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## Synthesis of lactone-fused pyrroles by ruthenium-catalyzed 1,2-carbon migration-cycloisomerization†

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A ruthenium-catalyzed cycloisomerization of 3-amino-4-alkynyl-2H-chromen-2-ones *via* 1,2-carbon migration was developed. Various 1-arylchromeno[3,4-*b*]pyrrol-4(3*H*)-ones were synthesized in good to excellent yields. The reaction was applied to the formal total synthesis of marine natural products Ningalin B and Lamellarin H. The efficient synthesis of  $\gamma$ -butyrolactone-fused pyrrole derivatives was also achieved.

### Introduction

1-Arylchromeno[3,4-*b*]pyrrol-4(3*H*)-one skeleton is found in natural products such as Ningalin B, Lamellarin H, and related compounds (Fig. 1).<sup>1</sup> These alkaloids are isolated from marine organisms and known to exhibit biological activities<sup>1</sup> such as cytotoxicity,<sup>2</sup> MDR reversal activity,<sup>2</sup> HIV-1 integrase inhibition,<sup>3</sup> and antitumor activity.<sup>4</sup> Due to their promising pharmacological potentials, these pyrrole-containing natural products have been synthesized by various strategies over the years.<sup>1,5</sup>

Recent examples for the synthesis of the chromeno[3,4-*b*]pyrrol-4(3*H*)-one skeleton include palladium-catalyzed cycloisomerization,<sup>6</sup> one-pot multistep synthesis from 4-chloro-3-nitrocoumarin,<sup>7</sup> the functionalization of 2,3-diarylpyrrole,<sup>8</sup> the cyclization of 3-nitrocoumarin and papaverine,<sup>9</sup> and so on. Among these synthetic methods, the palladium-catalyzed cycloisomerization of 3-amino-4-alkynyl-2*H*-chromen-2-ones is a straightforward and powerful method (Scheme 1a).<sup>6</sup> The reaction proceeds *via* intramolecular nucleophilic amination of the  $\pi$ -activated alkyne, and 2-substituted chromeno[3,4-*b*]pyrrol-4(3*H*)-ones were isolated.

We have recently developed ruthenium-catalyzed cycloisomerization reactions that involve the vinylidene rearrangement of internal alkynes by 1,2-carbon migration and cyclization.<sup>10–13</sup> For example, in the presence of a cationic ruthenium catalyst, various 2-alkynylanilides were converted into the 3-substituted indoles in high yields (Scheme 1b).<sup>11</sup> The mode of the reaction is different from other metal-catalyzed cycloisomerization of 2-alkynylanilines, where no 1,2-carbon migration was involved, and 2-substituted indoles were isolated.<sup>14</sup> In that study, we reported one example that 1-phenylchromeno[3,4-*b*]pyrrol-4(3*H*)-one can be synthesized by

applying the reaction. Considering the importance of the chromeno[3,4-*b*]pyrrol-4(3*H*)-one skeleton in medicinal chemistry and recent active studies related to the synthesis of Ningalin and Lamellarin derivatives, the development of a new and general method for the synthesis of chromeno[3,4-*b*]pyrrol-4(3*H*)-one derivatives would be highly desirable. In this paper, we report a ruthenium-catalyzed cycloisomerization of 3-amino-4-alkynyl-2*H*-chromen-2-ones that leads to various 1-arylchromeno[3,4-*b*]pyrrol-4(3*H*)-ones *via* 1,2-carbon migration (Scheme 1c). This new methodology enabled the formal total synthesis of Ningalin B and Lamellarin H. Moreover, we describe the synthesis of rare  $\gamma$ -lactone-fused pyrrole derivatives by a similar ruthenium-catalyzed 1,2-carbon migration/cyclization strategy.

