Open-shell nitrene- and carbene-complexes of cobalt

Characterisation and reactivity

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Chapter 7

Difluorocarbene ($CF_2$) transfer from a cobalt complex to an electron-deficient alkene.

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Introduction

The presence of a fluorine atom in organic compounds is known to alter their reactivity and physical properties. The high electronegativity of fluorine, its moderately small size and its three non-bonding electron pairs makes the match between the 2s orbitals of fluorine and the 2p orbitals of carbon unique. The C-F bonds are polarised and are stronger than other C-X bonds. Secondly, because of its high electronegativity fluorine also prefers to bind to carbon orbitals with higher p character, thus leading to smaller bond angles. For example, the F-C-F angle is 108.3°, which is significantly smaller than the H-C-H bond angle of 113.7° in CH₂F₂. These effects are even more pronounced in the three membered rings of cyclopropanes, which are considerably strained. Fluorine substitution in a cyclopropane ring has effect on its geometry, causes further destabilization and thereby makes the ring more reactive. These effects can be understood by considering the effects of the fluorine substitution on the hybridization of the carbon atom. Because of its high electronegativity, it is beneficial for fluorine to form bonds with carbon orbitals with enhanced p-character. In cyclopropanes this is already the case in the strained C-C bonds. When additionally a hydrogen atom is replaced by a fluorine atom, the C-C bond further lose p-character, which destabilizes the ring. Fluorinated-cyclopropanes thus exhibit novel reactivity, interesting regiochemistry and accelerated rates in reactions. Additionally, fluorine substituents typically also enhances the biological activity of cyclopropane-containing compounds, and in some cases the potency of known biologically active molecules.

Thus far, the synthesis of difluorocyclopropanes has been reported using various CF₂ generating reagents. In particular, the use of trimethylsilyltrimethyl silane (TMSCF₃ also known as the Ruppert-Prakash reagent) that was reported in 2011 is an attractive way to generate CF₂, as it circumvents the disadvantages of other synthetic routes such as harsh reaction conditions, high toxicity, lack of commercially available reagents and low yields; for example, in methods that involve the use of sodium chlorodifluoroacetate (or sodium bromodifluoroacetate), PhHgCF₃ and Me₃SnCF₃ (Seyferth reagents), FSO₂CF₂CO₂SiMe₃ (TFDA), and Zn/CF₂Br₂. It is also important to note that the synthesis of some of these reagents requires the use of ozone-depleting CBrClF₂.

The method described by Olah et al., that uses TMSCF₃, allows low to room temperature generation of the CF₂ carbene which then inserts into alkenes to form the gem-difluorinated cyclopropanes (Scheme 1). The initiator used to trigger the release of CF₂ from the CF₃⁻ anion is tetrabutylammonium fluoride (TBAF). On increasing the temperatures to 65°C and using NaI as the initiator this system can also cyclopropanate some more challenging alkenes (i.e. somewhat more electron-deficient ones). The mechanism by which NaI plays a role of the initiator is outlined in Scheme 2. Moreover, alkynes can be cyclofluoropropenated if temperatures are increased to 110°C, using THF as the solvent.

\[
\begin{align*}
R_2 & \quad \text{TMSCF}_3 (2.5 \text{ equiv}) \quad \text{THF, } 65 \degree C, 2\text{h} \\
R_3 & \quad \text{NaI (0.2 equiv.)} \\
R_4 & \quad \text{THF, } 65 \degree C, 2\text{h} \quad \text{R}_1-\text{R}_4 = \text{EDG} \\
\end{align*}
\]

Scheme 1. Gem-difluorocyclopropanation of alkenes using TMSCF₃ and NaI as initiator.
Scheme 2. Mechanism of activation of TMSCF₂ by NaI in gem-difluorocyclopropanation of alkenes.

This method was, however, not reported to be successful for the very electron deficient alkenes like acrylates. Same is the case for the PPh₃/CF₂Br₂ system that is reported to also function at room temperature. To the best of our knowledge the only systems that are known to be able to fluorocyclopropanate acrylates are the ones that employ sodium chlorodifluoroacetate (or sodium bromodifluoroacetate), TFDA or MDFA. The reaction conditions for these are, however, quite harsh and in some cases require a reaction time of days. It is therefore desirable to develop a protocol that can perform the addition of the CF₂ carbene to electron-deficient alkenes like acrylates.

