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Synthesis of tetracyclic spiroindolines by an interrupted Bischler–Napieralski reaction: total synthesis of akuammicine†

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Judicious substrate design allows interruption of the classical Bischler–Napieralski reaction, providing access to a range of diversely substituted tetracyclic spiroindolines. These complex polycyclic scaffolds are valuable building blocks for the construction of indole alkaloids, as showcased in a concise total synthesis of (±)-akuammicine.

Cascade reactions allow the rapid generation of molecular complexity through multiple sequential bond-forming (and bond-breaking) events in a one-pot process. These exceptional advantages over traditional stepwise procedures make them particularly suited to efficiently access complex molecules such as natural products.¹ Consequently, the use of cascade reactions in total synthesis is a well-established and prolific field that is constantly expanding in both methodology and scope, covering polyketides,² alkaloids,³ terpenes,⁴ and steroids.⁵ Owing to their abundance, structural variety, and diverse biological activities, indole alkaloids occupy a prominent position among natural products (Fig. 1).⁶ As a result, they have attracted considerable interest from the synthetic community, leading to numerous novel approaches to this compound class in recent years.⁷

Synthetic approaches toward β -carboline alkaloids (such as harmicine (1), Fig. 1) continue to rely on the classical Pictet–Spengler and Bischler–Napieralski reactions and their variations. Discovered as early as 1893, the Bischler–Napieralski reaction⁸ (together with its contemporary variations) is still an object of intensive study in natural product synthesis.⁹

Following our interest in indole alkaloids and related compounds,¹⁰ we recently discovered that reaction of styrylaceta-mides **4** under typical Bischler–Napieralski conditions (POCl_3 , MeCN, Δ) leads to near-quantitative formation of carbazoles **5**

instead of the expected dihydro- β -carbolines (Scheme 1A).¹¹ Our ensuing mechanistic investigation revealed a highly complex cascade pathway (Scheme 2) which proceeds *via* several intriguing intermediates.¹¹ In particular, the tetracyclic spiroindoline **10** caught our interest, owing to its wide-spread presence in indole alkaloids.⁷ⁱ Unfortunately, our efforts to isolate **10** ($\text{R}^1 = \text{H}$) were futile, frustrated by an elimination step (Scheme 2A) that always follows. Indeed, we only succeeded in diverting the cascade towards a different carbazole product if $\text{R}_3 = \text{Br}$ (**6**, Scheme 1A). This strongly suggests that

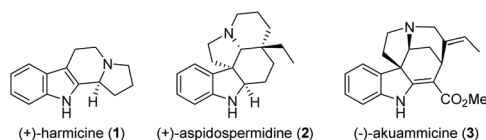
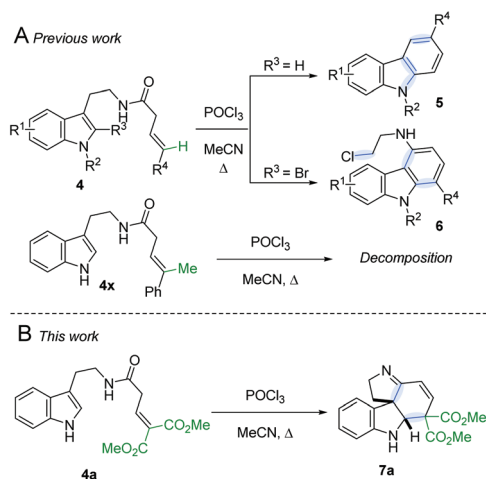


Fig. 1 Representative indole alkaloids.



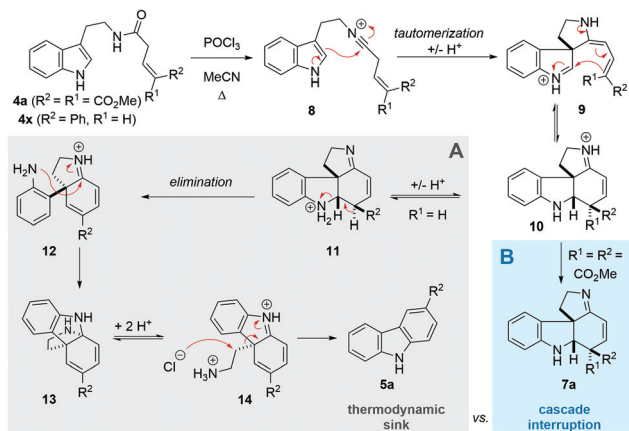
Scheme 1 A. Previously reported carbazole formation B. Cascade interrupted at the tetracyclic intermediate.