### Results and discussion

We investigated the scope and limitation of the reaction using various 3-amino-4-alkynyl-2*H*-chromen-2-one derivatives (1, Table 1). As previously reported, when a mixture of

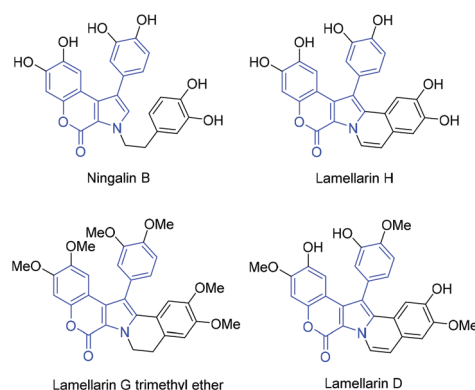
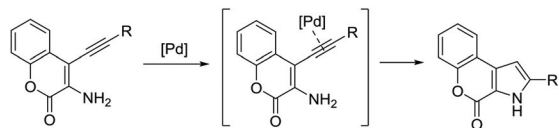


Fig. 1 Representative natural products and analogue containing 1-arylchromeno[3,4-*b*]pyrrol-4(3*H*)-one skeleton.

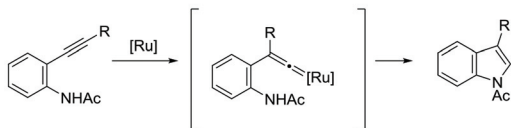
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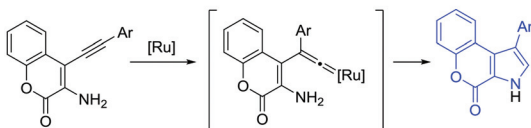


(a) Cycloisomerization via  $\pi$ -activation (non-migration)

## (b) Synthesis of indoles by ruthenium-catalyzed cycloisomerization via 1,2-carbon migration



## (c) This work: Synthesis of 1-arylchromeno[3,4-b]pyrrol-4(3H)-one via 1,2-carbon migration



**Scheme 1** Cycloisomerization of 3-amino-4-alkynyl-2H-chromen-2-ones.

aminocoumarin **1a**, [CpRuCl(dppe)] (Cp =  $\eta^5$ -C<sub>5</sub>H<sub>5</sub><sup>-</sup>; dppe = Ph<sub>2</sub>PCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>) (5 mol%), and NaBAR<sup>F</sup><sub>4</sub>·3H<sub>2</sub>O (Ar<sup>F</sup> = 3,5-(CF<sub>3</sub>)<sub>2</sub>C<sub>6</sub>H<sub>3</sub>) (6 mol%) was stirred at 145 °C for 2.5 h in chlorobenzene, the desired 1,2-aryl migration product 3-phenylpyrrolocoumarin (**2a**) was formed in 95% yield.<sup>10,15</sup> Isomeric 2-substituted pyrrole was not observed in the reaction mixture. Although the reaction of **1a** at 130 °C completed in 16 h at the same catalyst loading, the yield of **2a** was lower (82%). [IndRuCl(dppe)] (Ind =  $\eta^5$ -C<sub>9</sub>H<sub>7</sub><sup>-</sup>) and [CpFeCl(dppe)] were inactive catalysts for this reaction, and **2a** was not formed.

We studied the impact of the aryl groups bound to the ethynyl group (R<sup>1</sup>) on the reaction. Under the similar reaction conditions described above, 4-methoxyphenyl pyrrole **2b** was obtained in 98% yield with lower catalyst loading. Electron-withdrawing groups were tolerated for this reaction, and pyrrolocoumarins **2c** (92% yield) and **2d** (96% yield) were synthesized in the presence of 10 mol% [CpRuCl(dppe)]. The low reactivity of the alkynes with electron-withdrawing groups (**1c** and **1d**) compared to the substrate with electron-donating group (**1b**) was consistent with our previous studies on the ruthenium-catalyzed cycloisomerizations *via* 1,2-carbon migration<sup>10,11</sup> and probably attributed to the rates of the formation of the disubstituted ruthenium vinylidene complex.<sup>16</sup> Pyrrolocoumarin **2e** with 3,4-dimethoxyphenyl group was also formed from **1e** in 81% yield. When the reaction of sterically congested aminocoumarin **1f** bearing 1-naphthyl group at the alkyne terminus was examined in the presence of 5 mol% of the ruthenium catalyst, the progress of the reaction was sluggish. In the presence of an increased amount (25 mol%) of [CpRuCl(dppe)], however, the corresponding product **2f** was isolated in 89% yield. The compatibility of the substrates with heteroaryl groups was also evaluated, and 5-indolyl derivative **2g** (96% yield) and thiophen-3-yl derivative **2h** (90% yield) were synthesized cleanly.

