

Showcasing research from Professor Che's laboratory,  
Department of Chemistry, Southern University of Science and  
Technology, Shenzhen, P. R. China.

Chiral iron porphyrin (+)-D<sub>4</sub>-(por)FeCl catalyzes highly  
enantioselective cyclopropanation of alkenes using *in situ*  
generated diazoacetone nitrile with up to 35000 product turnover

With  $\alpha$ -diazoacetone nitrile, *in situ* generated through the reaction  
of commercially available aminoacetone nitrile hydrochloride with  
sodium nitrite, as carbene source, chiral iron porphyrin catalyzed  
asymmetric cyclopropanation reaction is applicable to a broad  
substrate scope (44 examples) with high enantioselectivity (up to  
98% ee) and product turnover (up to 35000 TON). The reactive  
chiral iron-cyanocarbene intermediate has been characterized by  
spectroscopic methods.

Image reproduced by permission of Chi-Ming Che from  
*Chem. Sci.*, 2025, **16**, 7191.

As featured in:



See Chi-Ming Che *et al.*,  
*Chem. Sci.*, 2025, **16**, 7191.

Cite this: *Chem. Sci.*, 2025, 16, 7191

All publication charges for this article have been paid for by the Royal Society of Chemistry

# Chiral iron porphyrin (+)-D<sub>4</sub>-(por)FeCl catalyzes highly enantioselective cyclopropanation of alkenes using *in situ* generated diazoacetonitrile with up to 35 000 product turnover†

Hao-Chong Tan,<sup>a</sup> Ka-Pan Shing,<sup>bd</sup> Hua-Hua Wang,<sup>a</sup> Yungen Liu<sup>ID</sup><sup>a</sup> and Chi-Ming Che<sup>ID</sup><sup>\*bcd</sup>

Transition metal-catalyzed asymmetric cyclopropanation of alkenes is an important strategy to construct chiral cyclopropane skeletons of pharmaceutical interest, but highly enantioselective and practical carbene transfer reactions based on Earth abundant and bio-compatible metals are still a difficult challenge. In this work, we use a chiral iron porphyrin (+)-D<sub>4</sub>-(por)FeCl catalyst and *in situ* generated  $\alpha$ -diazoacetonitrile for highly enantioselective cyclopropanation of arylalkene. This reaction is applicable to a wide range of arylalkenes (44 examples) with yield up to 99%, diastereomeric ratio (dr) up to 93 : 7, and enantiomeric excess (ee) values up to 98%. Importantly, for the cyclopropanation reaction of 3,4-difluorostyrene (1.40 g, 10.0 mmol) with  $\alpha$ -diazoacetonitrile in the presence of 0.002 mol% of (+)-D<sub>4</sub>-(por)FeCl as a catalyst, the turnover number and enantioselectivity of the cyclopropyl nitrile product reached 31 000 and 88% ee, respectively. Using cyclopropyl nitriles as a starting material, downstream functionalization derivatives including cyclopropyl carboxylic acids, cyclopropylamines, and cyclopropylmethanamines can be produced as key intermediates for the preparation of a series of bioactive or drug-like molecules. In addition, the chiral Fe(II)porphyrin–cyanocarbene intermediate [(–)-D<sub>4</sub>-(por)Fe<sup>II</sup>:(CHCN)], which is directly responsible for the carbene transfer reaction, has been characterized by <sup>1</sup>H NMR, HR ESI-MS, UV-vis and ATR-FTIR spectroscopy.

Received 18th January 2025  
Accepted 17th March 2025

DOI: 10.1039/d5sc00461f

rsc.li/chemical-science

## Introduction

Cyclopropane scaffolds are commonly found in many pharmaceuticals and bioactive natural products.<sup>1,2</sup> Typically, cyclopropane skeletons<sup>3–5</sup> are prepared by carbene transfer reactions using diazo compounds as precursors, especially in an asymmetric manner,<sup>6</sup> and noble metal catalysts of rhodium, ruthenium and iridium are often used in asymmetric carbene transfer reactions. In the context of developing sustainable catalysis, there has been great interest in developing iron catalysis for organic synthesis<sup>7–10</sup> due to iron's Earth abundance

and biocompatibility.<sup>11</sup> Although iron carbene complexes have been reported for a long time,<sup>12</sup> the development of practical iron-catalyzed carbene transfer reactions has lagged behind.<sup>13</sup> Furthermore, there are few studies on the detection and reactivity of reactive iron–carbene intermediates involved in the catalytic cycle. In the literature, Woo,<sup>14</sup> Che,<sup>15</sup> Gross<sup>16</sup> and Carreira<sup>17,18</sup> reported iron macrocyclic complexes (porphyrin and corrole) as catalysts for carbene transfer reactions (cyclopropanation of alkenes). In most cases, high product yields and high stereoselectivities (mainly *trans*-configuration) are obtained. Asymmetric cyclopropanation of alkenes using synthetic chiral iron porphyrin catalysts has only been reported sporadically by Gross,<sup>19</sup> Woo,<sup>20</sup> Simonneaux,<sup>21,22</sup> Wong and Che,<sup>23</sup> Zhang,<sup>24,25</sup> and Gallo.<sup>26,27</sup> Although good to high product yields (>80%) and high diastereoselectivities (dr > 10 : 1, mainly *trans*-configuration) were obtained, the enantioselectivities were moderate (typically <80% ee, excluding Zhang's recent report<sup>25</sup>). When chiral non-heme iron complexes are used as catalysts, lower enantioselectivities are obtained<sup>20,28,29</sup> except for the intramolecular cyclopropanation of  $\alpha$ -diazoesters or indoles catalyzed by iron bisoxazoline complexes.<sup>30,31</sup> So far, for iron-catalyzed carbene transfer reactions, only engineered iron enzymes (such as P450, P411 variants and myoglobins with iron

<sup>a</sup>Department of Chemistry, Southern University of Science and Technology, Shenzhen 518055, Guangdong, P. R. China

<sup>b</sup>State Key Laboratory of Synthetic Chemistry, Department of Chemistry, The University of Hong Kong, Pokfulam Road, Hong Kong, P. R. China. E-mail: cmche@hku.hk

<sup>c</sup>HKU Shenzhen Institute of Research and Innovation, Shenzhen, Guangdong 518057, P. R. China

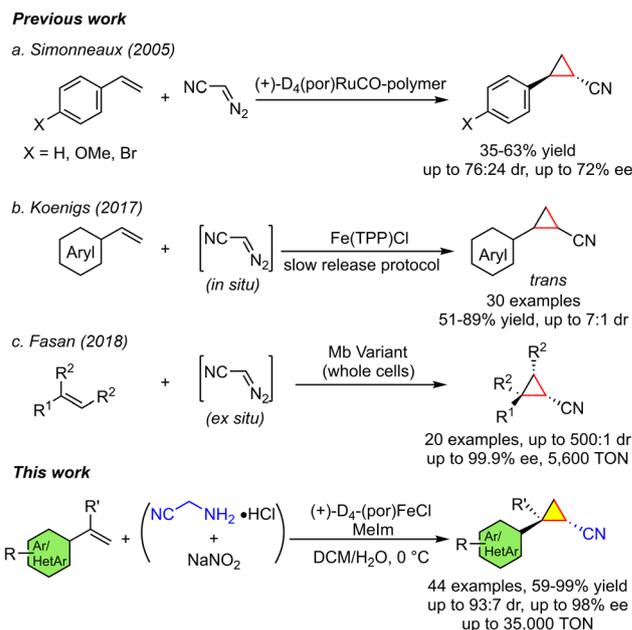
<sup>d</sup>Laboratory for Synthetic Chemistry and Chemical Biology Limited, Units 1503-1511, 15/F, Building 17W, Hong Kong Science Park, New Territories, Hong Kong, P. R. China

† Electronic supplementary information (ESI) available: Experimental procedures, characterization data and copies of <sup>1</sup>H NMR and <sup>13</sup>C NMR spectra. CCDC 2349759 (2g), 2349760 (2I), 2349761 (2z), 2349764 (2aa), and 2351894 (2ad). For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d5sc00461f>



porphyrins as co-factors) have been reported to achieve excellent enantioselectivity and high product turnover numbers (TONs) (Fig. 1).<sup>32–35</sup> In the literature, a rhodium-catalyzed styrene cyclopropanation using a donor/acceptor diazo-compound (trichloroethyl *p*-bromophenyl diazoacetate) resulted in a product TON and enantioselectivity of 100 000 and 94% ee, respectively. However, when the catalyst loading was reduced, the enantioselectivity decreased (400 000 with 90% ee, Fig. 1).<sup>36</sup> In this context, metal porphyrin complexes may be a promising catalyst choice due to their excellent activity and stability. Taking the asymmetric cyclopropanation of styrene with ethyl diazoacetate (EDA) as an example, chiral ruthenium porphyrin catalyst (–)-D<sub>4</sub>-(por)Ru(Ime)<sub>2</sub> gave the *trans*-cyclopropane product with a TON of 23 750 and an ee of 95%;<sup>37</sup> The artificial metalloenzyme Ir(Me)-PIX (with iridium porphyrin as a co-factor) afforded a *cis*-cyclopropane product of 10 000 TON and 98% ee (Fig. 1).<sup>38</sup> Engineered iron enzymes (with iron porphyrins as cofactors) produced even more exciting results: Mb (H64V, V68A) (myoglobin variant) gave a *trans*-product TON of 46 800 with 99.9% ee,<sup>39</sup> and the P411<sub>BM3</sub>-CIS variant achieved a *cis*-product TON of 67 800 with 99% ee (Fig. 1).<sup>40</sup>

Among various carbene precursors, diazo compounds are the most commonly used.<sup>41</sup> However, diazo compounds have inherent disadvantages in preparation and storage due to their potentially explosive properties. It is more applicable when diazo compounds can be generated and used *in situ*,<sup>42,43</sup> simplifying the reaction process and broadening the application scope of such reactions, especially when the reactions are carried out on a large scale.<sup>17,18</sup> In this context,  $\alpha$ -diazoacetone nitrile, which can be generated *in situ* through the reaction of commercially available aminoacetone nitrile hydrochloride with sodium nitrite,<sup>44</sup> was studied (Scheme 1). Simonneaux and co-workers reported the asymmetric cyclopropanation of styrene catalyzed by (+)-D<sub>4</sub>-(por)RuCO or polymer-supported (+)-D<sub>4</sub>-(por)RuCO using  $\alpha$ -diazoacetone nitrile as a carbene precursor; cyclopropane products were obtained with ee up to 90% and dr up to 93 : 7.<sup>45</sup> Using *in situ* generated  $\alpha$ -diazoacetone nitrile as the carbene precursor, Koenigs and co-workers<sup>46,47</sup> reported the catalytic cyclopropanation of styrene by Fe(TPP)Cl in a slow-release protocol, providing the product in up to 89% yields and up to 7 : 1 dr.<sup>48</sup> Using *in situ* generated  $\alpha$ -diazoacetone nitrile as the carbene precursor, Fasan and co-workers reported that Mb variants (in whole cells) catalyzed the asymmetric cyclopropanation of alkenes to provide up to 99.9% ee and up to 500 : 1 dr of cyclopropane product.<sup>49</sup> In this work, we used *in situ*



