FACILE TWO-STEP SYNTHESIS OF ISOQUINOLONES FROM BENZOIC ACIDS AND ALKYNES AND THEIR COMPARATIVE PHOTOLUMINESCENT STUDY *VS* ISOCOUMARINS§

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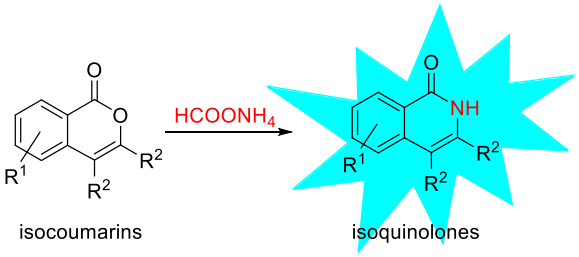
Abstract

An efficient two-step protocol for the synthesis of isoquinolones (isoquinolin-1(2*H*)-ones) has been developed based on the C–H annulation of benzoic acids with alkynes followed by the treatment of the isocoumarins formed with ammonium formate. This approach was applied for the synthesis of naturally occurring isoquinolone siaminine A. A comparative study of the optical properties revealed that isoquinolones display stronger luminescence emission than isocoumarins.



Key words: isocoumarins, isoquinolones, isoquinolinones, luminescence.

Introduction

Isocoumarins and isoquinolones are closely related heterocyclic compounds bearing either O- or NH-moiety at the carbonyl group. They are important scaffolds of various natural compounds, including alkaloids, as well as metabolites of bacteria and fungi [1–5]. In the last decade, isocoumarins have attracted much attention as building blocks for the construction of photoactive materials [6–8]. In particular, we showed that 7,8-diphenyl-10*H*-phenaleno[1,9-*gh*]isochromen-10-one can be used as an emissive layer in organic light-emitting diodes [9]. At the same time, the photophysical properties of closely related isoquinolones are less studied (for the rare examples of their application as photoinitiators or fluorescence sensors for fluoride ion, see Refs. [10–12]). More often isoquinolones are used as precursors in the synthesis of isoquinoline luminophores [13, 14].

Herein, we report a facile synthesis of a series of closely related isocoumarins and isoquinolones (including natural compound siaminine A [15, 16]), as well as the results of a comparative study of their photophysical behavior.