**Table 1** Scope of the ruthenium-catalyzed 1,2-carbon migration/cyclization of 3-amino-4-ethynyl-2H-chromen-2-one derivatives (**1**)<sup>a,b</sup>

Starting material <b>1a-l</b>	Reaction conditions	Product <b>2a-l</b>	Yield (%)	Catalyst loading	Time
<b>1a</b>	CpRuCl(dppe) (x mol%), NaBAR <sup>F</sup> <sub>4</sub> ·3H <sub>2</sub> O (1.2x mol%), PhCl, 145 °C	<b>2a</b>	95%	5 mol%	2.5 h
<b>1b</b>		<b>2b</b>	98%	1 mol%	3 h
<b>1c</b>		<b>2c</b>	92%	10 mol%	4 h
<b>1d</b>		<b>2d</b>	96%	10 mol%	4 h
<b>1e</b>		<b>2e</b>	81%	10 mol%	3 h
<b>1f</b>		<b>2f</b>	89%	25 mol%	15 h
<b>1g</b>		<b>2g</b>	96%	5 mol%	1 h
<b>1h</b>		<b>2h</b>	90%	5 mol%	5 h
<b>1i</b>		<b>2i</b>	89%	5 mol%	2 h
<b>1j</b>		<b>1j</b>	no reaction	5 mol%	3 h
<b>1k</b>		<b>2k</b>	92%	5 mol%	4 h
<b>1l</b>		<b>2l</b>	97%	5 mol%	1 h

<sup>a</sup> Reaction conditions: **1** (0.25–0.5 mmol), [**1**]<sup>0</sup> = 0.025–0.2 M in chlorobenzene, [CpRuCl(dppe)] (1–10 mol%), NaBAR<sup>F</sup><sub>4</sub>·3H<sub>2</sub>O (1.2–12 mol%).

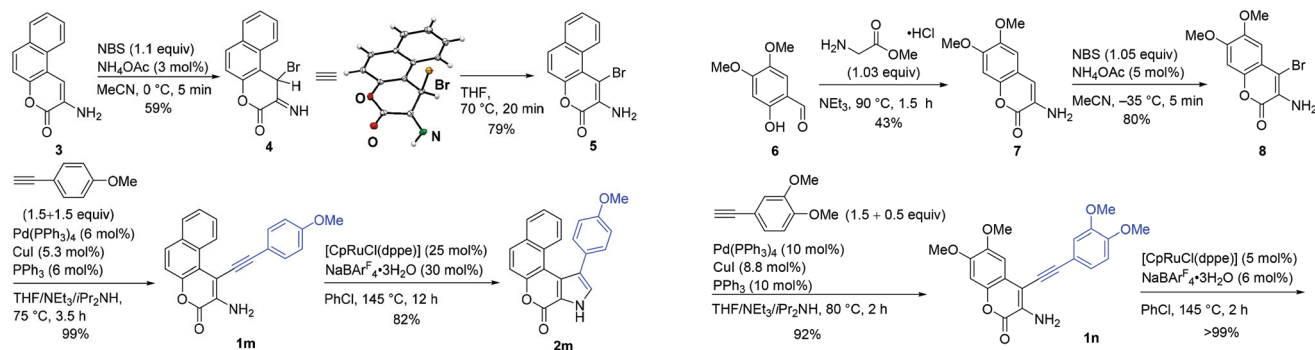
<sup>b</sup> Isolated yields are shown in parentheses except for **1j**.

The scope of the reaction was further studied by introducing non-aromatic substituents as R<sup>1</sup>. The reactivity of benzoyl aminocoumarin **1i** was similar to that of aryl-substituted aminocoumarins, and the corresponding pyrrole **2i** was prepared in 89% yield. The reaction of **1j** (R<sup>1</sup> = Bu) did not proceed, and the starting material was recovered. The low reactivity of **1j** is in contrast to our previous result: the cycloisomerization of a 2-hexynylaniline derivative generated the corresponding 3-butylindole derivative.<sup>10</sup> The reaction of **1j** in the presence of [CpRuCl(dppbz)] (dppbz = 1,2-bis(diphenylphosphino)benzene), which is a more effective catalyst for the synthesis of alkylated indoles,<sup>10,17</sup> also afforded no desired product. We assume that the decreased rate for the alkyne-to-vinylidene rearrangement of electron-deficient and alkyl-substituted acetylene<sup>16,18</sup> could be the reason for this unsuccessful result.