We therefore set out to develop a metal catalysed protocol for CF₂ transfer to electron-deficient alkenes. Compared to other metallocarbenes, the chemistry of metallo-difluorocarbenes is thus far rather underdeveloped. Only a handful of well-defined metal difluorocarbene complexes are reported, and an example of Fe and Ir based complexes is depicted in Scheme 3. Recently, the group of Baker disclosed some electron rich cobalt(I) and nickel(0) difluorocarbene complexes containing a nucleophilic M=CF₂ moiety (Scheme 4). These species undergo cycloaddition reactions with tetrafluoroethylene (C₂F₄) or difluorocarbene producing perfluorinated metallacyclobutanes and metallacycpropanes, respectively. A related electrophilic cobalt(III) complex mediated the insertion of difluorocarbene into a Co-perfluoroalkyl bond. However, the stability of the thus formed perfluoroalkyl metal complexes prohibited further reactivity.
Thus, to the best of our knowledge, no examples of catalytic CF$_2$ transfer to electron deficient alkenes have been reported, likely due to the electrophilic nature of the difluorocarbene moiety. We envisioned that by employing a transition metal centre that can render the difluorocarbene moiety more nucleophilic, the transfer of CF$_2$ to an electron deficient olefin would be facilitated (Scheme 5). Reaching this goal could enable catalytic gem-difluorocyclopropanation of electron deficient double bonds. Cobalt(II) porphyrin complexes are efficient catalysts for cyclopropanation of electron deficient alkenes using (stabilized) diazo esters as carbene precursors. This contrasts with the Fischer-type reactivity of the majority of cyclopropanation catalysts, which have a general preference for electron rich alkenes. The observed ‘umpolung’ of the reactivity of the cobalt-carbenoid species as compared to other metallo-carbenes is caused by the transfer a discrete unpaired electron to the coordinated (Fischer-type) carbene ligand. This renders the carbene moiety more nucleophilic and weakens the metal-carbon bond. We hypothesized that this feature might also promote the formation of difluorocyclopropanes from related cobalt difluorocarbenoid intermediates. In this perspective the use of trimethyl(trifluoromethyl)silane (Me$_3$SiCF$_3$) as the difluorocarbene source is attractive, as it can operate at mild temperatures.

Scheme 4. (top) A trifluoromethyl cobalt complex that upon reduction gives the corresponding difluorocarbene complex. (Bottom) A difluorocarbene complex of cobalt that upon reaction with excess tetrafluoroethylene gives a perfluoroalkylated metallacycle.

Thus, to the best of our knowledge, no examples of catalytic CF$_2$ transfer to electron deficient alkenes have been reported, likely due to the electrophilic nature of the difluorocarbene moiety. We envisioned that by employing a transition metal centre that can render the difluorocarbene moiety more nucleophilic, the transfer of CF$_2$ to an electron deficient olefin would be facilitated (Scheme 5). Reaching this goal could enable catalytic gem-difluorocyclopropanation of electron deficient double bonds. Cobalt(II) porphyrin complexes are efficient catalysts for cyclopropanation of electron deficient alkenes using (stabilized) diazo esters as carbene precursors. This contrasts with the Fischer-type reactivity of the majority of cyclopropanation catalysts, which have a general preference for electron rich alkenes. The observed ‘umpolung’ of the reactivity of the cobalt-carbenoid species as compared to other metallo-carbenes is caused by the transfer a discrete unpaired electron to the coordinated (Fischer-type) carbene ligand. This renders the carbene moiety more nucleophilic and weakens the metal-carbon bond. We hypothesized that this feature might also promote the formation of difluorocyclopropanes from related cobalt difluorocarbenoid intermediates. In this perspective the use of trimethyl(trifluoromethyl)silane (Me$_3$SiCF$_3$) as the difluorocarbene source is attractive, as it can operate at mild temperatures.

Scheme 5. The hypothesised route towards gem-difluorocyclopropanated products from electron deficient via trifluoromethyl complexes.
Results and discussion

To evaluate the feasibility of difluorocarbene transfer from cobalt to an olefin we first decided to investigate whether a difluorocarbene cobalt(II) complex can be formed by one-electron reduction of the novel trifluoromethyl cobalt(III) complex \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) (TPP = meso-tetraphenyl-porphyrinato). Formation of a cobalt difluorocarbene complex by reduction and subsequent dissociation of fluoride from a cobalt trifluoromethyl complex has been reported by Baker and co-workers.\(^{13a}\) Thus, we anticipated that the release of F\(^-\) from the anionic \([\text{Co}^{II}(\text{TPP})(\text{CF}_3)]^-\) complex could lead to formation of a \([\text{Co}(\text{TPP})(\text{CF}_3)]\) species, potentially capable of CF\(_2\) transfer to acrylates under mild reaction conditions.

The trifluoromethyl cobalt(III) porphyrin complex \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) required for these studies was obtained in 80% yield (see ESI for characterisation) by reacting \([\text{Co}^{III}(\text{TPP})(\text{Cl})]\) with Me\(_3\)SiCF\(_3\) and CsF as an initiator (Scheme 6).

\[\text{Scheme 6. Synthesis of } [\text{Co}^{III}(\text{TPP})(\text{CF}_3)] \text{ from the corresponding } [\text{Co}^{III}(\text{TPP})(\text{Cl})] \text{ complex.}\]