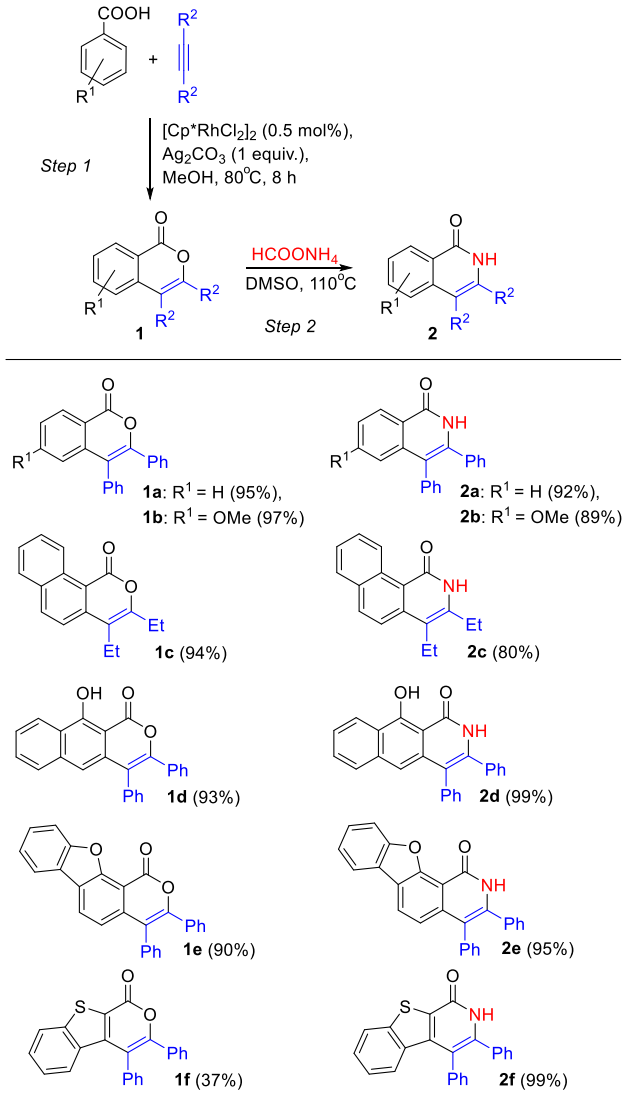
Results and discussion

C–H annulations of aromatic compounds with alkynes catalyzed by cyclopentadienyl rhodium complexes have proved to be one of the most efficient synthetic methods for heterocyclic compounds in terms of step- and atom-economy [17–19]. In particular, this approach affords isocoumarins in one step from readily available benzoic acids [20–22]. At the same time, the related direct synthesis of the isoquinolone derivatives requires the use of less available *N*-substituted benzamides [23] or aryl hydroxamates [24–26], the pre-synthesis of which involves additional steps. Therefore, the synthesis of isoquinolones through the replacement of an oxygen atom in isocoumarins with a nitrogen one seems to be more feasible. Ammonia and primary amines are usually used as a source of nitrogen in this reaction [27–29]. To avoid easy removal of a volatile ammonia gas from the reaction mixture, ammonium acetate or formamide are used [30–32]. In the present study, we showed for the first time that ammonium formate can also be used for the synthesis of isoquinolones from isocoumarins. Thus, we developed an efficient two-step protocol for the synthesis of isoquinolones starting from benzoic acids (Scheme 1). For the first step, the classical catalyst $[Cp^*RhCl_2]_2$ was applied at 0.5 mol % loading along with Ag_2CO_3 (1 equiv.) used as an oxidant in boiling methanol. These conditions have already shown high efficiency when working with tetrahydrofluorenyl and triphenylcyclopentadienyl rhodium complexes [33, 34]. We found that substituted benzoic acids as well as their π-conjugated derivatives (such as naphthoic and dibenzo[*b*,*d*]furan-4-carboxylic acids) are suitable for the reaction and give target isocoumarins **1a**–**e** in excellent yields (90–97%). Only benzo[*b*]thiophene-2-carboxylic acid gave isocoumarin **1f** in a moderate yield (37%), which can be attributed to the poisoning of the catalyst with the sulfur moiety. All obtained isocoumarins **1a**–**f** were smoothly converted into the corresponding isoquinolones **2a**–**f** by treating with ammonium formate in dimethyl sulfoxide at 110 °C. The structure of isoquinolone **2e** was confirmed by single-crystal X-ray diffraction study (Fig. 1).

The suggested approach allowed for the synthesis of the naturally occurring isoquinolone siaminine A (Scheme 2), previously isolated from the tropical tree *Senna siamea* [15]. At the last step, dimethoxyisoquinolone **2g** was demethylated by treating with boron tribromide at room temperature [35], giving desired siaminine A. The overall yield for three steps starting from 2,4-dimethoxybenzoic acid and dimethylacetylene was 68%.

To further emphasize the versatility of this protocol, we also

performed a simple modification of the naturally occurring isocoumarin oospalactone **1h** to isoquinolone derivative **2h** (Scheme 3).



Scheme 1. Substrate scope for the synthesis of isocoumarins and isoquinolones.

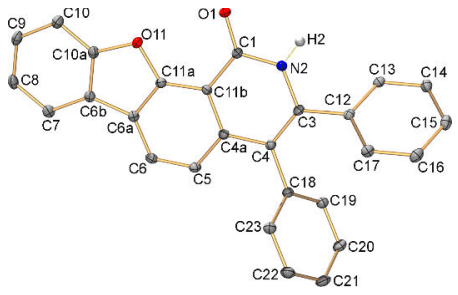
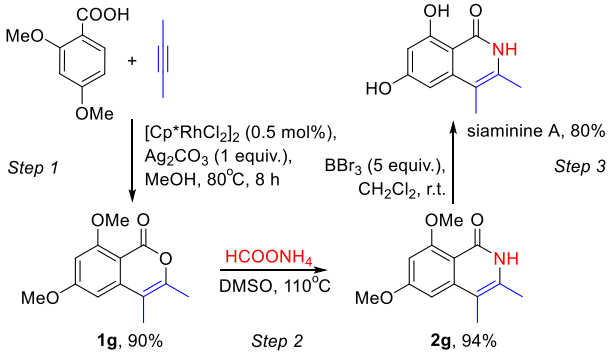
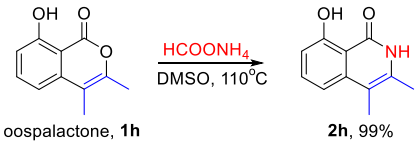