The effect of the substituents introduced to R<sup>2</sup> and R<sup>3</sup> on the coumarin moiety was explored. A methoxypyrrolocoumarin (**2k**, R<sup>2</sup> = OMe, R<sup>3</sup> = H) as well as a fluoropyrrolocoumarin (**2l**, R<sup>2</sup> = H, R<sup>3</sup> = F) were synthesized in high yields.

We further extended our study to the synthesis of a benzofused pyrrolocoumarin derivative.<sup>19</sup> The synthesis and ruthenium-catalyzed cycloisomerization of a benzochromeone derivative **1m** was summarized in Scheme 2. When we



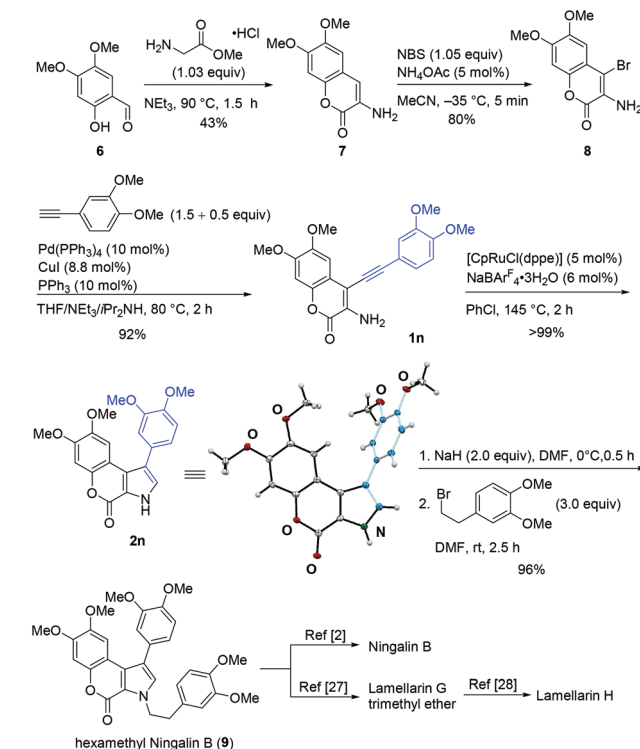


Scheme 2 Preparation of 1m and the synthesis of 2m.

tried to synthesize 5 by the bromination of 3<sup>20</sup> with NBS in the presence of a catalytic amount of NH<sub>4</sub>OAc at 0 °C,<sup>21</sup> an unexpected product 4 was isolated in 59% yield. Since the corresponding bromide was not isolated in the reaction of the bicyclic 3-amino-2*H*-chromen-2-one under similar reaction conditions,<sup>21</sup> we assume that the presence of the C–H bond in the proximity of the bromine atom inhibited the isomerization reaction of 4 at 0 °C. Due to the steric hindrance, the rate of the conversion of 4 to 5 should be lower compared to those of other aminocoumarins. The isomerization of 4 smoothly proceeded at elevated temperature (70 °C), and compound 5 was isolated in 79% yield. Subsequently, 1m was synthesized in 99% yield by Sonogashira reaction of 5 with 4-methoxyphenylacetylene under modified Stoddart's conditions.<sup>22</sup> The reactivity of 1m was similar to that of sterically congested substrate 1f: the desired product 2m was isolated in 82% yield when a larger amount (25 mol%) of the catalyst was employed.