To evaluate the potential of \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) to form a difluorocarbene complex we investigated its electrochemistry under reductive conditions. The cyclic voltammogram (CV) of complex \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) in THF reveals a reversible reduction wave at \(-1.71\) V, followed by an irreversible one with the peak wave at \(-2.13\) V vs Fc/Fc\(^+\) (Figure 1). The first wave can be attributed to the one-electron reduction of the \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) to form the anionic complex \([\text{Co}^{II}(\text{TPP})(\text{CF}_3)]^-\). The subsequent irreversible reduction leads to clean formation of \([\text{Co}^{I}(\text{TPP})]^-\) as evidenced by an independent measurement of an original \([\text{Co}^{II}(\text{TPP})]\) sample (Figure 2). These results show that one-electron reduction of \([\text{Co}^{III}(\text{TPP})(\text{CF}_3)]\) leads to formation of the anionic complex \([\text{Co}^{II}(\text{TPP})(\text{CF}_3)]^-\), which is stable on the CV timescale (scan rate 100 mV/sec). The second reduction step leads to rapid (net) loss of the CF\(_3^-\) anion from the cobalt centre.
Knowing that $[\text{Co}^{III}(\text{TPP})(\text{CF}_3)]^-$ can be selectively accessed using reductants with a reduction potential in the $-1.8$–$2.0$ V range (vs Fc/Fc$^+$), we next investigated its propensity to generate a metallodifluorocarbene species on an extended timescale and at elevated temperatures. Interestingly, the intended reduction of $[\text{Co}^{III}(\text{TPP})(\text{CF}_3)]$ with one equivalent of decamethylcobaltocene ($\text{CoCp}^*\text{H}_2\ E^0 = -1.91$ vs Fc/Fc$^+$) in the presence of n-butyl acrylate at 65°C indeed led to the formation of the desired gem-difluorocyclopropanated acrylate in 12% yield as determined by $^{19}$F NMR (Scheme 7 and Figure 3). Additionally, $\text{C}_2\text{F}_4$ was formed as a side product. In the absence of CoCp$^*$, no reaction took place.

**Scheme 7.** Reaction of $[\text{Co}^{III}(\text{TPP})(\text{CF}_3)]$ with n-butyl acrylate upon one-electron reduction.
The formation of the desired difluorocyclopropane suggests that upon reduction of [Co\textsuperscript{III}(TPP)(CF\textsubscript{3})] a cobalt-difluorocarbene complex is formed, which is apparently nucleophilic enough to facilitate CF\textsubscript{2} transfer to the electrophilic C=C bond of the acrylate.

The feasibility of the stoichiometric reaction shown in Scheme 7 triggered us to evaluate whether catalytic CF\textsubscript{2} transfer from Me\textsubscript{3}SiCF\textsubscript{3} to n-butyl acrylate is possible when directly using a divalent cobalt(II) porphyrin catalyst in the presence of NaI as the activator. Indeed, with 5 mol\% of [Co\textsuperscript{II}(TPP)] in THF catalytic formation (TON = 2.4) of the desired gem-difluorocyclopropanated acrylate was observed (Table 1, entry 1), albeit in low yield (12%). Besides the desired cyclopropane, the only other \textsuperscript{19}F-NMR detected fluorine containing side product was C\textsubscript{2}F\textsubscript{4}, presumably formed by free carbene dimerization. Control experiments show that in the absence of cobalt (Table 1, entry 2) no gem-difluorocyclopropane product was formed, which makes it unlikely that the cyclopropanation proceeds via free CF\textsubscript{2} or the free CF\textsubscript{3}\textsuperscript{-} anion. Additionally, we also tested other sources of CF\textsubscript{2} in this reaction but to no avail.
The low turnover numbers obtained using \([\text{Co(TPP)}]\) as the catalyst suggests that the catalyst quickly deactivates under the applied reaction conditions. Hence, in an attempt to increase the TONs we explored a few additional catalysts (Table 1). The complexes \([\text{Co}^{\text{II}}(\text{acac})_2]\) and \([\text{Co}^{\text{II}}(\text{salophen})]\) proved inactive (entries 3-4), but the perfluorinated porphyrin complex \([\text{Co(TPPF}_{20})]\) \((\text{TPPF}_{20} = \text{meso-tetra(pentafluorophenyl)-porphyrinato})\) indeed proved to be a somewhat more robust catalyst (entry 5) than \([\text{Co(TPP)}]\), producing the desired gem-difluorocyclopropanated acrylate in 24% yield (TON = 4.8). Changing the initiator, solvent and the amount of \(\text{Me}_3\text{SiCF}_3\) did not improve the yield of the difluorinated cyclopropane. However, when an additional batch of 4 equivalents of \(\text{Me}_3\text{SiCF}_3\) was added after 4 hours (Table 1, entry 6), the yield increased to 40% (TON = 8). Any further addition of \(\text{Me}_3\text{SiCF}_3\) did not lead to an increased yield.

The reactions reported in Table 1 serve as a proof-of-principle, clearly showing the feasibility of cobalt-catalysed \(\text{CF}_2\) transfer from \(\text{Me}_3\text{SiCF}_3\) to electron-deficient alkenes. However, the currently applied catalysts do not seem to be robust enough to obtain the cyclopropane product in high yields exceeding 40%. Hence, additional catalyst screening is clearly a subject of follow-up research.

