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## A modular approach to prepare enantioenriched cyclobutanes: synthesis of (+)-rumphellaone A<sup>†</sup>

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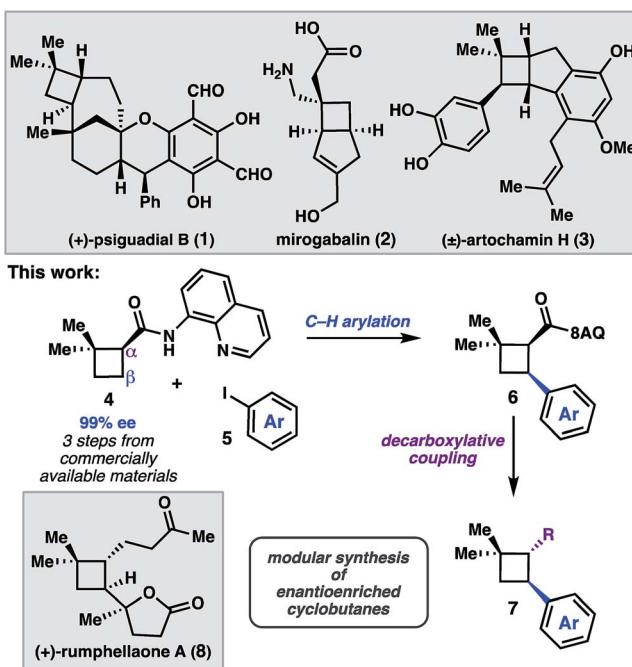
A modular synthesis of enantioenriched polyfunctionalized cyclobutanes was developed that features an 8-aminoquinolinamide directed C–H arylation reaction. The C–H arylation products were derivatized through subsequent decarboxylative coupling processes. This synthetic strategy enabled a 9-step enantioselective total synthesis of the antiproliferative meroterpenoid (+)-rumphellaone A.

## Introduction

The cyclobutane structural motif is present in a variety of natural products and pharmaceutical molecules (Scheme 1).<sup>1,2</sup>

Cyclobutanes are also versatile synthetic intermediates, as the ring strain inherent to these structures engenders them with unique reactivity that can be leveraged in a variety of transformations to build complex frameworks.<sup>3</sup> [2 + 2] cycloaddition reactions represent the most extensively developed approach to construct cyclobutanes, and recent advances have given rise to elegant enantioselective reactions.<sup>4</sup> An alternative strategy is to prepare a versatile cyclobutane building block, and then use C–H functionalization or cross-coupling chemistry to elaborate the scaffold in a modular fashion.<sup>5</sup> In this latter approach, a single enantioenriched intermediate can quickly be converted to a variety of more functionalized structures.

We recently reported a synthesis of the natural product (+)-psiguadial B (1), which featured a tandem Wolff–rearrangement/asymmetric ketene addition to prepare enantioenriched 8-aminoquinolinamide 4 (Scheme 1).<sup>6</sup> Given the short synthesis of 4 from commercially available starting materials, we became interested in further applications of this chiral building block. Specifically, we envisioned that directed C–H arylation could enable diversification at the  $\beta$ -position,<sup>7</sup> while hydrolysis of the 8-aminoquinolinamide followed by decarboxylative radical cross-coupling could enable diversification at the  $\alpha$ -position. A number of powerful methods have been developed that leverage the decarboxylative formation of carbon-centered radicals for C–C and C–X bond formation.<sup>8</sup> It was anticipated that the sequence of C–H arylation followed by decarboxylative coupling could provide access to a collection of enantioenriched polyfunctionalized cyclobutanes.



Scheme 1 A C–H functionalization strategy to access (+)-rumphellaone A.

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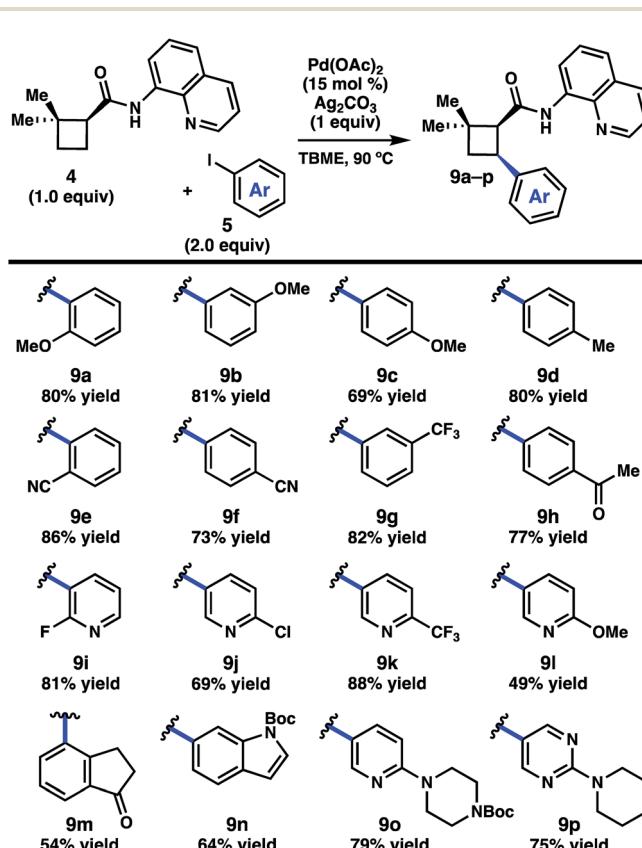
‡ These authors contributed equally to this work.