Scheme 1 Chiral iron porphyrin-catalyzed asymmetric cyclopropanation of alkenes.

generated  $\alpha$ -diazoacetone nitrile as the carbene precursor and chiral iron porphyrin (+)-D<sub>4</sub>-(por)FeCl as the catalyst for the asymmetric cyclopropanation of aryl alkenes. Good product yields (up to 99%), high diastereoselectivities (up to >93 : 7 dr), high enantioselectivities (up to 99% ee) and high product TONs (up to 35 000 with 85% ee) were achieved (Scheme 1). This catalytic reaction has a broad substrate scope (44 examples) and can be used to prepare core scaffolds for the synthesis of bioactive or drug-like molecules. In addition, the chiral Fe(II)-porphyrin–cyanocarbene intermediate [Fe<sup>II</sup>(por)(:CHCN)], which is directly responsible for the carbene transfer reaction, has been characterized by <sup>1</sup>H NMR, HR ESI-MS, UV-vis and ATR-FTIR spectroscopy.

## Results and discussion

Similar to Koenigs's strategy, we used aminoacetone nitrile hydrochloride to prepare  $\alpha$ -diazoacetone nitrile *in situ*.<sup>48,50</sup> Using (+)-D<sub>4</sub>-(por)FeCl as a catalyst, it was found that 93% ee and 85 : 15 dr were obtained at room temperature using a slow-addition protocol<sup>48</sup> (Table 1, entry 1). For comparison, 84% ee and 81 : 19 dr were obtained *via* the one-pot addition method (Table 1, entry 2). There was a slight decrease in enantioselectivity when using other biphasic solutions (toluene/H<sub>2</sub>O or PhCF<sub>3</sub>/H<sub>2</sub>O) (Table 1, entries 3 and 4). Higher enantioselectivities (88% ee) and diastereoselectivities (88 : 12 dr) were obtained when the one-pot reaction was performed at 0 °C (Table 1, entry 5). The best results were obtained with *N*-methyl imidazole (Melm) as an additive (Table 1, entry 6, 91% yield, 97% ee and 90 : 10 dr).<sup>23,51</sup> Using (–)-D<sub>4</sub>-(por)FeCl as a catalyst, the enantiomer of 2a was obtained in 92% yield and –95% ee (Table 1, entry 7 *vs.* entry 6). Under optimized conditions, using other chiral iron

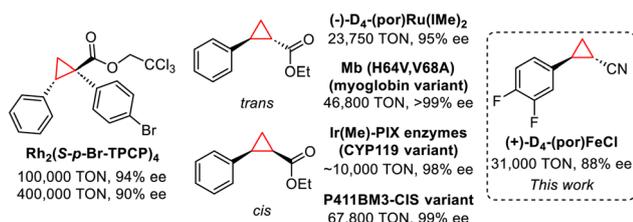
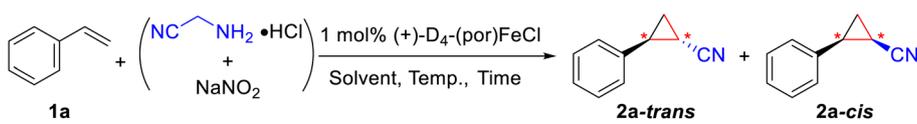
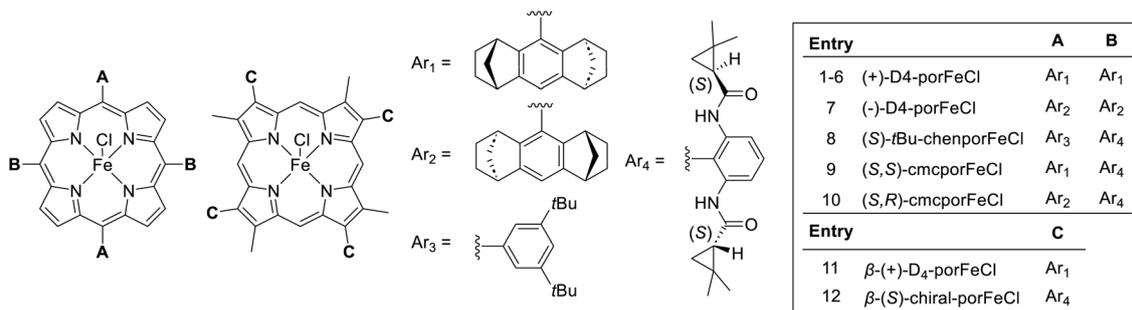


Fig. 1 Transition metal-catalyzed asymmetric cyclopropanation of alkenes.



Table 1 Optimization of reaction conditions for (+)-D<sub>4</sub>-(por)FeCl catalyzed asymmetric cyclopropanation of styrene<sup>a</sup>


Entry	Additive	Solvent	T (°C)	Time (h)	Yield <sup>b</sup> (%)	dr <sup>b</sup>	ee <sup>c</sup> (%)
1 <sup>d</sup>	None	DCM/H <sub>2</sub> O	r. t.	10 + 4 <sup>d</sup>	82	85 : 15	93
2	None	DCM/H <sub>2</sub> O	r. t.	14	85	81 : 19	84
3	None	Toluene/H <sub>2</sub> O	r. t.	14	83	85 : 15	78
4	None	PhCF <sub>3</sub> /H <sub>2</sub> O	r. t.	14	81	81 : 19	79
5	None	DCM/H <sub>2</sub> O	0	14	87	88 : 12	88
6	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	91	90 : 10	97
7 <sup>e</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	92	89 : 11	-95
8 <sup>f</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	90	80 : 20	65
9 <sup>g</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	93	92 : 8	81
10 <sup>h</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	93	80 : 20	15
11 <sup>i</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	86	77 : 23	20
12 <sup>j</sup>	MeIm (0.01 eq.)	DCM/H <sub>2</sub> O	0	14	77	82 : 18	10
13 <sup>k</sup>	None	DCM/H <sub>2</sub> O	0	14	NR	—	—



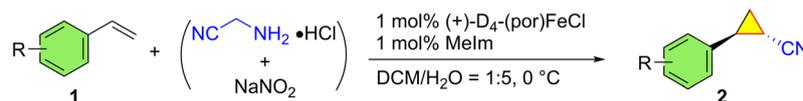
<sup>a</sup> Reaction conditions: **1a** (0.2 mmol) and catalyst (1 mol%) in 0.5 mL of DCM, diazo was generated *in situ* by one-pot reaction of amino-hydrochloride salt (0.4 mmol) with NaNO<sub>2</sub> (0.6 mmol) in 2 mL of degassed water. <sup>b</sup> Determined by <sup>1</sup>H NMR analysis of crude products. <sup>c</sup> Determined by HPLC. <sup>d</sup> Aminoacetonitrile hydrochloride (0.4 mmol, in 1 mL of degassed water) and sodium nitrite (0.6 mmol, in 1 mL of degassed water) were added dropwise using a syringe pump for 10 h and further reacted for 4 h. <sup>e</sup> (-)-D<sub>4</sub>-(por)FeCl (1 mol%) was used. <sup>f</sup> (S)-*t*Bu-chenporFeCl (1 mol%) was used. <sup>g</sup> (S,S)-cmcporFeCl (1 mol%) was used. <sup>h</sup> (S,R)-cmcporFeCl (1 mol%) was used. <sup>i</sup> β-(+)-D<sub>4</sub>-porFeCl (1 mol%) was used. <sup>j</sup> β-(S)-chiral-porFeCl (1 mol%) was used. <sup>k</sup> FeSalen(S,S)(3,5-*t*Bu)X (X = Cl or OTf) (10 mol%) was used. MeIm, methyl imidazole. NR, no reaction.

porphyrins such as (S)-*t*Bu-chenporFeCl, (S,R)-cmcporFeCl, (S,S)-cmcporFeCl, β-(+)-D<sub>4</sub>-porFeCl and β-(S)-chiral-porFeCl,<sup>52</sup> cyclopropanation products were obtained with an ee of 10–81% (Table 1, entries 8–12). With FeSalen(S,S)(3,5-*t*Bu)X (Salen(S,S)(3,5-*t*Bu) = (S,S)-(+)-N,N'-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexanediamine, X = Cl or OTf) as a catalyst, no reaction was observed (Table 1, entry 13). Under optimal conditions (as those in Table 1, entry 6), we examined the scope of styrene derivatives (Scheme 2). In general, good enantioselectivities (up to 98% ee) and high diastereoselectivities (up to 93 : 7 dr) and high product yields (up to 97%) were obtained. For *para*-substituted styrene derivatives, strong electron-donating groups such as MeO (**2f**, 87% ee), Me<sub>2</sub>N (**2h**, 87% ee) and strong electron-withdrawing groups such as CN (**2k**, 85% ee), NO<sub>2</sub> (**2l**, 85% ee), CF<sub>3</sub> (**2m**, 83% ee), CO<sub>2</sub>Me (**2n**, 63% ee) and steric bulky groups (**2i**, *t*Bu, 63% ee) were found to slightly reduce the enantioselectivity of the product (Scheme 2). Lowering the temperature to -15 °C

improved the enantioselectivity (to 90% ee for **2n**). When the substituent is located in the *meta*-position (**2o–2s**) or *ortho*-position (**2t–2x**), the enantioselectivity of the resulting cyclopropanation products decreases slightly (84–90% ee). This reaction is sensitive to substituents on disubstituted alkenes (Scheme 2). For  $\alpha$ -substituted styrene derivatives (**2aa–2ae**), both diastereoselectivity and enantioselectivity decrease significantly with increasing  $\alpha$ -substituent size. On the other hand, neither *cis*- nor *trans*- $\beta$ -methylstyrene could be converted into the corresponding cyclopropanation products (Scheme 2). The *trans*-configurations of compounds **2g**, **2l**, **2z**, **2aa** and **2ad** were unambiguously determined by X-ray crystallography.