Figure 1. Molecular structure of **2e** with atoms shown as thermal ellipsoids at 50% probability level (one of two independent molecules). Hydrogen atoms (except one at the nitrogen atom) are omitted. Selected bond lengths for the shown symmetry-independent molecule [Å]: C1–O1 1.242(2), C1–N2 1.371(2), C3–N2 1.387(2), C10a–O11 1.388(2), C11a–O11 1.378(2), C1–C11b 1.449(2), C3–C4 1.367(2), C4–C4a 1.448(2), C4a–C11b 1.417(2), C4a–C5 1.416(3), C5–C6 1.377(2), C6–C6a 1.400(3), C6a–C11a 1.395(3), C6a–C6b 1.448(2), C6b–C10a 1.392(3), C6b–C7 1.395(3), C7–C8 1.382(3), C8–C9 1.397(3), C9–C10 1.381(3), C10–C10a 1.380(3), C11a–C11b 1.400(2).



Scheme 2. Synthesis of siaminine A.



Scheme 3. Modification of oospalactone **1h**.

Finally, we recorded the UV–vis absorption and fluorescence spectra for isocoumarins **1a–f** and isoquinolones **2a–f** in dichloromethane (Table 1). Both types of the compounds display the same absorption behavior with several intense absorption bands at 260–400 nm (for example, see Figs. 2 and 3). According to the results of the TD-DFT calculations at the B3LYP/6-31G(d) level (see the Electronic Supplementary Information (ESI)), the long-wavelength band ($S_0 \rightarrow S_1$) is formed by the HOMO → LUMO orbitals and corresponds to the $\pi \rightarrow \pi^*$ transition, because both orbitals are delocalized over the phenyl substituent at position 3 and the isocoumarin or isoquinolone moieties.

Surprisingly, in general, isoquinolone derivatives **2a–f** display stronger luminescence emission than isocoumarins **1a–f**. For example, the emission quantum yield for **2e** (φ = 32%) is 16 times greater than that for **1e** (φ = 2%). Such a dramatic decrease in the quantum efficiency for the latter can be explained by a considerable difference in the geometries of the ground state S_0 and the first singlet excited state S_1 (Fig. 4), which is mainly responsible for the fluorescence emission. The phenyl substituent at position 3 in **1e**, adopting a quinoid structure with foldback from the main cyclic framework, plays an important role in the distortion of the S_1 state. On the contrary, the S_1 state for **2e** retains the planar structure of the isoquinolone moiety. The latter also correlates well with the presence of a fine vibronic structure for the emission band of **2e** (Fig. 3), which is typical for $\pi \rightarrow \pi^*$ transitions [36]. It is interesting to note that the additional π-conjugation in **1d** as well as the ethyl substituents in **1c** stabilize the planar structure of the S_1 state, which is in good agreement with small differences in the quantum efficiency between these isocoumarins and their isoquinolone derivatives.

Experimental section

General remarks

Unless otherwise stated, all reactions were carried out in air using chemical grade solvents. Complex $[Cp^*RhCl_2]_2$ was prepared as described elsewhere [37]. All other reagents were

Table 1. Optical properties of isocoumarins **1a–f** and isoquinolone derivatives **2a–f** in dichloromethane

Comp.	Absorption bands maxima, [nm]	Emission bands maxima, [nm] (λ_{ex}, [nm])	Emission quantum yields φ (λ_{ex} = 355 nm)
1a	299, 341	357 (297)	1%
2a	308, 352	395 (305)	3%
1b	263, 308	364, 471 (300)	<1%
2b	256, 314	405 (314)	1%
1c	262, 271, 286, 364, 380	418 (363)	9%
2c	281, 308, 368, 385	404, 421 (366)	17%
1d	288, 344, 393, 415	435, 460, 485 (391)	24%
2d	287, 358, 398, 420	439, 468, 498 (399)	20%
1e	291, 327, 369	423 (355)	2%
2e	294, 328, 365, 379	402, 420 (363)	32%
1f	267, 277, 362	415 (345)	<1%
2f	258, 355, 366	412 (355)	10%

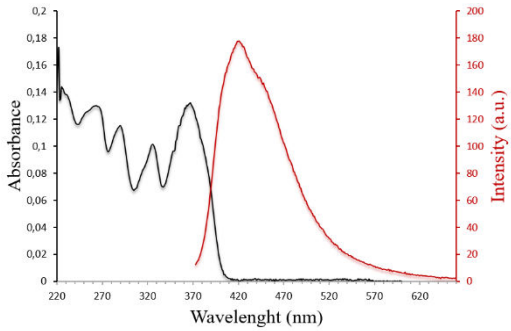


Figure 2. Absorption (C = $1.2 \cdot 10^{-5}$ M) and fluorescence (C = $1.2 \cdot 10^{-5}$ M, λ_{ex} = 355 nm) spectra of isocoumarin **1e** in CH_2Cl_2.