## Results and discussion

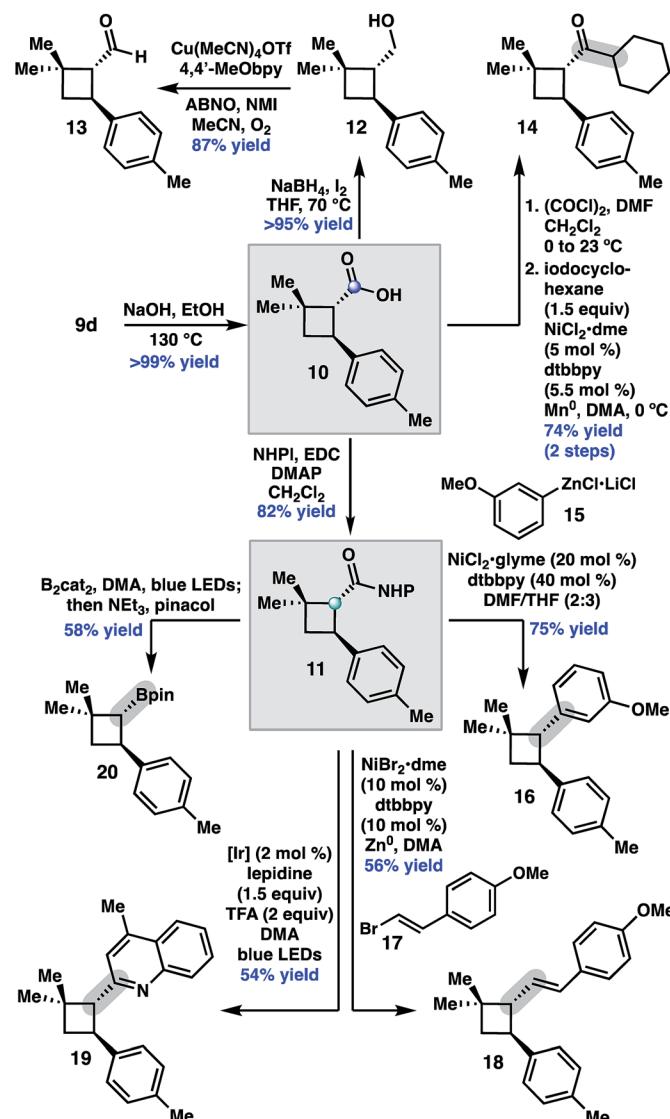
We began by investigating the scope of the directed C–H arylation of 8-aminoquinolinamide 4, which was prepared in three steps and 99% ee from commercially available 2,2-dimethylcyclopentan-1-one.<sup>6</sup> Using our previously developed conditions [ $\text{Pd}(\text{OAc})_2$  (15 mol%),  $\text{Ag}_2\text{CO}_3$  (1.0 equiv.), aryl iodide (2.0 equiv.), TBME, 90 °C], a series of *cis*-arylated cyclobutanes were

prepared in good yields (Scheme 2).<sup>9</sup> The reaction was compatible with both electron-rich and electron-deficient aryl iodides and tolerated substitution at the *ortho*, *meta*, and *para* positions. Heteroaryl iodides were also found to be competent coupling partners, allowing for incorporation of pyridines, pyrimidines, and indoles. Unfortunately, with 5-iodo-2-phenylpyridine or 5-iodo-2-methoxypyrimidine, the reaction proceeded in only modest yields (<40%). Aryl triflates failed to react under the optimized reaction conditions.