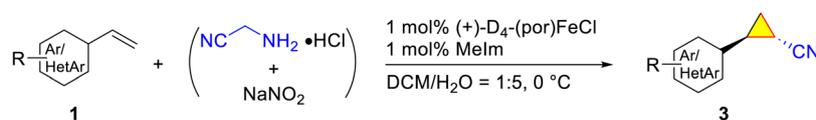
For alkenes tethered to aromatic heterocycles or benzo-heterocycles (Scheme 3, **3a–3i**), the yields of cyclopropanation products are 58–99%, ee is 76–91%, and dr is 80 : 20–92 : 8. *N*-Vinyl indoles also provided the corresponding cyclopropanation products (**3j**, **3k**) with 87% ee and 90% ee, respectively. The cyclopropanation product **4** was obtained from 4-phenyl-buta-





	yield	dr	ee		yield	dr	ee		yield	dr	ee				
<b>2b</b> R = F,	78%	93:7	98%	<b>2i</b> R = <i>t</i> Bu,	91%	83:17	63%		<b>2o</b> R = F,	92%	91:9	86%			
<b>2c</b> R = Cl,	97%	93:7	93%	<b>2j</b> R = Ph,	85%	90:10	89%		<b>2p</b> R = Cl,	80%	93:7	86%			
<b>2d</b> R = Br,	88%	90:10	95%	<b>2k</b> R = CN,	92%	91:9	85%		<b>2q</b> R = Br,	85%	92:8	85%			
<b>2e</b> R = Me,	91%	86:14	87%	<b>2l</b> R = NO <sub>2</sub> ,	98%	92:8	85%		<b>2r</b> R = Me,	97%	89:11	85%			
<b>2f</b> R = OMe,	91%	87:13	87%	<b>2m</b> R = CF <sub>3</sub> ,	97%	92:8	83%		<b>2s</b> R = OMe,	95%	84:16	84%			
<b>2g</b> R = OBn	65%	84:16	87%	<b>2n</b> R = CO <sub>2</sub> Me,	92%	88:12	63%								
<b>2h</b> R = NMe <sub>2</sub> ,	75%	88:12	87%	<b>2n</b> R = CO <sub>2</sub> Me,	85%	91:9	90% <sup>[b]</sup>								
<b>2t</b> R = F,	86%	85:15	88%		75% yield	87:13 dr,	91% ee		99% yield	60:40 dr,	48% ee	<b>2aa</b> R = Br,	91%	80:20	77%
<b>2u</b> R = Cl,	87%	87:13	88%									<b>2ab</b> R = Me,	89%	87:13	79%
<b>2v</b> R = Br,	91%	89:11	88%					<b>2ac</b> R = CH <sub>2</sub> Br,	59%	81:19	67%				
<b>2w</b> R = Me,	97%	90:10	85%					<b>2ad</b> R = CF <sub>3</sub> , <sup>[c]</sup>	90%	60:40	89%				
<b>2x</b> R = OMe,	97%	86:14	90%					<b>2ae</b> R = <i>i</i> Pr,	85%	56:44	60%				

**Scheme 2** (+)-D<sub>4</sub>-(por)FeCl catalyzed cyclopropanation of styrene derivatives<sup>a</sup>. <sup>a</sup>Reaction conditions: **1** (0.2 mmol), Melm (1.0 mol%) and (+)-D<sub>4</sub>-(por)FeCl (1.0 mol%) in 0.5 mL of DCM, diazoacetone nitrile (ca. 0.4 mmol) was *in situ* generated by reaction of aminoacetone nitrile hydrochloride (0.4 mmol) with sodium nitrite (0.6 mmol) in 2.0 mL of degassed water. After 4 h under argon at 0 °C, another batch of aminoacetone nitrile hydrochloride (0.4 mmol) and sodium nitrite (0.6 mmol) was added and further reacted for 14 h. <sup>b</sup>Replaced degassed water with saturated NaCl solution, reacted at -15 °C. <sup>c</sup>Two batches of aminoacetone nitrile hydrochloride (0.4 mmol) and sodium nitrite (0.6 mmol) were added consecutively with an interval of 4 h. For the X-ray structure, H atoms are omitted for clarity, except for the H atoms from the cyclopropyl group.



<b>3a</b>	<b>3b</b>	<b>3c</b>	<b>3d</b>	<b>3e</b>	<b>3f</b>
78% yield	83% yield	85% yield	80% yield	99% yield	82% yield
92:8 dr, 90% ee	80:20 dr, 89% ee	83:17 dr, 83% ee	90:10 dr, 86% ee	91:9 dr, 76% ee	83:17 dr, 85% ee
<b>3g</b>	<b>3h</b>	<b>3i</b>	<b>3j</b>	<b>3k</b>	<b>4</b>
92% yield	58% yield	97% yield	92% yield	65% yield	79% yield
88:12 dr, 64% ee	88:12 dr, 87% ee	91:9 dr, 87% ee	92:8 dr, 87% ee	88:12 dr, 90% ee	64:36 dr, 65% ee

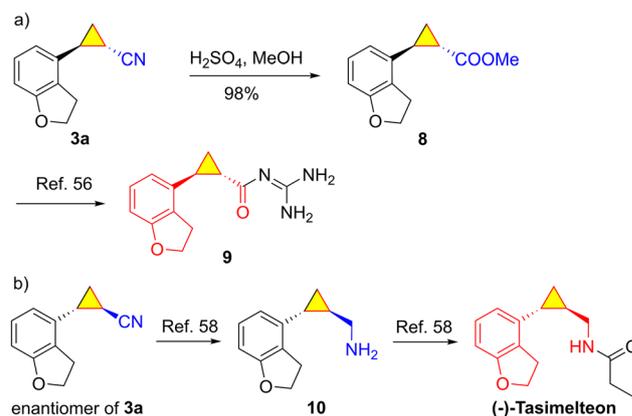
**Scheme 3** (+)-D<sub>4</sub>-(por)FeCl-catalyzed cyclopropanation of alkenes tethered to the heterocyclic ring and also an aryl 1,3-diene<sup>a</sup>. <sup>a</sup>Reaction conditions: **1** (0.2 mmol), Melm (1.0 mol%) and (+)-D<sub>4</sub>-(por)FeCl (1.0 mol%) in 0.5 mL of DCM, diazoacetone nitrile (ca. 0.4 mmol) was generated *in situ* by reaction of aminoacetone nitrile hydrochloride (0.4 mmol) with sodium nitrite (0.6 mmol) in 2.0 mL of degassed water. After 4 h under argon at 0 °C, another batch of aminoacetone nitrile hydrochloride (0.4 mmol) and sodium nitrite (0.6 mmol) was added and further reacted for 14 h.



1,3-diene, with a dr of 64 : 36 and a yield of 79%; the ee values of the *trans*-isomer and *cis*-isomer are 65% and 8%, respectively (Scheme 3). No cyclopropanation reaction was observed using allylic benzene as a substrate.

Our catalytic cyclopropanation reaction is scalable and user-friendly (Scheme 4). In the presence of 0.02 mol% of (+)-D<sub>4</sub>-(por)FeCl, 1.40 g of 3,4-difluorostyrene (**5**) was converted into 1.58 g of product **6** (88% yield, 88% ee, TON of 4400). For a batch reaction of 14.01 g of **5** in the presence of 0.002 mol% of (+)-D<sub>4</sub>-(por)FeCl as a catalyst, a product TON of 11 000 (86% ee) was obtained. We attribute the slight erosion in enantioselectivity to inefficient mechanical stirring. Finally, the optimized conditions were: 1.40 g of **5** was reacted in the presence of 0.002 mol% of (+)-D<sub>4</sub>-(por)FeCl to produce a cyclopropane product with a TON of up to 31 000 and 88% ee (Scheme 4). Under similar reaction conditions, styrene was used as the substrate (1.04 g scale) to give the corresponding cyclopropanation product with a TON of 35 000, an ee of 85% ee, and a dr of 92 : 8. Starting from **6**, Ticagrelor (AZD6140, antiplatelet agent)<sup>53</sup> and **7** (LSD1 inhibitor)<sup>54</sup> can be prepared. In the literature, for the cyclopropanation reaction of styrene/styrene derivatives and  $\alpha$ -diazoacetone, when Fe(F<sub>20</sub>TPP)Cl is used as the catalyst, the obtained product TON is up to 2133 (using styrene as a substrate).<sup>48</sup> Using engineered myoglobin as the catalyst and *p*-chlorostyrene as the substrate, the product TON is reported to be as high as 5600.<sup>49</sup>

Chiral cyclopropyl nitrile can be easily converted into a variety of structurally diverse cyclopropane scaffolds including cyclopropylmethanamine, cyclopropylcarboxylic acid and cyclopropylamine, as valuable chiral building blocks for the preparation of bioactive or drug-like molecules.<sup>55</sup> For examples: (1) alcoholysis of **3a** gives the corresponding cyclopropyl carboxylic ester **8** with a yield of 98%, from which **9** (selective sodium hydrogen exchanger isoform-1 inhibitor) can be prepared (Scheme 5a; for the synthetic route,<sup>56</sup> see the ESI†). (–)-Tasimelteon (a melatonin receptor agonist)<sup>57</sup> can be synthesized from the enantiomer of **3a** (**3a** can be prepared by

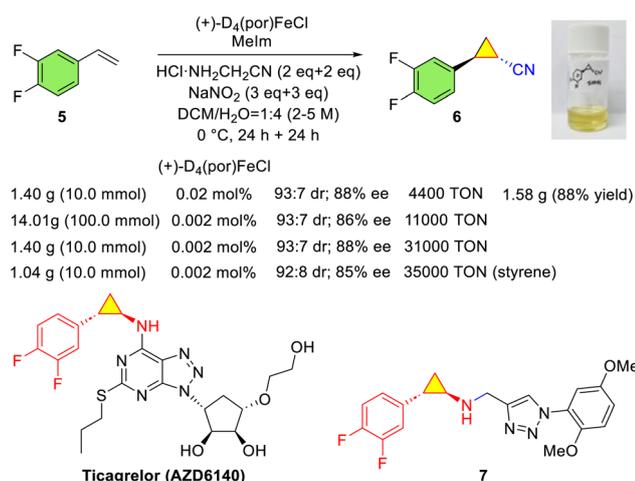


Scheme 5 (a) Preparation of **9** from **3a**. (b) Preparation of (–)-Tasimelteon from the enantiomer of **3a**.