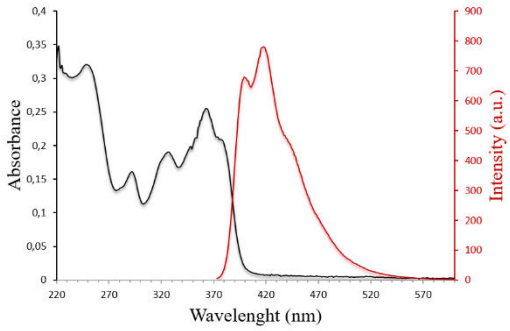


Figure 3. Absorption (C = $1.2 \cdot 10^{-5}$ M) and fluorescence (C = $1.2 \cdot 10^{-5}$ M, λ_{ex} = 363 nm) spectra of isoquinolone **2e** in CH_2Cl_2.

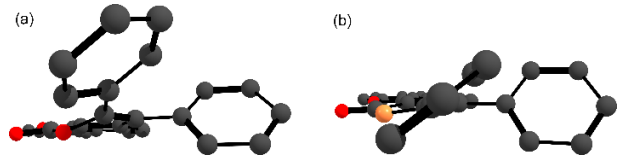


Figure 4. Geometries of the S_1 state for isocoumarin **1e** (***a***) and isoquinolone **2e** (***b***) optimized at the B3LYP/6-31G(d) level.

purchased from Acros or Aldrich and used as received. Column chromatography was carried out using Macherey-Nagel silica gel 60 (particle size 0.04–0.063 mm). The ^1H and $^{13}C\{^1H\}$ NMR spectra were recorded on a Varian Inova 400 spectrometer operating at 400 and 100 MHz, respectively. The chemical shifts are given in ppm using residual solvent signals as the internal standards. The HRMS spectra were recorded using TripleTOF 5600+ mass spectrometer (SCIEX) equipped with electrospray ionization.

Syntheses

General procedure for the synthesis of isocoumarins. Carboxylic acid (0.250 mmol, 1 equiv.), alkyne (0.375 mmol, 1.5 equiv.), $[Cp^*RhCl_2]_2$ (0.8 mg, 0.5 mol %), Ag_2CO_3 (34.5 mg, 0.125 mmol, 1 equiv.), and MeOH (2 mL) were placed in a Schlenk tube equipped with a stir bar. The reaction mixture was stirred at 80 °C (an oil bath) for 8 h. Then the resulting precipitate was centrifuged, the solvent was removed *in vacuo*, and the residue obtained was chromatographed on silica (1 × 15 cm). The first colorless band containing unreacted alkyne was eluted with petroleum ether. The second band was eluted with a mixture of petroleum ether and dichloromethane. Evaporation of solvents gave the corresponding isocoumarin as a colorless or yellow solid.

3,4-Diphenyl-1*H*-isochromen-1-one, 1a. Colorless solid. Yield: 70 mg (95%). Eluent: petroleum ether/CH_2Cl_2 (4:1). ^1H NMR (400 MHz, $CDCl_3$): δ 8.44 (d, 1H, J = 8.0 Hz), 7.63–7.69 (m, 1H), 7.53–7.57 (m, 1H), 7.42–7.45 (m, 3H), 7.34–7.37 (m, 2H), 7.27–7.30 (m, 3H), 7.18–7.23 (m, 3H) (*cf.* [34]).

6-Methoxy-3,4-diphenyl-1*H*-isochromen-1-one, 1b. Colorless solid. Yield: 79 mg (97%). Eluent: petroleum ether/CH_2Cl_2 (3:1). ^1H NMR (400 MHz, $CDCl_3$): δ 8.37 (d, J = 8.9 Hz, 1H), 7.40–7.46 (m, 3H), 7.32–7.37 (m, 2H), 7.18–7.29 (m, 5H), 7.09 (dd, J = 8.8, 2.4 Hz, 1H), 6.60 (d, J = 2.4 Hz, 1H), 3.78 (s, 3H) (*cf.* [34]).