Having established the generality of the C–H arylation step, we turned our attention to diversification at the carbon bearing the 8-aminoquinolinamide through functional group interconversion or decarboxylative cross-coupling. To this end, hydrolysis of **9d** proceeded with epimerization to the thermodynamically favored *trans* diastereomer, delivering *trans*-cyclobutanoic acid **10** (Scheme 3).<sup>10</sup> Reduction of the acid delivered alcohol **12**, which could be oxidized under Stahl conditions to aldehyde **13**.<sup>11</sup> Alternatively, **10** could be converted to the corresponding acid chloride and engaged in a nickel-catalyzed reductive cross-coupling with iodocyclohexane to access ketone **14**.<sup>12</sup> In order to investigate decarboxylative coupling processes, acid **10** was subjected to EDC-mediated coupling with *N*-hydroxyphthalimide to provide NHP ester **11**.<sup>13</sup> Ni-catalyzed coupling of **11** with arylzinc chloride **15** gave



**Scheme 2** Scope of the C–H arylation of **4**. Reactions were conducted on 0.20 mmol scale in a sealed 2-dram vial using  $\text{Pd}(\text{OAc})_2$  (15 mol%),  $\text{Ag}_2\text{CO}_3$  (1.0 equiv.), **5a–p** (2.0 equiv.),  $[\text{4}] = 0.2 \text{ M}$  in TBME. TBME = *tert*-butyl methyl ether.



**Scheme 3** Selected derivatizations of **10**. ABNO = 9-azabicyclo[3.3.1]nonane *N*-oxyl. NMI = *N*-methylimidazole. NHPI = *N*-hydroxyphthalimide. EDC = 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide. DMAP = 4-dimethylaminopyridine. TFA = trifluoroacetic acid. dtbbpy = di-*tert*-butylbipyridine. dme = dimethoxyethane. 4,4'-MeObpy = 4,4'-dimethoxybipyridine.  $[\text{Ir}]$  =  $\text{Ir}[\text{dF}(\text{CF}_3)\text{ppyl}]_2(\text{dtbbpy})\text{PF}_6$ .

*trans*-diaryl cyclobutane **16** in good yield as a single diastereomer.<sup>8d</sup> Similarly, NHP ester **11** underwent Ni-catalyzed reductive alkenylation with styrenyl bromide **17** to furnish cyclobutane **18** in 56% yield.<sup>8c,e</sup> Photoinduced decarboxylative borylation of **11** proceeded smoothly to afford boronic ester **20**,<sup>8h</sup> and decarboxylative Minisci type arylation of **11** under photoredox catalysis delivered quinoline **19**.<sup>8i</sup>

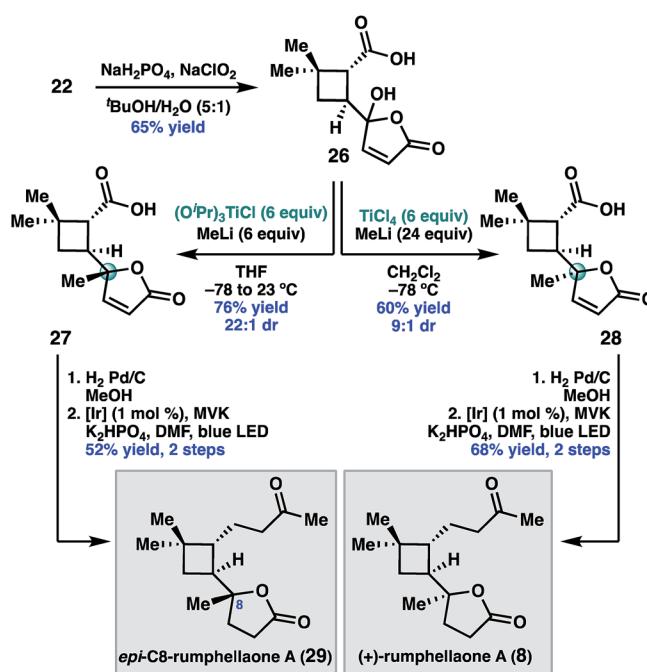
To further demonstrate the utility of this cyclobutane difunctionalization strategy, we designed and executed a synthesis of the natural product (+)-rumphellaone A (**8**).<sup>14</sup> (+)-Rumphellaone A (**8**) was isolated in 2010 from the gorgonian coral *Rumphella antipathies* and possesses anti-proliferative activity against human T-cell acute lymphoblastic leukemia tumor cells.<sup>2d</sup> Retrosynthetically, we envisioned disconnecting



through the C1–C2 bond to give **21** (Scheme 4); in the forward sense, the ketone fragment would be incorporated through a decarboxylative Giese addition with methyl vinyl ketone. The butenolide of **21** could derive from oxidation of furan **22**, which could be prepared from **4** by a directed C–H arylation. As a proof of concept, 8-aminoquinolinamide **4** was subjected to Pd-catalyzed C–H functionalization with furanyl iodide **23** to give *cis*-cyclobutane **24** in 90% yield.<sup>15</sup> Hydrolysis and subsequent decarboxylative Giese reaction with methyl vinyl ketone under photoredox catalysis provided **25** in 50% yield over two steps.<sup>16</sup>