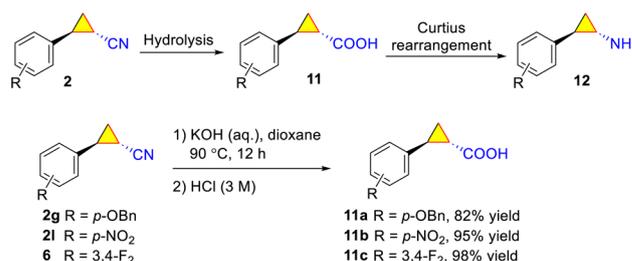
using (–)-D<sub>4</sub>-(por)FeCl as catalyst) according to literature methods (Scheme 5b).<sup>58</sup> This strategy is more step-economical<sup>59</sup> than similar approaches starting from EDA,<sup>60</sup> or *via* chiral epoxide intermediates.<sup>61,62</sup> Since our cyclopropanation reaction proceeds in an asymmetric manner, optical resolution of racemic amine **10** is unnecessary.<sup>58</sup>

(2) Hydrolysis of aryl cyclopropyl nitrile **2** under alkaline conditions gave the corresponding aryl cyclopropyl carboxylic acid (**11**) in high yield (Scheme 6).<sup>49</sup> Using acid **11** as the starting material, aryl cyclopropyl amines (**12**) were prepared in high yields *via* Curtius rearrangement.<sup>63–66</sup> A series of bio-active compounds containing a chiral cyclopropyl moiety such as **ST-161** (antiviral reagent against Lassa virus),<sup>67</sup> **VU0359595** (selective PLD1 inhibitor),<sup>68</sup> and **S 17092** (human proline endopeptidase inhibitor)<sup>69</sup> (Fig. 2) can be prepared from **2a** or its enantiomer. Our method is simpler<sup>70</sup> than the cyclopropanation of  $\alpha,\beta$ -unsaturated carboxylic acid derivative of Oppolzer's chiral sultam (bornane[10,2]sultam, auxiliary) using diazomethane (used to construct the stereochemistry of the cyclopropyl moiety).<sup>71</sup>

(3) Phenylcyclopropylamine (tranlycypromine, **TCP**) and its derivatives are key and versatile intermediates in the preparation of bioactive or drug-like molecules (Fig. 2).<sup>72,73</sup> For examples, **Diprovocim-1** (toll-like receptor agonist)<sup>74</sup> can be prepared from **2a**. **RN-1** (LSD1 inhibitor)<sup>75</sup> and **ORY-2001** (Vafidemstat, LSD1 inhibitor)<sup>76</sup> can be prepared starting from **2g**. **MC2580** derivative (LSD1 inhibitor)<sup>77</sup> can be prepared starting from **2l**.



Scheme 4 Gram-scale reactions catalyzed by chiral iron porphyrins and examples that can be prepared from **6**.



Scheme 6 Diversification of aryl cyclopropyl nitriles.



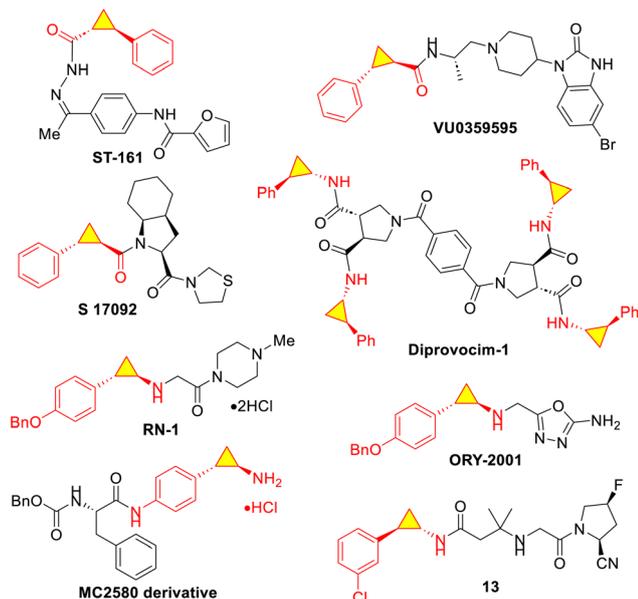


Fig. 2 Examples of cyclopropyl carboxamides and tranylcypromine derivatives.

Compound 13 (dipeptidyl peptidase IV inhibitor)<sup>78</sup> can be prepared starting from **2p**.

We performed time course experiments to gain a deeper understanding of the reaction mechanism (Fig. 3). There is a clear induction period before the reaction proceeds rapidly (Fig. 3a). Furthermore, MeIm shortened the induction period, possibly due to the *trans* effect *via* axial ligation to iron

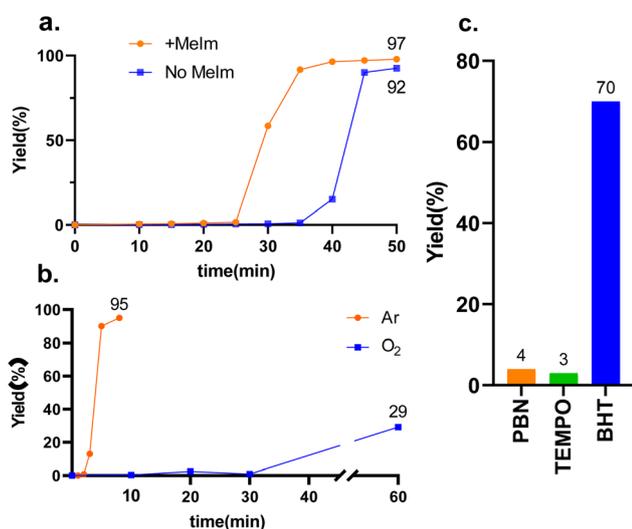
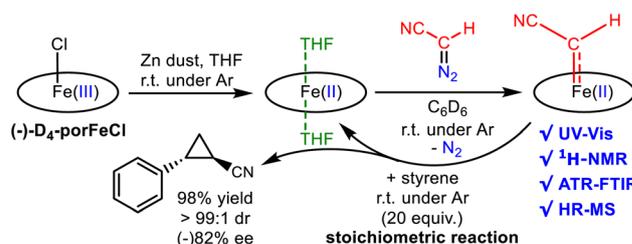


Fig. 3 Time course studies and the effect of radical scavengers. Reaction conditions: 0.8 mmol styrene, 1.6 mmol HCl·NH<sub>2</sub>CH<sub>2</sub>CN, 2.4 mmol NaNO<sub>2</sub>, 0.25 mol% (–)-D<sub>4</sub>-(por)FeCl, 1.6 mL DCM, 8 mL H<sub>2</sub>O, 25 °C under argon, one-pot addition. (a) Effect of MeIm (in the presence or absence of 0.25 mol% of MeIm). (b) With 0.25% MeIm, used prepared diazoacetone (0.4 mmol) under different atmospheres. (c) Reaction performed with different radical scavengers (1.2 eq. of diazoacetone), 12 h at 25 °C.

porphyrin. Under similar reaction conditions in the presence of MeIm, one-pot addition of diazoacetone drastically shortened the induction period (<3 min) and the catalytic reaction was finished within 10 min (Fig. 3b). The reaction was found to be sensitive to O<sub>2</sub> (Fig. 3b). When carried out under O<sub>2</sub>, the reaction slowed down significantly, and the product yield was only 29% in 60 min. In the presence of *N*-tert-butyl-2-phenylnitron (PBN) or 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), the cyclopropanation product was obtained in yield within 5% (Fig. 3c). However, the decrease in product yield in the presence of radical scavengers cannot exclude the interaction between free radical scavengers and metal catalysts, which can also lead to the loss of catalyst activity.<sup>79</sup> Butylated hydroxytoluene (BHT), which has weak interaction with metal catalysts, was used as a free radical scavenger, and the cyclopropanation product was obtained with a yield of 70%. The finding may differ from Zhang's recent report,<sup>25</sup> in which Fe(III)-based metalloradical species ( $\alpha$ -Fe(IV)-alkyl and  $\gamma$ -Fe(IV)-alkyl radicals) were proposed. On the other hand, non-radical pathways in iron porphyrin-catalyzed carbene transfer reactions have also been proposed and supported by both experimental and computational results.<sup>80</sup>

We performed a series of experiments to characterize the reactive Fe(II) porphyrin cyanocarbene [(por)Fe(:CHCN)] intermediate (Scheme 7). [(–)-D<sub>4</sub>-(por)Fe(THF)<sub>2</sub>] was prepared by stirring (–)-D<sub>4</sub>-(por)FeCl with Zn dust in degassed and anhydrous tetrahydrofuran (THF) overnight. [(–)-D<sub>4</sub>-(por)Fe(THF)<sub>2</sub>] can be characterized by <sup>1</sup>H NMR. All sharp resonance peaks appear within  $\delta$  –1.8 to 12.5 ppm. It was found that [(–)-D<sub>4</sub>-(por)Fe(THF)<sub>2</sub>] reacted with an equimolar diazoacetone (0.07 M solution in toluene) to immediately produce [(–)-D<sub>4</sub>-(por)Fe(:CHCN)], as shown by using UV-vis (in benzene) and <sup>1</sup>H NMR spectroscopy. In a non-coordinating solvent (benzene), [(–)-D<sub>4</sub>-(por)Fe(:CHCN)] has UV-vis absorption peaks at 417 and 509 nm (Fig. 4). Studies have found that [(–)-D<sub>4</sub>-(por)Fe(:CHCN)] is unstable in benzene under aerobic conditions, producing a species with UV-vis absorption spectrum similar to Fe(III) porphyrin (spectral changes in benzene solution show isosbestic points at 387, 512 and 554 nm, see Fig. S2, ESI<sup>†</sup>). Comparing the UV-vis absorption spectra of [(–)-D<sub>4</sub>-(por)Fe(THF)<sub>2</sub>] and [(–)-D<sub>4</sub>-(por)Fe(:CHCN)], the Soret and Q bands blue shift from 430 and 547 nm to 422 and 538 nm (solvent: THF), respectively (see Fig. S1, ESI<sup>†</sup>).



Scheme 7 Synthesis, characterization and reactivity studies of Fe(II) porphyrin-cyanocarbene.