3,4-Diethyl-1*H*-benzo[*h*]isochromen-1-one, 1c. Colorless solid. Yield: 59 mg (94%). Eluent: petroleum ether/CH_2Cl_2 (7:1). ^1H NMR (400 MHz, $CDCl_3$): δ 9.82 (d, J = 8.8 Hz, 1H), 8.16 (d, J = 8.9 Hz, 1H), 7.91 (d, J = 8.1 Hz, 1H), 7.77 (t, J = 7.8 Hz, 1H), 7.60–7.69 (m, 2H), 2.67–2.83 (m, 4H), 1.36 (t, J = 7.6 Hz, 3H), 1.27 (t, J = 7.5 Hz, 3H) (*cf.* [34]).

10-Hydroxy-3,4-diphenyl-1*H*-benzo[*g*]isochromen-1-one, 1d. Yellow solid. Yield: 82 mg (90%). Eluent: CH_2Cl_2. ^1H NMR (400 MHz, $CDCl_3$): δ 12.53 (s, 1H), 8.43 (d, J = 8.3 Hz, 1H), 7.53–7.66 (m, 2H), 7.49 (t, J = 7.4 Hz, 1H), 7.39–7.46 (m, 3H), 7.27–7.33 (m, 4H), 7.17–7.24 (m, 3H), 6.92 (s, 1H). $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$): δ 167.4, 161.9, 148.6, 137.8, 134.5, 133.1, 132.7, 131.2, 130.5, 129.2, 129.1, 128.9, 128.2, 128.0, 127.9, 125.8, 124.0, 123.0, 118.2, 114.6, 100.3. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{25}H_{17}O_3$ 365.1172, found: 365.1168.

3,4-Diphenyl-1*H*-benzofuro[3,2-*h*]isochromen-1-one, 1e. Yellow solid. Yield: 82 mg (90%). Eluent: CH_2Cl_2. ^1H NMR (400 MHz, $CDCl_3$): δ 8.17 (d, J = 8.3 Hz, 1H), 7.98 (d, J = 7.2 Hz, 1H), 7.87 (d, J = 8.2 Hz, 1H), 7.57 (t, J = 7.8 Hz, 1H), 7.42–7.50 (m, 4H), 7.37–7.41 (m, 2H), 7.32–7.36 (m, 2H), 7.21–7.29 (m, 3H), 7.18 (d, J = 8.4 Hz, 1H). $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$): δ 158.9, 157.3, 155.1, 151.5, 138.9, 134.8, 132.9, 131.4, 129.4, 129.2, 129.1, 128.3, 128.0, 127.9, 126.8, 124.7, 122.8, 120.4, 120.3, 117.2, 112.8, 106.5. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{27}H_{17}O_3$ 389.1177, found: 389.1180.

3,4-Diphenyl-1*H*-benzo[4,5]thieno[2,3-*c*]pyran-1-one, 1f. Yellow solid. Yield: 33 mg (37%). Eluent: CH_2Cl_2. ^1H NMR (400 MHz, $CDCl_3$): δ 7.91 (d, J = 8.2 Hz, 1H), 7.42–7.50 (m,

4H), 7.34–7.38 (m, 4H), 7.18–7.25 (m, 3H), 7.09 (t, *J* = 7.7 Hz, 1H), 6.66 (d, *J* = 8.5 Hz, 1H) (*cf.* [34]).

6,8-Dimethoxy-3,4-dimethyl-1*H*-isochromen-1-one, 1g. Colorless solid. Yield: 53 mg (90%). Eluent: CH_2Cl_2. ^{1}H NMR (400 MHz, $CDCl_3$): *δ* 6.41 (d, *J* = 2.2 Hz, 1H), 6.37 (d, *J* = 2.4 Hz, 1H), 3.94 (s, 3H), 3.89 (s, 3H), 2.23 (s, 3H), 2.04 (s, 3H) (*cf.* [34]).

8-Hydroxy-3,4-dimethyl-1*H*-isochromen-1-one, 1h. Colorless solid. Yield: 44 mg (93%). Eluent: petroleum ether/CH_2Cl_2 (2:1). ^{1}H NMR (400 MHz, $CDCl_3$): *δ* 11.30 (s, 1H), 7.61 (t, *J* = 8.1 Hz, 1H), 6.90-6.94 (m, 2H), 2.31 (s, 3H), 2.12 (s, 3H) (*cf.* [34]).