Having validated the feasibility of the two key cyclobutane functionalization reactions, attention turned to the unmasking of the butenolide functionality prior to the decarboxylative Giese reaction. Treatment of **22** with sodium chlorite under buffered conditions<sup>17</sup> delivered 5-hydroxybutenolide **26** (Scheme 5). The remaining challenge was installation of the C8 methyl substituent with the required *S*-configuration. In prior syntheses of **8**, this stereogenic center was set under the guidance of chiral catalyst control.<sup>14</sup> Given that the C8 diastereomers were inseparable by column chromatography, high diastereoselectivity for this methyl addition was important.

After exploring a range of conditions to effect the methylation, we were pleased to discover that either C8 diastereomer (**27** or **28**) could be prepared using the appropriate methyltitanium reagent. Thus, addition of **26** to a pre-formed 1 : 1 mixture of  $(^{\text{t}}\text{PrO})_3\text{TiCl}$  and  $\text{MeLi}$  at  $-78\text{ }^{\circ}\text{C}$ , with warming to  $23\text{ }^{\circ}\text{C}$ , delivered the undesired C8 diastereomer, **27**, in 76% yield and 22 : 1 dr.<sup>18</sup> Alternatively, addition of **26** to a  $-78\text{ }^{\circ}\text{C}$  solution of  $\text{Ti}(\text{Me})_4$  in dichloromethane,<sup>19</sup> which was prepared *in situ* by combining  $\text{MeLi}$  and  $\text{TiCl}_4$  in a 4 : 1 ratio, provided the desired diastereomer **28** in 60% yield and 9 : 1 dr. We hypothesize that the divergent diastereoselectivity for these two reactions resulted from the different methylating reagents,  $(^{\text{t}}\text{PrO})_3\text{TiMe}$  or  $\text{Ti}(\text{Me})_4$ ,



Scheme 5 Synthesis of (+)-rumphellaone A (8).

prepared *in situ*. One possible explanation is that **27** formed by ligand exchange of the carboxylic acid of **26** with  $(^{\text{t}}\text{PrO})_3\text{TiMe}$  followed by intramolecular delivery of the methyl nucleophile, while **28** resulted from addition of  $\text{Ti}(\text{Me})_4$  without the assistance of chelation.

To complete the synthesis, **28** was reduced under standard hydrogenation conditions. Decarboxylative Giese addition of **28** to methyl vinyl ketone under photoredox catalysis provided (+)-rumphellaone A (8) in good yield, completing the synthesis in 9 steps from commercially available material. Epimeric acid **27** could be analogously elaborated to (+)-*epi*-C8-rumphellaone A (29).

## Conclusions

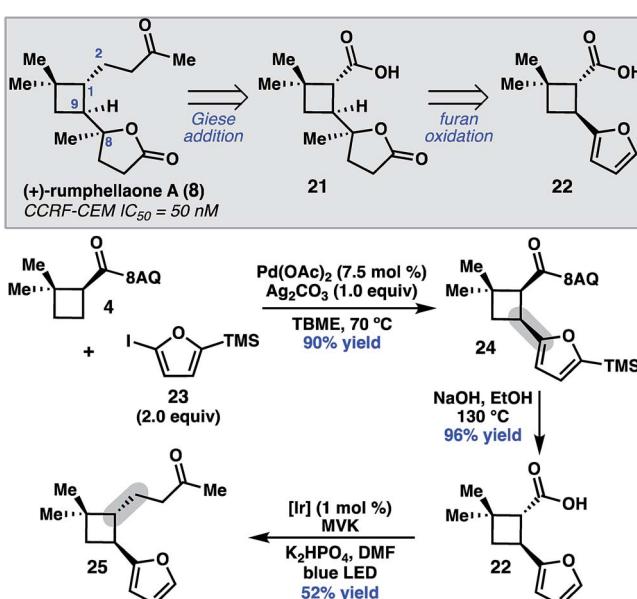
Through a strategy for difunctionalization, we have demonstrated that 8-aminoquinolinamide **4** can serve as a valuable building block for the synthesis of enantioenriched cyclobutanes. We further illustrated this concept in a 9-step synthesis of (+)-rumphellaone A (8). We anticipate that this general strategy could enable the expedient synthesis of additional natural products and other bioactive molecules.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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Scheme 4 Retrosynthetic analysis of **8** and key proof-of-concept study. TMS = trimethylsilyl. MVK = methyl vinylketone.



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