Due to the redox non-innocent behaviour of carbenes,\(^{17}\) the electronic structure of oxidation state +II group 9 transition metal carbene complexes is best described as metal(III) ‘carbene radical’ species in which the unpaired electron resides mainly in the p-orbital of the carbene moiety (the SOMO being the metal d - carbene p antibonding \(\pi^*\) molecular orbital, which is strongly polarized to carbon). This phenomenon has been reported for various transition metal carbene complexes, and can lead to unique reactivity of the carbene moiety.\(^{17-18}\) A similar behaviour has been reported for group 9 nitrene complexes.\(^{19}\) However, as pointed out by Woodcock and co-workers, cobalt porphyrinato difluorocarbene complexes actually might not behave as so-called ‘carbene radicals’.\(^{20}\) According to their NBO analysis (DFT, M06-L functional) the spin density is mainly located on the metal (71%) rather than on the carbon atom (28%) and thus \(\text{Co(por)}\text{CF}_2\) should have a substantial Fischer-type carbene character. Hence, unlike all other reported carbene adducts of cobalt(II) porphyrins,\(^{17,18,20}\) the \(\text{CF}_2\) adduct might not behave as a genuine ‘carbene radical’. Thus, we wondered if the \(\text{CF}_2\) carbene adduct reacts with alkenes via a stepwise (typical for ‘carbene radicals’) or a concerted (typical for Fischer carbenes) mechanism. Therefore we performed additional DFT calculations to shed light on the

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**Table 1. Catalyst screening for CF$_2$ transfer from Me$_3$SiCF$_3$ to n-butyl acrylate**

<table>
<thead>
<tr>
<th>#</th>
<th>Catalyst</th>
<th>Solvent</th>
<th>T (°C)</th>
<th>Yield</th>
<th>TON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>([\text{Co}^{\text{II}}(\text{TPP})])</td>
<td>THF</td>
<td>50</td>
<td>12%</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>None</td>
<td>THF</td>
<td>50</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>([\text{Co}^{\text{II}}(\text{acac})_2])</td>
<td>THF</td>
<td>50</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>([\text{Co}^{\text{II}}(\text{salophen})])</td>
<td>THF</td>
<td>50</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>([\text{Co}^{\text{II}}(\text{TPPF}_{20})])</td>
<td>THF</td>
<td>50</td>
<td>24%</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>([\text{Co}(\text{TPPF}_{20})]) (^c)</td>
<td>THF</td>
<td>50</td>
<td>40%</td>
<td>8</td>
</tr>
</tbody>
</table>

Reaction conditions: 0.5 mmol of n-butyl acrylate; 2 mL of solvent; 5 mol% catalyst and 4 equivalents of TMSCF$_3$. \(^a\) with respect to n-butyl acrylate using $^{19}$F NMR spectroscopy and fluorobenzene as an internal standard. \(^b\) Turnover numbers. \(^c\) A second batch of 4 equivalents of Me$_3$SiCF$_3$ was added after 4 hours.
mechanistic details concerning the observed CF$_2$ transfer reactions from the [Co(por)(CF$_2$)] complex to the electron deficient acrylate.

Scheme 8. Spin density plot and resonance structures of [Co(por)(CF$_2$)].

In agreement with the results reported by Woodcock, the DFT (BP86, def2-TZVP) calculated NBO spin populations of [Co(por)(CF$_2$)], which is a simplified model of the experimental porphyrin complexes without meso-substituents, are 65% for cobalt and only 23% for the carbene carbon atom (Scheme 8).

Figure 4. DFT calculated pathway for difluorocyclopropanation of methyl acrylate by a cobalt(II) porphyrinato complex (red) and metal-free CF$_2$ insertion on the left (blue).

However, despite the dominant metalloradical character of the [Co(por)(CF$_2$)] species, the computed carbene transfer to methylacrylate proceeds via a stepwise radical process, just like for other cobalt(II) porphyrin catalysed carbene and nitrene transfer reactions (Figure 4, right). All attempts to find the transition state for a concerted addition of acrylate failed and converged to the stepwise pathway. Addition of the difluorocarbene species A to the olefin proceeds via a relatively low energy transition state (TS1, $\Delta G^\ddagger_{298K} = +14.4$ kcal mol$^{-1}$), generating the [Co(por)(CF$_2$-CH$_2$-CH•COOMe)] species B, which has its unpaired electron primarily localized at the γ-carbon of the ‘alkyl’ moiety. Hence, despite its significant Fischer-type character in the ground state, the reactivity of [Co(por)(CF$_2$)] follows the characteristics of a ‘carbene radical’ species. The transition state TS2 for ring closure leading to formation of the cyclopropane product involves simultaneous C–C bond formation and homolytic cleavage of the Co–C bond. The barrier for this process is higher ($\Delta G^\ddagger_{298K} = +20.7$ kcal mol$^{-1}$) and seems to be the rate limiting step of the overall reaction.
We also investigated an alternative pathway in which the difluorocarbene generated on the cobalt centre dissociates to react with the acrylate outside the metal coordination sphere. The release of free difluorocarbene from cobalt is energetically uphill ($\Delta G^{\circ}_{298K} = +16.3$ kcal mol$^{-1}$) and the reverse reaction is barrierless (Figure 4, left). This energy is comparable to the energy barrier for coupling of the cobaltocarbene with methyl acrylate. Formation of free CF$_2$ in this manner could be responsible for the observed formation of CF$_4$ as a side product in the reaction. However, free CF$_2$ carbene formation is unlikely associated with formation of the cyclopropane product, as the addition of free difluorocarbene to methyl acrylate has a much higher barrier ($\Delta G^{\circ*}_{298K} = 28.0$ kcal mol$^{-1}$) than those associated with the metal-mediated pathway (TS1 and TS2 in Figure 4). Lewis-acid activation of the acrylate also seems unlikely, as in a separate control experiment with [Zn(TPP)] only traces (< 1%) of the gem-difluorocyclopropane product was formed.

