a crucial role in activating the reactive carbene groups.

#### **Conflicts of interest**

There are no conflicts to declare.

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## Stable group 8 metal porphyrin mono- and bis(dialkylcarbene) complexes. Synthesis, characterization, and catalytic activity

Hai-Xu Wang, Qingyun Wan, Kam-Hung Low, Cong-Ying Zhou, Jie-Sheng Huang, Jun-Long Zhang and Chi-Ming Che

We report herein the isolation, X-ray crystal structures, spectroscopy, reactivity and DFT calculations of iron- and ruthenium-mono(dialkylcarbene) and osmium-bis(dialkylcarbene) porphyrins and diarylcarbene transfer/insertion reactions catalyzed by highly stable iron-mono(dialkylcarbene) porphyrin.