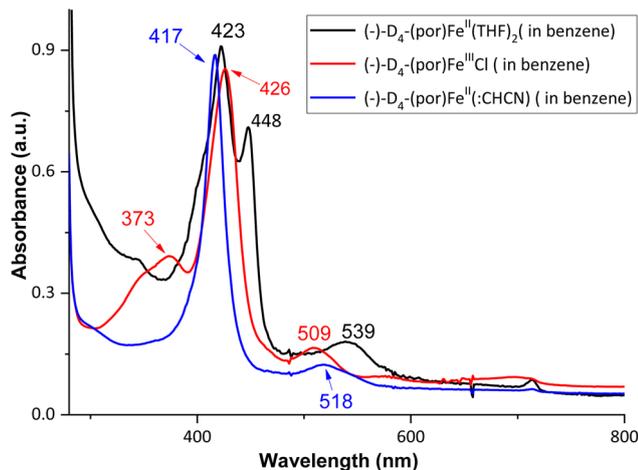


Fig. 4 UV-vis absorption spectrum of  $[(-)-D_4-(por)Fe(THF)_2]$ ,  $[(-)-D_4-(por)FeCl]$  and  $[(-)-D_4-(por)Fe(:CHCN)]$  in benzene- $d_6$ .

The  $^1H$  NMR spectrum (Fig. 5) of  $[(-)-D_4-(por)Fe(:CHCN)]$  in  $C_6D_6$  shows characteristic peaks at  $\delta$  17.8 (s, 1H,  $[ :CHCN ]$ ), 8.77–8.82 ( $d \times 2$ , 8H, splitting *via* desymmetrization of the chiral Fe-carbene species) and 7.30 (s, 4H) ppm, consistent with diamagnetic Fe(II) carbene porphyrins.<sup>81</sup> The  $^1H$  NMR chemical shifts fall into a similar range for typical terminal metal-carbene

porphyrins containing  $[ :CH(CN) ]$  fragment such as  $[Fe(TTP)(-CHY)]$  (Y = mesityl, 19.71 ppm in  $C_6D_6$ ),<sup>82</sup>  $[Ru(TTP)(-CHY)]$  (Y =  $CO_2Et$ , 13.43 ppm in  $C_6D_6$ ),<sup>83</sup>  $[Ru(TMP)(-CHY)]$  (Y =  $CO_2Et$ , 13.79 ppm in  $C_6D_6$ )<sup>84</sup> and  $[Ru(TTPPP)(H_2O)(-CHY)]$  (Y =  $CO_2Et$ , 13.07 ppm in  $CDCl_3$ ).<sup>85</sup> The highly de-shielded protons may originate from multiple bonding features between Fe and  $C_{carbene}$ , bringing the coordinated carbene group closer to the de-shielded zone around Fe porphyrin. The  $[(-)-D_4-(por)Fe(:CHCN)]$  intermediate was also characterized by HR-MS (Fig. 5). The experimental mass value ( $C_{86}H_{77}FeN_5$ , 1235.5517  $m/z$ ) and isotopic pattern of the spectrum match well with the theoretical values (1235.5523  $m/z$ ).

$[(-)-D_4-(por)FeII(:CHCN)]$  was characterized based on the absorbance band of  $\nu(C\equiv N)$  using ATR-FTIR spectroscopy (Fig. 6). The  $\nu(C\equiv N)$  of  $[(-)-D_4-(Por)FeII(:CHCN)]$  is observed at  $2178\text{ cm}^{-1}$ , which is different from the organic species  $NCCH=CHCN$  (*trans*) ( $2235\text{ cm}^{-1}$ ) and  $CH(CN)N_2$  ( $2100\text{ cm}^{-1}$ ). This excludes the possibility that Fe(II) porphyrin is mixed with organic species after treatment with diazoacetonitrile and the possible dimeric byproduct  $NCCH=CHCN$  coordinated with the Fe(II)porphyrin.

Shortly after adding styrene (20 equiv.) to a solution of  $[(-)-D_4-(por)FeII(:CHCN)]$  in  $C_6D_6$  at room temperature, the cyclopropanation product was obtained in 98% yield. This enantioselectivity ( $-82\%$  ee) is in good agreement with the

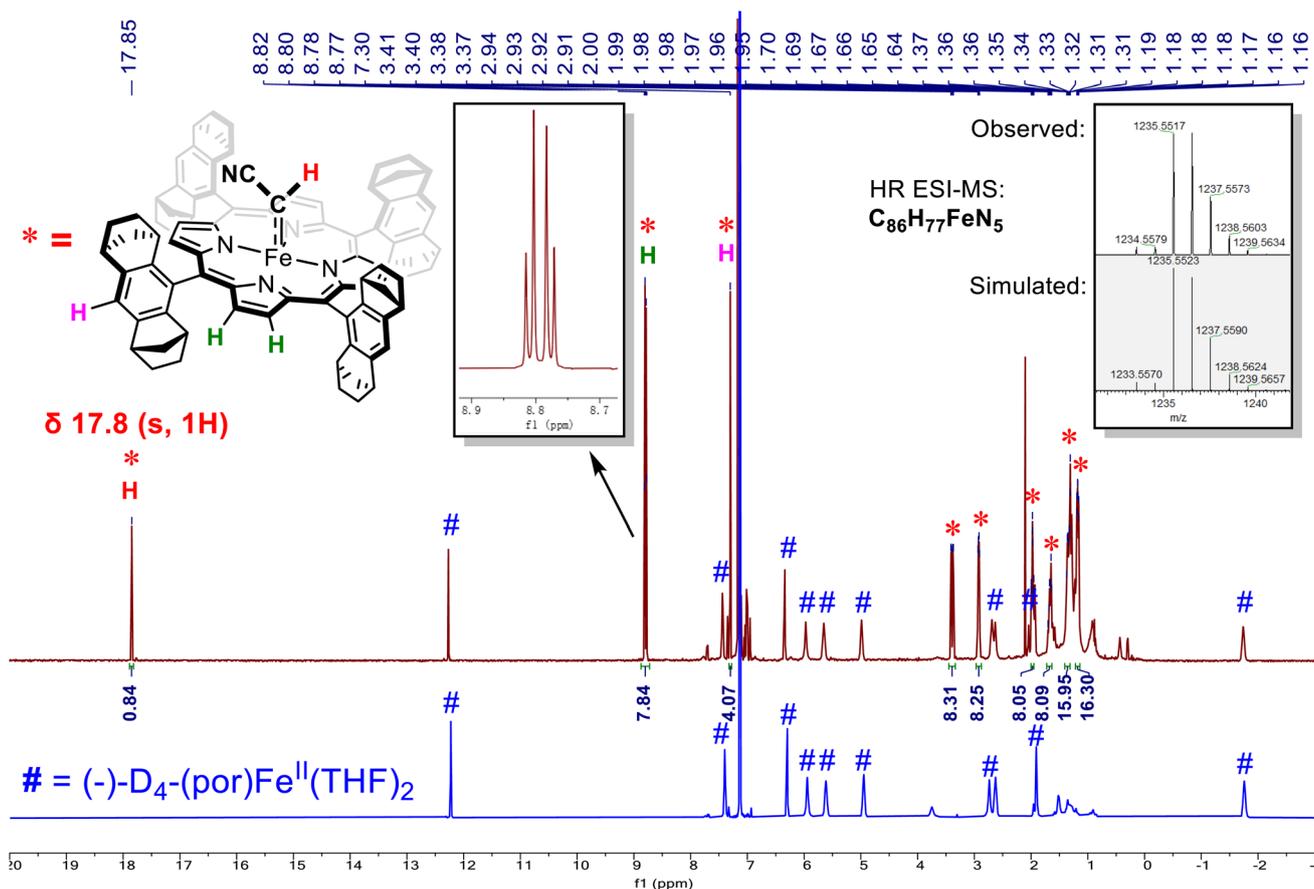


Fig. 5  $^1H$  NMR spectrum of  $[(-)-D_4-(por)FeII(:CHCN)]$  (in benzene- $d_6$ ).

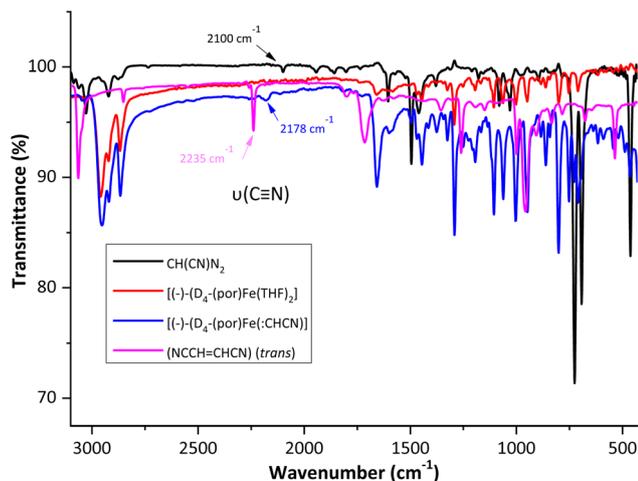


Fig. 6 ATR-FTIR spectroscopy for comparison of  $\nu(\text{C}\equiv\text{N})$ .

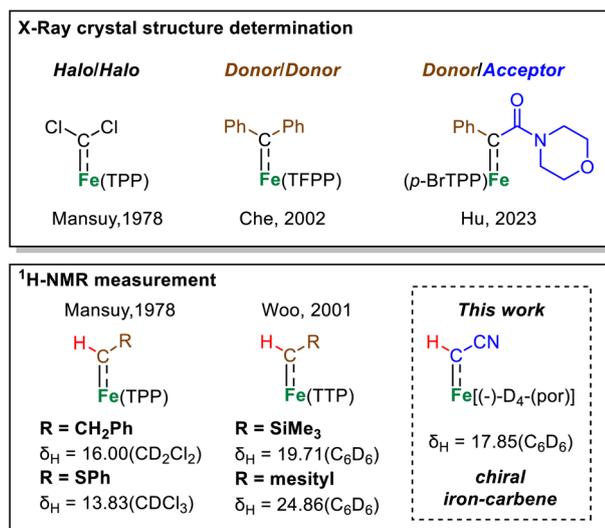
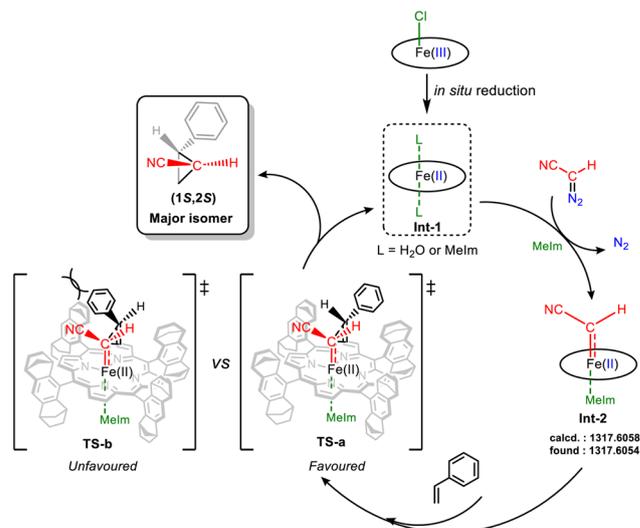


Fig. 7 Fe(porphyrin)–carbene complexes reported in the literature.

value determined under catalytic conditions (84% ee by (+)- $\text{D}_4\text{-}(\text{por})\text{FeCl}$ , Table 1, entry 2), showing that  $[(-)\text{-D}_4\text{-}(\text{por})\text{Fe}^{\text{II}}(\text{:CHCN})]$  is an active reaction intermediate directly involved in the cyclopropanation reaction.