**Scheme 9. Proposed catalytic cycle for the difluorocyclopropanation of n-butyl acrylate catalysed by a cobalt(II) porphyrinato complex.**

Based on the above considerations we propose a mechanism in which the CF$_3^-$ anion (generated by the reaction of Me$_3$SiCF$_3$ and NaI) coordinates to [Co(TPP)] to form the anionic complex [Co(TPP)(CF$_3$)]$^-$, which produces the neutral carbene adduct [Co(TPP)(CF$_2$)] upon loss of a fluoride anion (Scheme 9). The cobalt difluorocarbene complex subsequently undergoes a stepwise radical-type addition to the acrylate double bond, forming an alkylcobalt(III) intermediate with the unpaired electron residing at the γ-carbon atom of the alkyl chain. Subsequent (and likely rate limiting) ring closure with concerted Co-C bond cleavage furnishes the difluorocyclopropane and regenerates the [Co(TPP)] catalyst.

**Summary and conclusions**

In conclusion, cobalt(II)-porphyrinato complexes catalyse difluorocarbene transfer from the trifluoromethyl anion to n-butyl acrylate forming a gem-difluorocyclopropane. The reactions reported here serve as a proof-of-principle, clearly showing the feasibility of cobalt-catalysed CF$_2$ transfer from Me$_3$SiCF$_3$ to electron-deficient alkenes. The data further show that the current cobalt(II) porphyrin catalysts quickly deactivate under the applied reaction conditions (maximum TON = 8), thus suggesting that future investigations aimed at the development of efficient protocols for catalytic CF$_2$
transfer reactions using Me$_3$SiCF$_3$ as the carbene source should focus on using catalysts that are more stable in the presence of the reactive, free CF$_2$ and CF$_3$ intermediates generated under the applied reaction conditions.

Experimental and computational details

General information

All manipulations were performed under an N$_2$ atmosphere by standard Schlenk techniques or in a glovebox. Methanol and acetonitrile were distilled under nitrogen from CaH$_2$. THF, toluene and pentane were distilled under nitrogen from Na wire. The n-butyl acrylate substrate was passed through a plug of basic alumina, deoxygenated by bubbling dinitrogen for at least an hour and stored at 4°C in a Schlenk flask. [Co(TPP)] was purchased from STREM and used without further purification. [Co(TPPF$_{20}$)], [Co(TPP)Cl]$_2$ and Co(salophen) (N,N'-bis(3,5-di-tert-butylsalicylidine)-1,2-benzenediamine(-2H))cobalt(II) and PPh$_3$BrCF$_2$ were synthesised according to published procedures. [Co(acac)$_2$], TMSCF$_3$, TBAT (Tetrabutylammonium difluorotriphenylsilicate), LiI, SCDA (Sodium chlorodifluoroacetate), MDFA (Methyl 2,2-difluoro-2-(fluorosulfonyl)acetate), KI, TMSCI, K$_2$CO$_3$ Tetrabutyl ammonium bromide, CoCp$_2$Bis(pentamethylcyclopentadienyl) cobalt(II) and TMSCF$_3$Br was purchased from commercial sources and used without further purification. NaI was dried at 100 °C in a vacuum oven overnight prior to use. Fluorobenzene was purchased from Sigma-Aldrich, degassed prior to use and stored with molecular sieves.

All NMR spectra were recorded at room temperature.

$^1$H NMR: Bruker Avance 400 (400 MHz) or Mercury 300 (300 MHz) machine was used and spectra were referenced internally to residual solvent resonance of CDCl$_3$ ($\delta = 7.26$ ppm).

$^{13}$C ($^1$H) NMR: Bruker Avance 400 (101 MHz), or Mercury 300 (75 MHz) machine were used and spectra were referenced internally to residual solvent resonance of CDCl$_3$ ($\delta = 77.2$ ppm) or THF-$d_8$ (67.21, 25.31).

Abbreviations used are: s = singlet, d = doublet, t = triplet, m = multiplet, br = broad.