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Scheme 2 Previous cascade mechanism towards carbazoles (A) and interruption at the tetracyclic intermediate (B).

interrupting the cascade at the stage of tetracyclic scaffold **10** is challenging due to the high thermodynamic driving force for the system to evolve towards aromatic products. Moreover, the intermediate **10** could revert back to **9** by retro-Mannich reaction and subsequently undergo Plancher rearrangement, irreversibly leading to β-carbolines.¹²

A potentially viable strategy to achieve the desired interruption would be to employ a γ,γ-disubstituted vinylacetamide as the substrate, as the elimination cannot occur in this case. Since the introduction of a methyl group at this position only led to decomposition (Scheme 1A), and given our success in employing ester R⁴ substituents,¹¹ we identified malonate-derived tryptamide **4a** as a promising substrate. To our delight, upon subjecting **4a** to the cyclization conditions (Scheme 1B), we were able to isolate imine **7a** in 27% yield after basic workup. Optimization of the conditions (Table 1) showed that only POCl₃ is able to promote the reaction (entries 1–5). Conveniently, we could avoid the strictly anhydrous conditions required for (both reactions and storage of) the highly reactive Tf₂O that is often employed for related transformations.^{9a–d}

Small adjustments of POCl₃ stoichiometry and reaction time (entries 6–10) allowed us to increase the isolated yield of **7a** to 58%. The reaction proceeded with nearly identical efficiency on a 1.5 g scale.

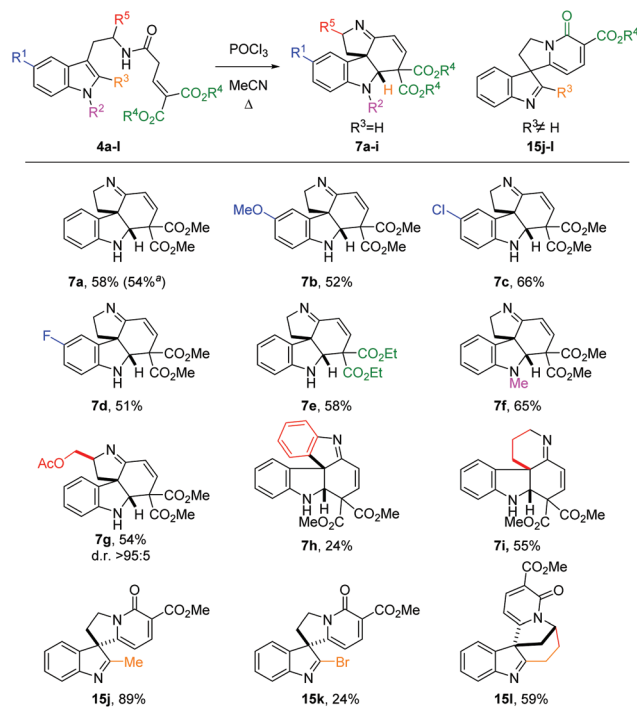
We then focused on the generality of the process, subjecting differently substituted amide precursors to the optimized conditions (Scheme 3). Substituents on the benzenoid ring do not significantly affect the reactivity: reaction of the 5-F- and 5-MeO-substituted tryptamides afforded the corresponding tetracyclic scaffolds **7b** and **7d** in nearly identical yield (51–52%). The best result was obtained using the Cl-substituted amide **4c**, producing the tetracyclic product **7c** in 66% yield. Ethyl esters are also well tolerated, affording the desired product **7e** in the same yield as the benchmark product **7a**. The introduction of an N1-substituent on the indole ring proved to be beneficial, possibly because of the more reactive iminium ion intermediate (*cf.* **9**, Scheme 2) favoring the cycli-

Table 1 Reaction optimization

Reaction scheme showing the conversion of substrate **4a** to product **7a** using POCl₃ in MeCN at reflux.

| Entry ^a | Reagent | Solvent | T (°C) | Yield ^b (%) |
|--------------------|---------------------------|-------------------|--------|------------------------|
| 1 | POCl ₃ | MeCN | Reflux | 27 ^c |
| 2 | Tf ₂ O/2-Cl-Py | MeCN | Reflux | — |
| 3 | Tf ₂ O/3-CN-Py | MeCN | Reflux | — |
| 4 | Ac ₂ O | MeCN | Reflux | — |
| 5 | TFAA | MeCN | Reflux | — |
| 6 | POCl ₃ | Toluene | 90 | 16 |
| 7 ^d | POCl ₃ | MeCN | Reflux | 20 |
| 8 ^e | POCl ₃ | MeCN | Reflux | 18 |
| 9 ^f | POCl ₃ | MeCN | Reflux | 37 |
| 10 ^g | POCl ₃ | MeCN | Reflux | 58 ^c |
| 11 ^h | POCl ₃ | MeCN | Reflux | 48 |
| 12 ^g | POCl ₃ | MeCN ⁱ | Reflux | 58 ^c |