In the literature, Mansuy,<sup>86</sup> Che<sup>15</sup> and Hu<sup>87</sup> reported the crystal structures of some Fe(porphyrin)–monocarbene complexes containing carbene moieties, such as  $[\text{:CCl}_2]$ ,  $[\text{:CPh}_2]$  and  $[\text{:C}(\text{Ph})\text{CO}(\text{morpholine})]$  (Fig. 7). On the other hand, the Fe(porphyrin)–carbene complex containing the  $[\text{CHR}]$  carbene moiety was only characterized by  $^1\text{H-NMR}$ .<sup>82,88,89</sup> In this work, we captured and characterized a highly reactive iron carbene containing a chiral porphyrin ligand and further performed the stoichiometric reaction of this chiral iron carbene intermediate with styrene. The enantioselectivity of the chiral cyclopropanation product was found to be comparable to that obtained under catalytic conditions, indicating that the chiral iron carbene intermediate is directly involved in and responsible for the asymmetric cyclopropanation reaction.



Scheme 8 Plausible mechanism of (+)- $\text{D}_4\text{-}(\text{por})\text{FeCl}$ -catalyzed asymmetric cyclopropanation.

Based on the above experimental results, a plausible mechanism for the asymmetric cyclopropanation of alkenes catalyzed by (+)- $\text{D}_4\text{-}(\text{por})\text{FeCl}$  was proposed (Scheme 8). Under the reaction conditions, (+)- $\text{D}_4\text{-}(\text{por})\text{Fe}(\text{III})\text{Cl}$  is reduced *in situ* to give  $[(+)\text{-D}_4\text{-}(\text{por})\text{Fe}(\text{II})(\text{L})]$  ( $\text{L} = \text{H}_2\text{O}$  or  $\text{MeIm}$ ) (**Int-1**). After further reaction with diazoacetone, the  $\text{Fe}(\text{II})$ –carbene intermediate  $[(+)\text{-D}_4\text{-}(\text{por})\text{Fe}^{\text{II}}(\text{:CHCN})(\text{MeIm})]$  (**Int-2**) was generated and detected by HR ESI-MS (*calcd.*: 1317.6058 *m/z*, *found*: 1317.6054 *m/z*, Fig. S6<sup>†</sup>). The sterically bulky  $\text{D}_4\text{-porphyrin}$  ligand provides a chiral environment, resulting in enantioselectivity of the carbene transfer reaction. Styrene attacks the iron–carbene intermediate in different directions, producing two transition states, one of which is energetically unfavorable (**TS-a** vs. **TS-b**). The favorable conformation (**TS-a**) dominates during the reaction and produces the (1*S*,2*S*)-isomer as the major product.

## Conclusions

In summary, by using chiral iron porphyrin (+)- $\text{D}_4\text{-}(\text{por})\text{FeCl}$  as the catalyst and diazoacetone (generated *in situ*) as the carbene precursor, we have achieved the iron-catalyzed arylalkene cyclopropanation reaction with a broad substrate scope, excellent diastereoselectivity, high enantioselectivity, and good product yield. Reactive chiral Fe–carbene intermediates have been characterized by  $^1\text{H-NMR}$ , HR ESI-MS, UV-vis and ATR-FTIR spectroscopy. The scalable reaction and product TONs up to 35 000 demonstrate the versatility of our approach in preparing key intermediates for the synthesis of bioactive or drug-like molecules using chiral iron porphyrin catalysts.

## Data availability

The data supporting this article have been included as part of the ESI<sup>†</sup>. Crystallographic data have been deposited at the

CCDC under 2349759 (**2g**), 2349760 (**2l**), 2349761 (**2z**), 2349764 (**2aa**), and 2351894 (**2ad**).

## Author contributions

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

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We thank the Southern University of Science and Technology for financial support. This work was supported by the General Research Fund from the Hong Kong Research Grants Council (17315122), the research grant from the Innovation and Technology Commission (HKSAR, China) to the State Key Laboratory of Synthetic Chemistry, and the Laboratory for Synthetic Chemistry and Chemical Biology under the Health@InnoHK Program launched by the Innovation and Technology Commission, Hong Kong, P. R. China.

## References

- 1 T. T. Talele, The "Cyclopropyl Fragment" is a Versatile Player that Frequently Appears in Preclinical/Clinical Drug Molecules, *J. Med. Chem.*, 2016, **59**, 8712–8756.
- 2 Z. Časar, Synthetic Approaches to Contemporary Drugs that Contain the Cyclopropyl Moiety, *Synthesis*, 2020, **52**, 1315–1345.
- 3 C. Ebner and E. M. Carreira, Cyclopropanation Strategies in Recent Total Syntheses, *Chem. Rev.*, 2017, **117**, 11651–11679.
- 4 W. Wu, Z. Lin and H. Jiang, Recent advances in the synthesis of cyclopropanes, *Org. Biomol. Chem.*, 2018, **16**, 7315–7329.
- 5 G. L. Beutner and D. T. George, Opportunities for the Application and Advancement of the Corey–Chaykovsky Cyclopropanation, *Org. Process Res. Dev.*, 2023, **27**, 10–41.
- 6 D. Intrieri, D. M. Carminati and E. Gallo, The ligand influence in stereoselective carbene transfer reactions promoted by chiral metal porphyrin catalysts, *Dalton Trans.*, 2016, **45**, 15746–15761.
- 7 M. J. Weissenborn and R. M. Koenigs, Iron-porphyrin Catalyzed Carbene Transfer Reactions – an Evolution from Biomimetic Catalysis towards Chemistry-inspired Non-natural Reactivities of Enzymes, *ChemCatChem*, 2020, **12**, 2171–2179.
- 8 C. Damiano, P. Sonzini and E. Gallo, Iron catalysts with N-ligands for carbene transfer of diazo reagents, *Chem. Soc. Rev.*, 2020, **49**, 4867–4905.
- 9 V. F. Batista, D. C. G. A. Pinto and A. M. S. Silva, Iron: A Worthy Contender in Metal Carbene Chemistry, *ACS Catal.*, 2020, **10**, 10096–10116.
- 10 P. Kaur and V. Tyagi, Recent Advances in Iron-Catalyzed Chemical and Enzymatic Carbene-Transfer Reactions, *Adv. Synth. Catal.*, 2021, **363**, 877–905.
- 11 S. Rana, J. P. Biswas, S. Paul, A. Paik and D. Maiti, Organic synthesis with the most abundant transition metal-iron: from rust to multitasking catalysts, *Chem. Soc. Rev.*, 2021, **50**, 243–472.
- 12 M. Brookhart and G. O. Nelson, Isolation of stable secondary cationic iron carbene complexes dicarbonyl( $\eta^5$ -cyclopentadienyl)phenylcarbeneiron hexafluorophosphate and carbonyl( $\eta^5$ -cyclopentadienyl)triphenylphosphine(phenylcarbene)iron hexafluorophosphate, *J. Am. Chem. Soc.*, 1977, **99**, 6099–6101.
- 13 P. Helquist, in *Advances in Metal–Organic Chemistry*, ed. L. S. Liebeskind, JAI, 1991, vol. 2, pp. 143–194.
- 14 J. R. Wolf, C. G. Hamaker, J.-P. Djukic, T. Kodadek and L. K. Woo, Shape and stereoselective cyclopropanation of alkenes catalyzed by iron porphyrins, *J. Am. Chem. Soc.*, 1995, **117**, 9194–9199.
- 15 Y. Li, J.-S. Huang, Z.-Y. Zhou, C.-M. Che and X.-Z. You, Remarkably Stable Iron Porphyrins Bearing Nonheteroatom-Stabilized Carbene or (Alkoxy-carbonyl) carbenes: Isolation, X-ray Crystal Structures, and Carbon Atom Transfer Reactions with Hydrocarbons, *J. Am. Chem. Soc.*, 2002, **124**, 13185–13193.
- 16 I. Aviv and Z. Gross, Corrole-based applications, *Chem. Commun.*, 2007, 1987–1999.
- 17 B. Morandi and E. M. Carreira, Iron-Catalyzed Cyclopropanation with Trifluoroethylamine Hydrochloride and Olefins in Aqueous Media: In Situ Generation of Trifluoromethyl Diazomethane, *Angew. Chem., Int. Ed.*, 2010, **49**, 938–941.
- 18 B. Morandi and E. M. Carreira, Iron-Catalyzed Cyclopropanation in 6 M KOH with in Situ Generation of Diazomethane, *Science*, 2012, **335**, 1471–1474.
- 19 Z. Gross, N. Galili and L. Simkhovich, Metalloporphyrin catalyzed asymmetric cyclopropanation of olefins, *Tetrahedron Lett.*, 1999, **40**, 1571–1574.
- 20 G. Du, B. Andrioletti, E. Rose and L. K. Woo, Asymmetric Cyclopropanation of Styrene Catalyzed by Chiral Macrocyclic Iron(II) Complexes, *Organometallics*, 2002, **21**, 4490–4495.
- 21 P. Le Maux, S. Juillard and G. Simonneaux, Asymmetric Synthesis of Trifluoromethylphenyl Cyclopropanes Catalyzed by Chiral Metalloporphyrins, *Synthesis*, 2006, 1701–1704.
- 22 I. Nicolas, T. Roisnel, P. L. Maux and G. Simonneaux, Asymmetric intermolecular cyclopropanation of alkenes by diazoketones catalyzed by Halterman iron porphyrins, *Tetrahedron Lett.*, 2009, **50**, 5149–5151.
- 23 T.-S. Lai, F.-Y. Chan, P.-K. So, D.-L. Ma, K.-Y. Wong and C.-M. Che, Alkene cyclopropanation catalyzed by Halterman iron porphyrin: participation of organic bases as axial ligands, *Dalton Trans.*, 2006, 4845–4851.
- 24 Y. Chen and X. P. Zhang, Asymmetric Cyclopropanation of Styrenes Catalyzed by Metal Complexes of D<sub>2</sub>-Symmetrical