General procedure for the synthesis of isoquinolones. Isocoumarin (0.150 mmol, 1 equiv.), $HCOONH_4$ (75 mg, 8 equiv.), and dimethyl sulfoxide (1 mL) were placed in a Schlenk tube equipped with a stir bar. The reaction mixture was stirred at 110 °C (an oil bath) for 10 h. After cooling to room temperature, water (10 mL) was added, and the product was extracted with dichloromethane (3×10 mL). The organic layers were combined and dried over Na_2SO_4. The solvent was removed *in vacuo*. The residue was chromatographed on silica (1 × 15 cm). The first band containing unreacted isocoumarin was eluted with a mixture of petroleum ether and dichloromethane (the ratio is the same as described above for the synthesis of isocoumarins). The second band was eluted with a mixture of acetone and dichloromethane. Evaporation of the solvents gave the corresponding isoquinolone as a colorless or yellow solid.

3,4-Diphenylisoquinolin-1(2*H*)-one, 2a. Colorless solid. Yield: 41 mg (92%). Eluent: CH_2Cl_2. ^{1}H NMR (400 MHz, $CDCl_3$): *δ* 11.62 (s, 1H), 8.36–8.42 (m, 1H), 7.69 (t, *J* = 7.5 Hz, 1H), 7.57 (t, *J* = 7.5 Hz, 1H), 7.31–7.38 (m, 3H), 7.26–7.31 (m, 5H), 7.19–7.23 (m, 3H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 162.2, 139.0, 138.6, 136.3, 135.0, 133.0, 132.2, 130.3, 129.5, 128.71, 128.65, 128.2, 127.5, 127.3, 126.7, 125.5, 125.4, 115.9. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{21}H_{16}NO$ 298.1226, found: 298.1226.

6-Methoxy-3,4-diphenylisoquinolin-1(2*H*)-one, 2b. Colorless solid. Yield: 43 mg (89%). Eluent: CH_2Cl_2. ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 11.32 (s, 1H), 8.20 (d, *J* = 8.7 Hz, 1H), 7.21–7.27 (m, 3H), 7.14–7.19 (m, 5H), 7.07–7.12 (m, 3H), 6.46 (d, *J* = 2.5 Hz, 1H), 3.62 (s, 3H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 162.8, 161.8, 140.6, 139.7, 136.4, 135.1, 132.1, 130.3, 129.6, 128.7, 128.7, 128.1, 127.6, 119.4, 115.6, 115.0, 107.6, 55.6. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{22}H_{18}NO_2$ 328.1337, found: 328.1328.

3,4-Diethylbenzo[*h*]isoquinolin-1(2*H*)-one, 2c. Colorless solid. Yield: 30 mg (80%). Eluent: acetone/CH_2Cl_2 (1:20). ^{1}H NMR (400 MHz, $CDCl_3$): *δ* 11.15 (s, 1H), 10.32 (d, *J* = 8.7 Hz, 1H), 8.09 (d, *J* = 9.1 Hz, 1H), 7.92 (d, *J* = 8.0 Hz, 1H), 7.83 (d, *J* = 9.0 Hz, 1H), 7.72–7.78 (m, 1H), 7.62 (t, *J* = 7.4 Hz, 1H), 2.85–2.93 (m, 4H), 1.45 (t, *J* = 7.6 Hz, 3H), 1.29–1.32 (m, 3H). ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$): *δ* 164.4, 141.7, 140.0, 133.6, 132.5, 131.4, 128.0, 127.9, 127.3, 125.9, 121.3, 118.2, 114.6, 24.3, 20.0, 15.2, 14.2. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{17}H_{18}NO$ 252.1388, found: 252.1380.

10-Hydroxy-3,4-diphenylbenzo[*g*]isoquinolin-1(2*H*)-one, 2d. Yellow solid. Yield: 54 mg (99%). The chromatographic purification was not required. ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 14.87 (s, 1H), 11.81 (s, 1H), 8.32 (d, *J* = 8.4 Hz, 1H), 7.74 (d, *J* = 8.3 Hz, 1H), 7.60 (t, *J* = 7.5 Hz, 1H), 7.51 (t, *J* = 7.6 Hz, 1H), 7.30–7.38 (m, 3H), 7.20–7.29 (m, 7H), 6.94 (s, 1H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 168.0, 160.9, 137.1, 136.7, 136.3, 135.0, 134.8, 132.0, 130.4, 129.9, 128.8, 128.8, 128.2, 128.2, 127.7, 121.3, 118.1, 112.7, 105.4. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{25}H_{18}NO_2$ 364.1332, found: 364.1335.