High Resolution Mass spectra were measured on an AccuTOF LC, JMS-T100LP Mass spectrometer (JEOL, Japan). FD/FI probe (FD/FI) is equipped with FD Emitter, Carbotec or Linden (Germany), FD 10 μm. Current rate 51.2 mA/min over 1.2 min FI Emitter, Carbotec or Linden (Germany), FI 10 μm. Flashing current 40 mA on every spectra of 30 ms. Typical measurement conditions are: Counter electrode –10kV, Ion source 37V.

Synthesis of compounds

- Synthesis of [Co$^{III}$(TPP)(CF$_3$)]

113 mg of [Co(TPP)(Cl)] (0.16 mmol) and 1.5 mg of CsF (0.01 mmol) were dissolved in 3 mL of THF in a flame-dried Schlenk tube at room temperature. Subsequently 48 μL of TMSCF$_3$ (0.32 mmol) was added dropwise with a microsyringe. Subsequently, the reaction mixture was allowed to stir overnight. Evaporation of solvent led to formation of a red solid which was washed successively with water (5 mL) and pentane (5 mL) and dried in vacuo. Yield: 94 mg (80%).

$^1$H NMR (300 MHz, Chloroform-$d$) $\delta$ 8.96 (s, 8H, belonging to pyrrolic protons from the porphyrin ring), 8.13 (s, br, 8H, α-protons from the phenyl rings in the porphyrin ring), 7.75 (m, br, 12H, $m$-and $p$-protons of the phenyl rings)). $^{19}$F NMR (CDCl$_3$) $\delta$ 19.08 ppm. $^{13}$C NMR (75 MHz, THF-$d_8$) $\delta$ 142.64, 140.30, 131.90, 130.43, 125.68, 124.67, 118.38. (The CF$_3$ carbon was not detectible). UV-vis (MeOH), $\lambda_{max}$/nm:
HRMS (FD): calculated for C_{45}H_{28}CoF_{3}N_{4} \ (m/z) = 740.1598 \ (Da/e), found \ (m/z) 740.1624 \ (Da/e).

Elemental analysis: No reliable CHNF analysis could be obtained even after multiple trials due to incomplete combustion (which is more commonly observed for F-containing compounds).

- **Gem-difluorocyclopropanation of n-butyl acrylate with [Co^{III}(TPP)(CF_{3})]**

Inside a glove-box, 37 mg (0.05 mmol) of [Co^{III}(TPP)(CF_{3})] and 8 µL (0.05 mmol) of n-butyl acrylate were dissolved in a Schlenk tube in 2 mL THF. Then 16.5 mg (0.05 mmol) of CoCp_{2} and 9.4 µL of fluorobenzene (0.1 mmol) were added. The Schlenk tube was then taken out of the glovebox and heated at 65 °C for 6 hours. An aliquot of the reaction mixture was dissolved in CDCl_{3}, filtered through a Teflon syringe filter and conversion to the product was determined using \textsuperscript{19}F NMR.

- **General procedure for catalytic gem-difluorocyclopropanation of n-butyl acrylate with TMSCF_{3} and optimisation studies**

0.025 mmol of the catalyst and 15 mg (0.1 mmol) of NaI was added to a flame dried Schlenk tube equipped with a stirring bar. Then 4 mL of THF was added followed by 72 µL (0.5 mmol) of n-butyl acrylate and 94 µL (1 mmol) of fluorobenzene internal standard. Finally 300 µL (~2 mmol) of TMSCF_{3} was added. The reaction mixture was then heated to a given temperature. At the end of the reaction an aliquot of the reaction mixture was dissolved in CDCl_{3} and the yield was determined by integration of the \textsuperscript{19}F NMR signals of butyl 2,2-difluorocyclopropane-1-carboxylate and fluorobenzene. Analytical data matched those reported in literature.\textsuperscript{25}

Different CF_{2} precursors were also tested in this reaction. The results of these reactions are summarised in the following table.

<table>
<thead>
<tr>
<th>catalyst</th>
<th>CF_{2} source</th>
<th>Initiator or another reagent</th>
<th>Temperature</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Co(TPP)] and [Co(TPPF_{3})]</td>
<td>PPh_{3}CF_{2}Br</td>
<td>none</td>
<td>80 °C</td>
<td>0%</td>
</tr>
<tr>
<td>[Co(TPP)] and [Co(TPPF_{3})]</td>
<td>MDFA</td>
<td>KI, TMSCI</td>
<td>60 °C</td>
<td>0%</td>
</tr>
<tr>
<td>[Co(TPP)] and [Co(TPPF_{3})]</td>
<td>SCDA</td>
<td>K_{2}CO_{3} in DMF</td>
<td>60 °C</td>
<td>0%</td>
</tr>
<tr>
<td>[Co(TPP)] and [Co(TPPF_{3})]</td>
<td>TMSCF_{3}Br</td>
<td>Tetrabutyl ammonium bromide</td>
<td>60 °C</td>
<td>0%</td>
</tr>
</tbody>
</table>