- Chiral Porphyrin: Superiority of Cobalt over Iron, *J. Org. Chem.*, 2007, **72**, 5931–5934.
- 25 W.-C. C. Lee, D.-S. Wang, Y. Zhu and X. P. Zhang, Iron(III)-based metalloradical catalysis for asymmetric cyclopropanation via a stepwise radical mechanism, *Nat. Chem.*, 2023, **15**, 1569–1580.
- 26 D. Intrieri, S. Le Gac, A. Caselli, E. Rose, B. Boitrel and E. Gallo, Highly diastereoselective cyclopropanation of alpha-methylstyrene catalysed by a C<sub>2</sub>-symmetrical chiral iron porphyrin complex, *Chem. Commun.*, 2014, **50**, 1811–1813.
- 27 D. M. Carminati, D. Intrieri, A. Caselli, S. Le Gac, B. Boitrel, L. Toma, L. Legnani and E. Gallo, Designing 'Totem' C<sub>2</sub>-Symmetrical Iron Porphyrin Catalysts for Stereoselective Cyclopropanations, *Chem.–Eur. J.*, 2016, **22**, 13599–13612.
- 28 C.-T. Yeung, K.-C. Sham, W.-S. Lee, W.-T. Wong, W.-Y. Wong and H.-L. Kwong, Cobalt and iron complexes of chiral C<sub>1</sub>- and C<sub>2</sub>-terpyridines: Synthesis, characterization and use in catalytic asymmetric cyclopropanation of styrenes, *Inorg. Chim. Acta*, 2009, **362**, 3267–3273.
- 29 B. Wang, I. G. Howard, J. W. Pope, E. D. Conte and Y. Deng, Bis(imino)pyridine iron complexes for catalytic carbene transfer reactions, *Chem. Sci.*, 2019, **10**, 7958–7963.
- 30 J. J. Shen, S. F. Zhu, Y. Cai, H. Xu, X. L. Xie and Q. L. Zhou, Enantioselective Iron-Catalyzed Intramolecular Cyclopropanation Reactions, *Angew. Chem., Int. Ed.*, 2014, **53**, 13188–13191.
- 31 H. Xu, Y. P. Li, Y. Cai, G. P. Wang, S. F. Zhu and Q. L. Zhou, Highly Enantioselective Copper- and Iron-Catalyzed Intramolecular Cyclopropanation of Indoles, *J. Am. Chem. Soc.*, 2017, **139**, 7697–7700.
- 32 J. G. Gober and E. M. Brustad, Non-natural carbenoid and nitrenoid insertion reactions catalyzed by heme proteins, *Curr. Opin. Chem. Biol.*, 2016, **35**, 124–132.
- 33 O. F. Brandenberg, R. Fasan and F. H. Arnold, Exploiting and engineering hemoproteins for abiological carbene and nitrene transfer reactions, *Curr. Opin. Biotechnol.*, 2017, **47**, 102–111.
- 34 Y. Yang and F. H. Arnold, Navigating the Unnatural Reaction Space: Directed Evolution of Heme Proteins for Selective Carbene and Nitrene Transfer, *Acc. Chem. Res.*, 2021, **54**, 1209–1225.
- 35 R. Fasan and M. G. Siriboe, Engineered Myoglobin Catalysts for Asymmetric Intermolecular Cyclopropanation Reactions, *Bull. Jpn. Soc. Coord. Chem.*, 2022, **80**, 4–13.
- 36 B. Wei, J. C. Sharland, P. Lin, S. M. Wilkerson-Hill, F. A. Fullilove, S. McKinnon, D. G. Blackmond and H. M. L. Davies, In Situ Kinetic Studies of Rh(II)-Catalyzed Asymmetric Cyclopropanation with Low Catalyst Loadings, *ACS Catal.*, 2020, **10**, 1161–1170.
- 37 K.-H. Chan, X. Guan, V. K.-Y. Lo and C.-M. Che, Elevated Catalytic Activity of Ruthenium(II)-Porphyrin-Catalyzed Carbene/Nitrene Transfer and Insertion Reactions with N-Heterocyclic Carbene Ligands, *Angew. Chem., Int. Ed.*, 2014, **53**, 2982–2987.
- 38 H. M. Key, P. Dydio, Z. Liu, J. Y. E. Rha, A. Nazarenko, V. Seyedkazemi, D. S. Clark and J. F. Hartwig, Beyond Iron: Iridium-Containing P450 Enzymes for Selective Cyclopropanations of Structurally Diverse Alkenes, *ACS Cent. Sci.*, 2017, **3**, 302–308.
- 39 M. Bordeaux, V. Tyagi and R. Fasan, Highly Diastereoselective and Enantioselective Olefin Cyclopropanation Using Engineered Myoglobin-Based Catalysts, *Angew. Chem., Int. Ed.*, 2015, **54**, 1744–1748.
- 40 P. S. Coelho, Z. J. Wang, M. E. Ener, S. A. Baril, A. Kannan, F. H. Arnold and E. M. Brustad, A serine-substituted P450 catalyzes highly efficient carbene transfer to olefins in vivo, *Nat. Chem. Biol.*, 2013, **9**, 485–487.
- 41 A. Ford, H. Miel, A. Ring, C. N. Slattery, A. R. Maguire and M. A. McKerver, Modern Organic Synthesis with alpha-Diazocarbonyl Compounds, *Chem. Rev.*, 2015, **115**, 9981–10080.
- 42 V. K. Aggarwal, J. de Vicente and R. V. Bonnert, Catalytic Cyclopropanation of Alkenes Using Diazo Compounds Generated in Situ. A Novel Route to 2-Arylcyclopropylamines, *Org. Lett.*, 2001, **3**, 2785–2788.
- 43 Q. Xiao, Y. Zhang and J. Wang, Diazo Compounds and N-Tosylhydrazones: Novel Cross-Coupling Partners in Transition-Metal-Catalyzed Reactions, *Acc. Chem. Res.*, 2013, **46**, 236–247.
- 44 P. K. Mykhailiuk, New Life for Diazoacetone nitrile (N<sub>2</sub>CHCN): in situ Generation and Practical Synthesis of CN-Pyrazoles, *Eur. J. Org. Chem.*, 2015, **2015**, 7235–7239.
- 45 Y. Ferrand, P. Le Maux and G. Simonneaux, Macroporous chiral ruthenium porphyrin polymers: a new solid-phase material used as a device for catalytic asymmetric carbene transfer, *Tetrahedron: Asymmetry*, 2005, **16**, 3829–3836.
- 46 C. Empel, K. J. Hock and R. M. Koenigs, Dealkylative intercepted rearrangement reactions of sulfur ylides, *Chem. Commun.*, 2019, **55**, 338–341.
- 47 K. J. Hock, A. Knorrscheidt, R. Hommelsheim, J. Ho, M. J. Weissenborn and R. M. Koenigs, Tryptamine Synthesis by Iron Porphyrin Catalyzed C–H Functionalization of Indoles with Diazoacetone nitrile, *Angew. Chem., Int. Ed.*, 2019, **58**, 3630–3634.
- 48 K. J. Hock, R. Spitzner and R. M. Koenigs, Towards nitrile-substituted cyclopropanes – a slow-release protocol for safe and scalable applications of diazo acetone nitrile, *Green Chem.*, 2017, **19**, 2118–2122.
- 49 A. L. Chandgude and R. Fasan, Highly Diastereo- and Enantioselective Synthesis of Nitrile-Substituted Cyclopropanes by Myoglobin-Mediated Carbene Transfer Catalysis, *Angew. Chem., Int. Ed.*, 2018, **57**, 15852–15856.
- 50 P. K. Mykhailiuk and R. M. Koenigs, Diazoacetone nitrile (N<sub>2</sub>CHCN): A Long Forgotten but Valuable Reagent for Organic Synthesis, *Chem.–Eur. J.*, 2020, **26**, 89–101.
- 51 V. K.-Y. Lo, K.-P. Shing and C.-M. Che, in *Advances in Organometallic Chemistry*, ed. P. J. Pérez, Academic Press, 2023, vol. 79, pp. 195–259.
- 52 H.-H. Wang, H. Shao, G. Huang, J. Fan, W.-P. To, L. Dang, Y. Liu and C.-M. Che, Chiral Iron Porphyrins Catalyze Enantioselective Intramolecular C(sp<sup>3</sup>)–H Bond Amination Upon Visible-Light Irradiation, *Angew. Chem., Int. Ed.*, 2023, **62**, e202218577.