3,4-Diphenylbenzofuro[3,2-*h*]isoquinolin-1(2*H*)-one, 2e. Yellow solid. Yield: 55 mg (95%). The chromatographic purification was not required. ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 11.77 (s, 1H), 8.34 (dd, *J* = 8.6, 1.9 Hz, 1H), 8.15 (d, *J* = 7.7 Hz, 1H), 7.86 (d, *J* = 8.3 Hz, 1H), 7.55 (t, *J* = 7.8 Hz, 1H), 7.44 (t, *J* = 7.7 Hz, 1H), 7.17–7.34 (m, 10H), 7.11 (dd, *J* = 8.6, 1.9 Hz, 1H). ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$): *δ* 160.6, 157.0, 154.8, 139.2, 137.6, 136.1, 134.9, 132.0, 129.2, 128.8, 128.5, 128.5, 127.5, 127.3, 124.9, 123.3, 123.1, 122.9, 120.9, 120.1, 117.6, 112.8, 111.9. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{27}H_{18}NO_2$ 388.1337, found: 388.1328.

3,4-Diphenyl-4b,8a-dihydrobenzo[4,5]thieno[2,3-*c*]pyridin-1(2*H*)-one, 2f. Yellow solid. Yield: 52 mg (99%). Eluent: acetone/CH_2Cl_2 (1:10). ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 12.11 (s, 1H), 8.08 (d, *J* = 8.1 Hz, 1H), 7.43 (t, *J* = 7.7 Hz, 1H), 7.28–7.36 (m, 3H), 7.22–7.28 (m, 4H), 7.16–7.22 (m, 3H), 7.07 (t, *J* = 7.7 Hz, 1H), 6.49 (d, *J* = 8.4 Hz, 1H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 158.8, 142.0, 141.6, 140.9, 136.3, 135.8, 134.3, 131.9, 130.4, 128.9, 128.7, 128.3, 128.0, 127.9, 125.5, 124.8, 124.2, 116.0. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{23}H_{16}NOS$ 354.0952, found: 354.0944.

6,8-Dimethoxy-3,4-dimethylisoquinolin-1(2*H*)-one, 2g. Colorless solid. Yield: 33 mg (94%). The chromatographic purification was not required. ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 10.54 (s, 1H), 6.48 (s, 1H), 6.42 (s, 1H), 3.82 (s, 3H), 3.74 (s, 4H), 2.12 (s, 3H), 2.01 (s, 3H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 163.1, 162.7, 160.2, 143.5, 136.2, 109.0, 105.4, 97.3, 96.8, 56.1, 55.7, 17.1, 13.3. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{13}H_{16}NO_3$ 234.1130, found: 234.1124.

8-Hydroxy-3,4-dimethylisoquinolin-1(2*H*)-one, 2h. Colorless solid. Yield: 26 mg (99%). The chromatographic purification was not required. ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 13.39 (s, 1H), 11.56 (s, 1H), 7.52 (t, *J* = 7.7 Hz, 1H), 6.99 (d, *J* = 7.6 Hz, 1H), 6.69 (d, *J* = 7.7 Hz, 1H), 2.21 (s, 3H), 2.07 (s, 3H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 166.1, 161.8, 140.1, 135.1, 134.6, 112.8, 111.3, 110.5, 109.3, 16.9, 12.9. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{11}H_{12}NO_2$ 190.0868, found: 190.0864.

Synthesis of siaminine A. Isoquinolone **2g** (0.100 mmol, 1 equiv.) and CH_2Cl_2 (2 mL) were placed in a Schlenk tube equipped with a stir bar. The solution was cooled over an ice bath, and BBr_3 (47 mg, 0.500 mmol, 5 equiv.) was added slowly. The reaction mixture was allowed to warm to room temperature and stirred for 1 day. The reaction was quenched with a MeOH/AcOH (1:1) mixture (1 mL). The solvent was removed *in vacuo*, and the residue obtained was washed with chloroform and acetone to give siaminine A as a colorless solid. Yield: 16 mg (80%). ^{1}H NMR (400 MHz, $(CD_3)_2SO$): *δ* 13.71 (s, 1H), 11.27 (s, 1H), 6.73 (d, *J* = 2.0 Hz, 1H), 6.56 (d, *J* = 1.9 Hz, 1H), 2.43 (s, 3H), 2.27 (s, 3H). ^{13}C{^{1}H} NMR (101 MHz, $(CD_3)_2SO$): *δ* 167.6, 158.1, 157.0, 141.2, 135.6, 116.9, 103.0, 100.5, 100.0, 17.0, 13.0. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{11}H_{12}NO_3$ 206.0812, found: 206.0811.