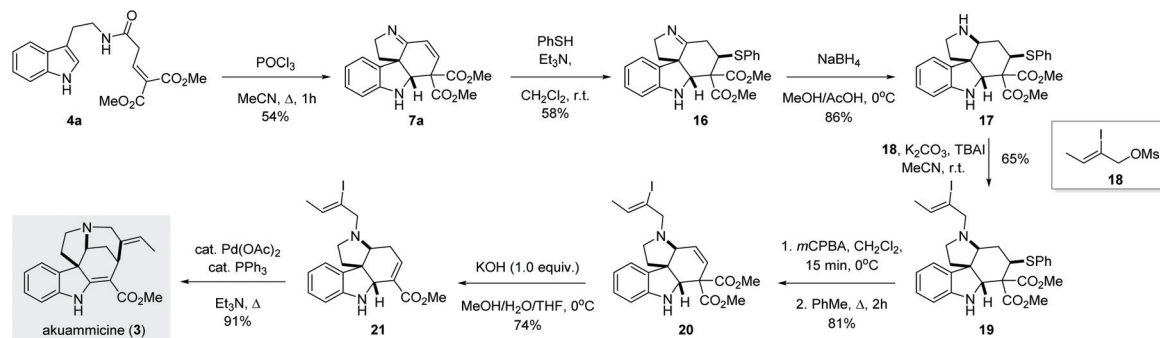
^a Reaction conditions **4a** (0.2 mmol), reagent (0.3 mmol) solvent (1 mL). ^b Determined by ¹H NMR using 2,5-dimethylfuran as an internal standard. ^c Isolated yield. ^d Performed with 0.4 mmol of POCl₃. ^e Performed with 0.5 mmol of POCl₃. ^f Additional POCl₃ (0.1 mmol) added after 30 min (1 h total reaction time). ^g Additional POCl₃ (0.1 mmol) added after 30 min and 1 h (1.5 h total reaction time). ^h Additional POCl₃ (0.1 mmol) added after 30 min, 1 h and 1.5 h (2 h total reaction time). ⁱ Non-anhydrous MeCN was used.



Scheme 3 Scope of the cyclization. Reaction conditions: **4** (0.2 mmol), POCl₃ (0.3 mmol), MeCN (1.0 mL), 1.5 h, reflux. Additional portions of POCl₃ (0.1 mmol) were added after 30 min and 1 h. ^aReaction performed on 4.49 mmol scale.

zation step. Substituents on the R⁵ position are also tolerated: amide **4g**, derived from tryptophanol, was converted to **7g** in good yield (54%) as a single diastereomer. Replacing the ethyl-





Scheme 4 Total synthesis of (±)-akuammicine.

ene linker with an *ortho*-phenylene linker also furnished the desired spiro product **7h**, albeit in lower yield (24%). Gratifyingly, the homotryptamine derivative **4i** was smoothly converted to the corresponding tetracycle **7i** in 55% yield. Interestingly, when substituents are present on the C2 position, a different type of product was observed (**15j–l**). Indeed, when $R^3 \neq H$, the C2-position of the indole becomes too hindered to undergo ring closure. In this case, enamine **9** can only undergo cycloaromatization (after *E/Z* isomerization) by attack on one of the two ester moieties to give the corresponding 2-pyridones **15**. Curiously, when $R^3 = Me$, we observed the highest yield (**15j**, 89%), possibly owing to the higher stability of the product. On the other hand, the bromide-substituted product **15k** was obtained in lower yield. This is hardly surprising, considering the typical lability of imidoyl bromides. Similarly, the intriguing, but rather strained polycycle **15l** was isolated in 59% yield. Indeed, for both **15k** and **15l** decomposition was already observed during purification, accounting for the lower yields.

Once we established the scope and limitation of this transformation, we set out to investigate the utility of these valuable intermediates in the total synthesis of indole alkaloids. Notably, we envisioned the transformation of **7a** to akuammicine (Scheme 4). Unfortunately, **7a** proved recalcitrant towards selective 1,2-reduction under various conditions ($NaBH_4$, $LiBH_4$, $NaBH_3CN$, $NaHB(OAc)_3$, or Et_3SiH , both in the presence and absence of acidic promoters). Presumably, the conjugated imine is too rigid and/or sterically congested to undergo efficient 1,2-reduction. To circumvent this issue, we first performed a conjugate addition with thiophenol to give imine **16**, which could then be smoothly reduced by treatment with $NaBH_4$ to give the desired amine **17** in 86% yield. Subsequent alkylation with **18** afforded the tertiary amine **19**. In order to reinstall the double bond, the thioether was first oxidized and then eliminated in a two-step procedure, producing the olefin **20** in 81% yield. Subsequently, the use of KOH (1.0 equiv.) in a $MeOH/THF/H_2O$ mixture at $0^\circ C$ afforded **21** via one-pot saponification, decarboxylation and double bond migration.¹³ Finally, known intermediate **21** was converted to (±)-akuammicine (**3**) by intramolecular Heck reaction as reported previously.¹⁴

In conclusion, we report an alternative, interrupted variation of our previously serendipitously discovered diverted Bischler–Napieralski cascade reaction. The reaction generates complex polycyclic scaffolds in a single step and is compatible with a wide range of substituents, allowing straightforward access to highly functionalized and versatile intermediates. Moreover, tetracyclic indoline **7a** could be converted in only six steps to akuammicine, constituting a very short and efficient total synthesis of this Strychnos-type alkaloid. The scope and variability of the interrupted Bischler–Napieralski cyclization likely allow access to various other natural products as well.

Conflicts of interest

The authors declare no competing financial interest.

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