- 53 B. Springthorpe, A. Bailey, P. Barton, T. N. Birkinshaw, R. V. Bonnert, R. C. Brown, D. Chapman, J. Dixon, S. D. Guile, R. G. Humphries, S. F. Hunt, F. Ince, A. H. Ingall, I. P. Kirk, P. D. Leeson, P. Leff, R. J. Lewis, B. P. Martin, D. F. McGinnity, M. P. Mortimore, S. W. Paine, G. Pairaudeau, A. Patel, A. J. Rigby, R. J. Riley, B. J. Teobald, W. Tomlinson, P. J. H. Webborn and P. A. Willis, From ATP to AZD6140: The discovery of an orally active reversible P2Y<sub>12</sub> receptor antagonist for the prevention of thrombosis, *Bioorg. Med. Chem. Lett.*, 2007, **17**, 6013–6018.
- 54 M.-J. Huang, J.-W. Guo, Y.-D. Fu, Y.-Z. You, W.-Y. Xu, T.-Y. Song, R. Li, Z.-T. Chen, L.-H. Huang and H.-M. Liu, Discovery of new tranlycypromine derivatives as highly potent LSD1 inhibitors, *Bioorg. Med. Chem. Lett.*, 2021, **41**, 127993.
- 55 Y. Ota and T. Suzuki, Drug Design Concepts for LSD1-Selective Inhibitors, *Chem. Rec.*, 2018, **18**, 1782–1791.
- 56 S. Ahmad, L. M. Doweyko, S. Dugar, N. Grazier, K. Ngu, S. C. Wu, K. J. Yost, B.-C. Chen, J. Z. Gougoutas, J. D. DiMarco, S.-J. Lan, B. J. Gavin, A. Y. Chen, C. R. Dorso, R. Serafino, M. Kirby and K. S. Atwal, Arylcyclopropanecarboxyl Guanidines as Novel, Potent, and Selective Inhibitors of the Sodium Hydrogen Exchanger Isoform-1, *J. Med. Chem.*, 2001, **44**, 3302–3310.
- 57 S. Dhillon and M. Clarke, Tasimelteon: First Global Approval, *Drugs*, 2014, **74**, 505–511.
- 58 S. Mi, X. Sun, C. Wu and X. Zhang, A Facile and Practical Synthesis of (–)-tasimelteon, *J. Chem. Res.*, 2016, **40**, 667–669.
- 59 X.-A. Li, L. Yue, J. Zhu, H. Ren, H. Zhang, D.-y. Hu, G. Han, J. Feng and Z.-d. Nan, Total synthesis of Tasimelteon, *Tetrahedron Lett.*, 2019, **60**, 1986–1988.
- 60 P. Bajaj, G. Sreenilayam, V. Tyagi and R. Fasan, Gram-Scale Synthesis of Chiral Cyclopropane-Containing Drugs and Drug Precursors with Engineered Myoglobin Catalysts Featuring Complementary Stereoselectivity, *Angew. Chem., Int. Ed.*, 2016, **55**, 16110–16114.
- 61 A. K. Singh, M. N. Rao, J. H. Simpson, W.-S. Li, J. E. Thornton, D. E. Kuehner and D. J. Kacsur, Development of a Practical, Safe, and High-Yielding Process for the Preparation of Enantiomerically Pure trans-Cyclopropane Carboxylic Acid, *Org. Process Res. Dev.*, 2002, **6**, 618–620.
- 62 W. Wang, X. Meng, J. Zhu and X. Zhang, An efficient and practical asymmetric synthesis of (–)-tasimelteon, *Synth. Commun.*, 2019, **49**, 129–135.
- 63 J. Weinstock, Notes- A Modified Curtius Reaction, *J. Org. Chem.*, 1961, **26**, 3511.
- 64 R. Csuk, M. J. Schabel and Y. v. Scholz, Synthesis of the enantiomer of the antidepressant tranlycypromine, *Tetrahedron: Asymmetry*, 1996, **7**, 3505–3512.
- 65 M. Pannala, S. Kher, N. Wilson, J. Gaudette, I. Sircar, S.-H. Zhang, A. Bakhirev, G. Yang, P. Yuen, F. Goresan, N. Sakurai, M. Barbosa and J.-F. Cheng, Synthesis and structure–activity relationship of 4-(2-aryl-cyclopropylamino)-quinoline-3-carbonitriles as EGFR tyrosine kinase inhibitors, *Bioorg. Med. Chem. Lett.*, 2007, **17**, 5978–5982.
- 66 R. Yu, S. Z. Cai, C. Li and X. Fang, Nickel-Catalyzed Asymmetric Hydroaryloxy- and Hydroalkoxycarbonylation of Cyclopropenes, *Angew. Chem., Int. Ed.*, 2022, **61**, e202200733.
- 67 J. R. Burgeson, D. N. Gharaibeh, A. L. Moore, R. A. Larson, S. M. Amberg, T. C. Bolken, D. E. Hrubby and D. Dai, Lead optimization of an acylhydrazone scaffold possessing antiviral activity against Lassa virus, *Bioorg. Med. Chem. Lett.*, 2013, **23**, 5840–5843.
- 68 J. A. Lewis, S. A. Scott, R. Lavieri, J. R. Buck, P. E. Selvy, S. L. Stoops, M. D. Armstrong, H. A. Brown and C. W. Lindsley, Design and synthesis of isoform-selective phospholipase D (PLD) inhibitors. Part I: Impact of alternative halogenated privileged structures for PLD1 specificity, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 1916–1920.
- 69 B. Portevin, A. Benoist, G. Rémond, Y. Hervé, M. Vincent, J. Lepagnol and G. De Nanteuil, New Prolyl Endopeptidase Inhibitors: In Vitro and in Vivo Activities of Azabicyclo [2.2.2]octane, Azabicyclo[2.2.1]heptane, and Perhydroindole Derivatives, *J. Med. Chem.*, 1996, **39**, 2379–2391.
- 70 H. Wang, X. Zhou and Y. Mao, Asymmetric Synthesis of Cyclopropylamine Derivatives, *Heterocycles*, 2014, **89**, 1767–1800.
- 71 J. Vallgård and U. Hacksell, Stereoselective palladium-catalyzed cyclopropanation of  $\alpha,\beta$ -unsaturated carboxylic acids derivatized with oppolzer's sultam, *Tetrahedron Lett.*, 1991, **32**, 5625–5628.
- 72 S. Miyamura, K. Itami and J. Yamaguchi, Syntheses of Biologically Active 2-Arylcyclopropylamines, *Synthesis*, 2017, **49**, 1131–1149.
- 73 X.-J. Dai, Y. Liu, X.-P. Xiong, L.-P. Xue, Y.-C. Zheng and H.-M. Liu, Tranlycypromine Based Lysine-Specific Demethylase 1 Inhibitor: Summary and Perspective, *J. Med. Chem.*, 2020, **63**, 14197–14215.
- 74 M. D. Morin, Y. Wang, B. T. Jones, Y. Mifune, L. Su, H. Shi, E. M. Y. Moresco, H. Zhang, B. Beutler and D. L. Boger, Diprovocims: A New and Exceptionally Potent Class of Toll-like Receptor Agonists, *J. Am. Chem. Soc.*, 2018, **140**, 14440–14454.
- 75 R. Neelamegam, E. L. Ricq, M. Malvaez, D. Patnaik, S. Norton, S. M. Carlin, I. T. Hill, M. A. Wood, S. J. Haggarty and J. M. Hooker, Brain-Penetrant LSD1 Inhibitors Can Block Memory Consolidation, *ACS Chem. Neurosci.*, 2012, **3**, 120–128.
- 76 T. Maes, C. Mascaró, D. Rotllant, M. M. P. Lufino, A. Estiarte, N. Guibourt, F. Cavalcanti, C. Griñan-Ferré, M. Pallàs, R. Nadal, A. Armario, I. Ferrer, A. Ortega, N. Valls, M. Fyfe, M. Martinell, J. C. Castro Palomino and C. Buesa Arjol, Modulation of KDM1A with vafidemstat rescues memory deficit and behavioral alterations, *PLoS One*, 2020, **15**, e0233468.
- 77 Y.-C. Zheng, B. Yu, Z.-S. Chen, Y. Liu and H.-M. Liu, TCPs: privileged scaffolds for identifying potent LSD1 inhibitors for cancer therapy, *Epigenomics*, 2016, **8**, 651–666.



- 78 T.-Y. Tsai, T. Hsu, C.-T. Chen, J.-H. Cheng, T.-K. Yeh, X. Chen, C.-Y. Huang, C.-N. Chang, K.-C. Yeh, S.-H. Hsieh, C.-H. Chien, Y.-W. Chang, C.-H. Huang, Y.-W. Huang, C.-L. Huang, S.-H. Wu, M.-H. Wang, C.-T. Lu, Y.-S. Chao and W.-T. Jiaang, Novel trans-2-aryl-cyclopropylamine analogues as potent and selective dipeptidyl peptidase IV inhibitors, *Bioorg. Med. Chem.*, 2009, **17**, 2388–2399.
- 79 T. R. Porter and J. M. Mayer, Radical reactivity of the Fe(III)/(II) tetramesitylporphyrin couple: hydrogen atom transfer, oxyl radical dissociation, and catalytic disproportionation of a hydroxylamine, *Chem. Sci.*, 2014, **5**, 372–380.
- 80 Y. Wei, A. Tinoco, V. Steck, R. Fasan and Y. Zhang, Cyclopropanations via Heme Carbenes: Basic Mechanism and Effects of Carbene Substituent, Protein Axial Ligand, and Porphyrin Substitution, *J. Am. Chem. Soc.*, 2018, **140**, 1649–1662.
- 81 H. X. Wang, Q. Wan, K. H. Low, C. Y. Zhou, J. S. Huang, J. L. Zhang and C. M. Che, Stable group 8 metal porphyrin mono- and bis(dialkylcarbene) complexes: synthesis, characterization, and catalytic activity, *Chem. Sci.*, 2020, **11**, 2243–2259.
- 82 C. G. Hamaker, G. A. Mirafzal and L. K. Woo, Catalytic Cyclopropanation with Iron(II) Complexes, *Organometallics*, 2001, **20**, 5171–5176.
- 83 J. P. Collman, P. J. Brothers, L. McElwee-White, E. Rose and L. J. Wright, Cleavage of ruthenium and osmium porphyrin dimers: formation of organometallic ruthenium porphyrin complexes and highly reduced metalloporphyrin species, *J. Am. Chem. Soc.*, 1985, **107**, 4570–4571.
- 84 J. P. Collman, E. Rose and G. D. Venburg, Reactivity of ruthenium 5,10,15,20-tetramesitylporphyrin towards diazoesters: formation of olefins, *J. Chem. Soc., Chem. Commun.*, 1993, 934–935.
- 85 Q. H. Deng, J. Chen, J. S. Huang, S. S. Y. Chui, N. Zhu, G. Y. Li and C. M. Che, Trapping Reactive Metal–Carbene Complexes by a Bis-Pocket Porphyrin: X-ray Crystal Structures of Ru=CHCO<sub>2</sub>Et and trans-[Ru(CHR)(CO)] Species and Highly Selective Carbenoid Transfer Reactions, *Chem.–Eur. J.*, 2009, **15**, 10707–10712.
- 86 D. Mansuy, M. Lange, J. C. Chottard, J. F. Bartoli, B. Chevrier and R. Weiss, Dichlorocarbene Complexes of Iron(II)-Porphyrins—Crystal and Molecular Structure of Fe(TPP)(CCl<sub>2</sub>)(H<sub>2</sub>O), *Angew. Chem., Int. Ed.*, 1978, **17**, 781–782.
- 87 C. Ma, S. Wang, Y. Sheng, X.-L. Zhao, D. Xing and W. Hu, Synthesis and Characterization of Donor–Acceptor Iron Porphyrin Carbenes and Their Reactivities in N–H Insertion and Related Three-Component Reaction, *J. Am. Chem. Soc.*, 2023, **145**, 4934–4939.
- 88 J. P. Battioni, J. C. Chottard and D. Mansuy, A new route to thiocarbonyliron complexes: preparation of Fe<sup>II</sup>[porphyrin][C(Cl)SR] carbene complexes and their conversion into Fe<sup>II</sup>[porphyrin][CS] complexes, *Inorg. Chem.*, 1982, **21**, 2056–2062.
- 89 I. Artaud, N. Gregoire, P. Leduc and D. Mansuy, Formation and fate of iron–carbene complexes in reactions between a diazoalkane and iron-porphyrins: relevance to the mechanism of formation of N-substituted hemes in cytochrome P-450-dependent oxidation of sydnonones, *J. Am. Chem. Soc.*, 1990, **112**, 6899–6905.