- **CV studies**

0.01 mmol (7.4 mg) of [Co^{III}(TPP)(CF_{3})] and 50 mg of tetrabutylammonium hexafluorophosphate (NBu_{4}PF_{6}) were dissolved in 4 mL of THF. The solution was placed in a gastight single-compartment three-electrode cell equipped with a glassy carbon working electrode, coiled platinum wire auxiliary, and silver wire pseudoreference electrodes. All redox potentials are reported against the ferrocene/ferrocinium (Fc/Fc') redox couple. Decamethylferrocene was used as an internal standard (E = 0.427 V vs. Fc/Fc’).\textsuperscript{26}

- **EPR studies**

In order to trap any reactive intermediates formed during the reaction of [Co^{III}(TPP)(CF_{3})] with CoCp_{2} we attempted the following reaction:
Inside a glove box, 1.7 mg (0.005 mmol) of CoCp*₂ was dissolved in 2 mL of 2-MeTHF. This solution was added to 3.7 mg (0.005 mmol) of [Co^III(TPP)(CF₃)] in a Schlenk tube. The Schlenk tube was sealed and taken out of the glove-box. To this, 7 μL of BF₃·Et₂O was added at −78° C under an N₂ atmosphere and allowed to stir for 10 minutes. The Schlenk tube was then reintroduced to the glove-box and 0.2 mL was transferred to an EPR tube. This sample was then measured at 20K. The corresponding spectrum is reported in Figure 5.

![EPR spectrum (20 K) of a mixture of [Co^III(TPP)(CF₃)], CoCp*₂ and BF₃·Et₂O in 2-MeTHF](image)

Consequently we also measured the EPR spectrum of the parent [Co^II(TPP)] complex in 2-MeTHF. This gave the same spectrum as observed previously on adding BF₃·Et₂O to the reduced [Co^III(TPP)(CF₃)] complex. This means that no intermediates were observed under these reaction conditions and the reduced complex underwent follow-up reactions to give the [Co^II(TPP)]. Adding acrylate to this reaction mixture did not lead to a different EPR spectrum.

An EPR spectrum was also measured directly after adding the CoCp*₂ (1.7 mg, 0.005 mmol) reductant to the [Co^III(TPP)(CF₃)] (3.7 mg, 0.005 mmol) complex in 2 mL THF. This time a distinctly different spectrum was obtained pointing to the formation of the anionic, paramagnetic [Co^II(TPP)(CF₃)]⁻ complex (Figure 6). Addition of acrylate to this mixture led to rapid loss of intensity of the signal, and apparently any other intermediates involved in the difluorocyclopropanation reaction of the n-butyl acrylate are too short-lived to detect with EPR spectroscopy.
Figure 6. (red) EPR spectrum of \([\text{Co}^{II}(\text{TPP})]\) complex in 2-MeTHF (20K). (blue) EPR spectrum of reduced \([\text{Co}^{III}(\text{TPP})\text{CF}_3]\) complex under the same conditions.

Computational details
Geometry optimizations were carried out using the TURBOMOLE 6.5 program package\(^27\) coupled with the PQS Baker optimizer\(^28\) via the BOpt package\(^29\) using the BP86 functional,\(^30\) def2-TZVP basis set\(^31\) and the resolution-of-identity method.\(^32\) All minima (no imaginary frequencies) and transition states (one imaginary frequency) were characterized by numerical calculation of the Hessian matrix. Zero point energy and gas phase thermal corrections (enthalpy and entropy, 298K, 1 bar) were calculated. Estimated condensed phase (1 L mol\(^{-1}\)) free energies were obtained from these data by neglecting the enthalpy RT term and subsequent correction of the condensed phase (CP) reference volume \([S_{CP} = S_{GP} + R \ln(1/24.5)]\) for all steps involving a change in the number of species.

Figure 7. Two possible pathways for cyclopropanation of methyl acrylate mediated by \([\text{Co(por)}(\text{CF}_3)]\). Free energies in kcal mol\(^{-1}\). Selected bond distances (Å) are presented as well.
Table 2. Absolute calculated SCF energies ($E_{SCF}$), zero point corrections (ZPE), thermal corrections (ZPE+RT+TRV), entropy contribution (TS), zero point energies ($E_{ZPE}$), enthalpies (H) and free energies ($G_{298}$).