X-ray crystallography

Crystals of **2e** were grown by slow interdiffusion of a two-phase system containing petroleum ether and a solution of the compound in dichloromethane. X-ray diffraction data were collected with a Bruker Quest D8 CMOS diffractometer using graphite monochromated Mo-Kα radiation (λ= 0.71073 Å, ω-scans) at 100 K. Using Olex2 [38], the structures were solved with the ShelXT [39] structure solution program using Intrinsic Phasing and refined with the XL [40] refinement package using Least-Squares minimization against F^2 in anisotropic approximation for non-hydrogen atoms. The positions of hydrogen atoms were calculated, and they were refined in the isotropic approximation in the riding model.

Crystal data: $C_{27}H_{17}NO_2$, monoclinic, space group $P2_1/c$, a = 14.0709(3) Å, b = 10.2915(3) Å, c = 26.7963(7) Å, β = 103.3480(10)°, V = 3775.56(17) Å^3, Z = 8, d_{calc} = 1.363 g cm^{-3}, μ = 0.86 mm^{-1}, $F(000)$ = 1616, R_1 = 0.0615 (from 6420 unique reflections with $I>2\sigma(I)$), and wR_2 = 0.1462 (from all 11555 unique reflections).

CCDC 2249310 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Absorption and fluorescence spectroscopy

The absorption spectra were recorded on an Agilent Cary 300 double-beam UV-vis spectrophotometer in a standard 1 cm quartz cell (Helma QS with PTFE stopper). The fluorescence spectra were recorded on an Agilent Cary Eclipse spectrofluorometer at 20 ± 1 °C in a standard 1 cm quartz cell. The observed fluorescence was detected at a direct angle relative to the excitation beam. The fluorescence spectra were corrected for the non-uniformity of detector spectral sensitivity and normalized by the excitation light intensity, derived from the calibrated built-in reference sensor values. Phenanthrene (PQY = 0.125 ± 0.007) in ethanol was used as a reference for the luminescence quantum yield measurements [41]. The luminescence quantum yields were calculated using equation

$$\varphi_i = \varphi_0 \frac{(1-10^{-D_0}) \cdot S_i \cdot n_i^2}{(1-10^{-D_i}) \cdot S_0 \cdot n_0^2}$$

where φ_i and φ_0 are the luminescence quantum yields of the studied solution and the standard compound, respectively; D_i and D_0 are the absorbance of the studied solution and the standard, respectively; S_i and S_0 are the areas underneath the curves of the luminescence spectra of the studied solution and the standard, respectively; and n_i and n_0 are the refractive indices of the solvents of the studied solution and the standard compound (n_i = 1.4246 for DCM; n_0 = 1.3614 for ethanol).

Calculations

Geometry optimizations at the S_0 minimum were performed without constraints at the B3LYP/6-31G(d) level using Gaussian 09 software (revision D.01) [42] with corrections for solvation in dichloromethane (the PCM model). The optimized geometry was verified to have no negative frequencies. Then TD-DFT was adopted at the same level to optimize the S_1 geometry, taking into account the first 5 singlet excited states.

Conclusions

In summary, we have elaborated the facile two-step synthetic approach to isoquinolones based on the reaction of ammonium formate with isocoumarin intermediates formed *via* the Rh-catalyzed annulation of benzoic acids with acetylenes. In particular, this method avoids the use of less accessible starting materials such as *N*-substituted benzamides or aryl hydroxamates, which are commonly used in the classical C–H activation reactions. Based on this easy transformation of isocoumarins to isoquinolones, we have developed an efficient three-step protocol for the synthesis of the naturally occurring isoquinolone siaminine A starting from 2,4-dimethoxybenzoic acid, dimethylacetylene, and ammonium formate. A comparative study of the photophysical properties revealed that isoquinolones display stronger luminescence emission than isocoumarins, which is mainly caused by the retention of a planar structure of the isoquinolone moiety in the first singlet excited state. We hope that this work will inspire chemists to use isoquinolones as luminophores to create various photoactive materials, and not just as convenient precursors in the synthesis of isoquinoline derivatives.

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Electronic supplementary information

The NMR spectra for the compounds obtained and atomic coordinates for the optimized geometries. For ESI, see DOI: 10.32931/io2228a

References and notes

§ This work is dedicated to the 100th anniversary of academician M. E. Volpin, who has contributed much to organic and catalytic chemistry in Russia.

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