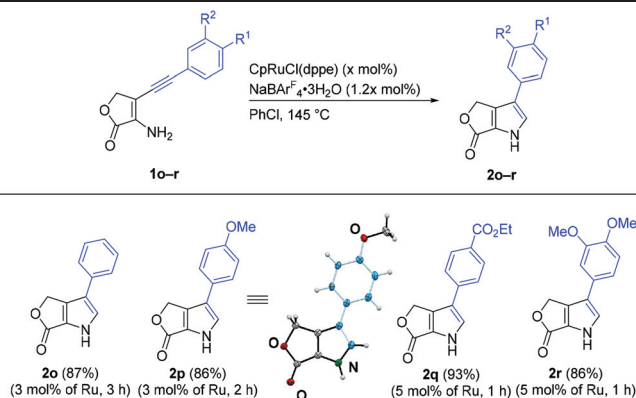
Next, we applied this reaction to the formal total synthesis of Ningalin B and Lamellarin H (Scheme 3). When 6<sup>23,24</sup> was treated with methyl aminoacetate hydrochloride,<sup>25</sup> aminocoumarin 7 was obtained in 43% yield. The bromination of 7 proceeded at –35 °C to afford 8 in 80% yield. No α-bromoimine, which was similar to 4, was isolated. Compound 1n was synthesized in 92% yield by Sonogashira reaction. To our delight, 2n was obtained in quantitative yield in the presence of 5 mol% of the ruthenium catalyst. The structure of 2n was confirmed by an X-ray diffraction analysis.<sup>26</sup> With the key intermediate (2n) in hand, hexamethyl Ningalin B (9) was synthesized in 96% yield by alkylation of 2n.<sup>7</sup> The demethylation of 9 to Ningalin B was reported by Boger and co-workers.<sup>2</sup> Compound 9 is also the intermediate of Lamellarins, and the conversion of 9 into Lamellarin G trimethyl ether<sup>27</sup> and subsequent transformation to Lamellarin H were reported.<sup>28</sup> Therefore, we achieved the formal total synthesis of natural products, Ningalin B and Lamellarin H.

Furthermore, we examined the synthesis of γ-butyrolactone-fused pyrroles to exemplify the application of this reaction (Table 2). In spite of the simplicity of the structure, only a couple of γ-butyrolactone-fused pyrroles has been reported in the literature,<sup>29,30</sup> and a general method for the synthesis of these compounds has not been established. We successfully



Scheme 3 Synthesis of the key intermediate 2n for the synthesis of bioactive compounds.

Table 2 Synthesis of γ-butyrolactone-fused pyrrole derivatives<sup>a,b</sup>



<sup>a</sup> Reaction conditions: 1 (0.25–0.4 mmol), [1]<sup>0</sup> = 0.1–0.2 M in chlorobenzene), [CpRuCl(dppe)] (3–5 mol%), NaBARF<sub>4</sub>·3H<sub>2</sub>O (3.6–6.0 mol%).  
<sup>b</sup> Isolated yields are shown in parentheses.

synthesized a series of γ-butyrolactone-fused pyrroles by the ruthenium-catalyzed cycloisomerization of 3-amino-4-arylethynylfuranones. Under the established reaction conditions described for the reaction of 3-amino-4-alkynyl-2*H*-chromen-2-one, the desired γ-butyrolactone-fused pyrroles 2o and 2p were isolated in 87% and 86% yields, respectively. The molecular structure of 2p was confirmed by a single-crystal X-ray diffraction analysis. The reaction of aminobutenolide 1q with an



ethoxycarbonyl group also afford the corresponding pyrrole **2q** in high yield. The reaction of **1r** with 3,4-dimethoxyphenyl group proceeded cleanly, and **2r** was obtained in 86% yield.

## Conclusions

We have developed a synthetic method for various 1-arylchromeno[3,4-*b*]pyrrol-4(3*H*)-ones by ruthenium-catalyzed cycloisomerization of 3-amino-4-ethynyl-2*H*-chromen-2-ones via 1,2-carbon migration. The formal total synthesis of Ningalin B and Lamellarin H was achieved by employing this reaction. Moreover, a general method for the synthesis of uncommon  $\gamma$ -butyrolactone-fused pyrroles was established. Our studies will contribute to the development of a new method for the synthesis of heavily substituted pyrrole derivatives.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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- It has been reported that the rate of the 1,2-carbon migration decreases in the reaction of an electron-deficient aromatic alkyne or an aliphatic alkyne. See, ref. 13*d* and *f*.
- The importance of dppbz ligand is unclear at this stage.



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