<table>
<thead>
<tr>
<th>Species</th>
<th>$E_{SCF}$/hartree</th>
<th>ZPE/hartree</th>
<th>ZPE+RT+TRV/hartree</th>
<th>TS/hartree</th>
<th>$E_{ZPE}$/hartree</th>
<th>H/hartree</th>
<th>$G_{298}$/hartree</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF$_2$</td>
<td>-237.8190788</td>
<td>0.00651</td>
<td>0.01048</td>
<td>0.0274</td>
<td>-237.813</td>
<td>-237.809</td>
<td>-237.836</td>
</tr>
<tr>
<td>Methylacrylate (MA)</td>
<td>-306.6104266</td>
<td>0.0921</td>
<td>0.09983</td>
<td>0.03833</td>
<td>-306.518</td>
<td>-306.511</td>
<td>-306.549</td>
</tr>
<tr>
<td>TS3</td>
<td>-544.4259534</td>
<td>0.10064</td>
<td>0.1116</td>
<td>0.04788</td>
<td>-544.325</td>
<td>-544.314</td>
<td>-544.362</td>
</tr>
<tr>
<td>Cyclopropane</td>
<td>-544.5041566</td>
<td>0.10485</td>
<td>0.11487</td>
<td>0.04479</td>
<td>-544.399</td>
<td>-544.389</td>
<td>-544.434</td>
</tr>
<tr>
<td>Co(por)</td>
<td>-2371.924224</td>
<td>0.26691</td>
<td>0.28559</td>
<td>0.06188</td>
<td>-2371.66</td>
<td>-2371.64</td>
<td>-2371.7</td>
</tr>
<tr>
<td>Co(por)CF$_2$</td>
<td>-2609.78417</td>
<td>0.27591</td>
<td>0.29839</td>
<td>0.07267</td>
<td>-2609.51</td>
<td>-2609.49</td>
<td>-2609.56</td>
</tr>
<tr>
<td>TS1</td>
<td>-2916.388542</td>
<td>0.36903</td>
<td>0.39901</td>
<td>0.09089</td>
<td>-2916.02</td>
<td>-2915.99</td>
<td>-2916.08</td>
</tr>
<tr>
<td>B</td>
<td>-2916.41412</td>
<td>0.37122</td>
<td>0.40082</td>
<td>0.08919</td>
<td>-2916.04</td>
<td>-2916.01</td>
<td>-2916.1</td>
</tr>
<tr>
<td>TS2</td>
<td>-2916.379734</td>
<td>0.3703</td>
<td>0.40021</td>
<td>0.09097</td>
<td>-2916.01</td>
<td>-2915.98</td>
<td>-2916.07</td>
</tr>
</tbody>
</table>
Table 3. Relative calculated SCF energies ($\Delta E_{\text{SCF}}$), zero point energies ($\Delta E_{\text{ZPE}}$), enthalpies ($\Delta H$) entropy contributions (TS), and free energies in gas ($\Delta G^{298}$) and solution phase ($\Delta G_{\text{sol}}^{298}$).

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{\text{SCF}}$</th>
<th>$\Delta E_{\text{ZPE}}$</th>
<th>$\Delta H$</th>
<th>$\Delta S$</th>
<th>$\Delta G^{298}$</th>
<th>$\Delta G_{\text{sol}}^{298}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Co(por)CF$_2$]+ MA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TS3 + [Co(por)]</td>
<td>27.87356</td>
<td>27.5849</td>
<td>27.22722</td>
<td>-0.04788</td>
<td>28.01205</td>
<td>28.01205</td>
</tr>
<tr>
<td>B</td>
<td>-12.251</td>
<td>-10.2367</td>
<td>-10.6195</td>
<td>13.68802</td>
<td>3.068524</td>
<td>0.582524</td>
</tr>
</tbody>
</table>

Figure 8. Calculated structure of [Co(por)CF$_2$], and of the stationary points along the stepwise addition of methyl acrylate to Co(Por)CF$_2$: TS1; intermediate B; and TS2.
Single crystal X-ray diffraction studies

Despite numerous attempts of crystallization of \([\text{Co}^{\text{III}}(\text{TPP})(\text{CF}_3)]\) using various solvent combinations, the obtained crystals were always diffracted very poorly or were of bad quality. The best data could be obtained from the material obtained by slow evaporation of a chloroform solution of \([\text{Co}^{\text{III}}(\text{TPP})(\text{CF}_3)]\) in dark. This resulted in formation of clustered crystals of \([\text{Co}^{\text{III}}(\text{TPP})(\text{CF}_3)]\) chloroform solvate which despite twinning and overall poor data quality, have shown the expected connectivity between atoms.

Data was collected on a Bruker D8 Quest Eco diffractometer, equipped with a TRIUMPH monochromator and a CMOS PHOTON 50 detector, using Mo-Kα radiation (\(\lambda = 0.71073 \text{ Å}\)). Data collection was conducted at 150(2) K. The intensity data were integrated with the Bruker APEX2 software.\(^{33}\) Absorption correction and scaling was performed with SADABS.\(^{34}\) The structures were solved with SHELXS-97.\(^{35}\) Least-squares refinement was performed with SHELXL-2013\(^{35}\) against \(F^2\) of all reflections. All non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were located at calculated positions using a riding model.

Apparent crystal data: \(C_{45}H_{28}CoF_3N_4\cdot CHCl_3\) \(Fw = 860.01\), red rough fragment, 0.32 x 0.21 x 0.20 mm, monoclinic, \(P 21/n\) (no. 14), \(a = 13.4359(9), b = 18.2392(13), c = 15.6674(11) \text{ Å}, \beta = 90.312(4), \ V = 3839.4(5)\text{Å}^3, Z = 4, R1/wR2: 0.1221/0.3091. S = 2.081.

![Figure 9. Connectivity of \([\text{Co}^{\text{III}}(\text{TPP})(\text{CF}_3)]\) as determined by single crystal X-ray diffraction. The CHCl\(_3\) solvate molecule is shown.](image)

Acknowledgements

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References and notes


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