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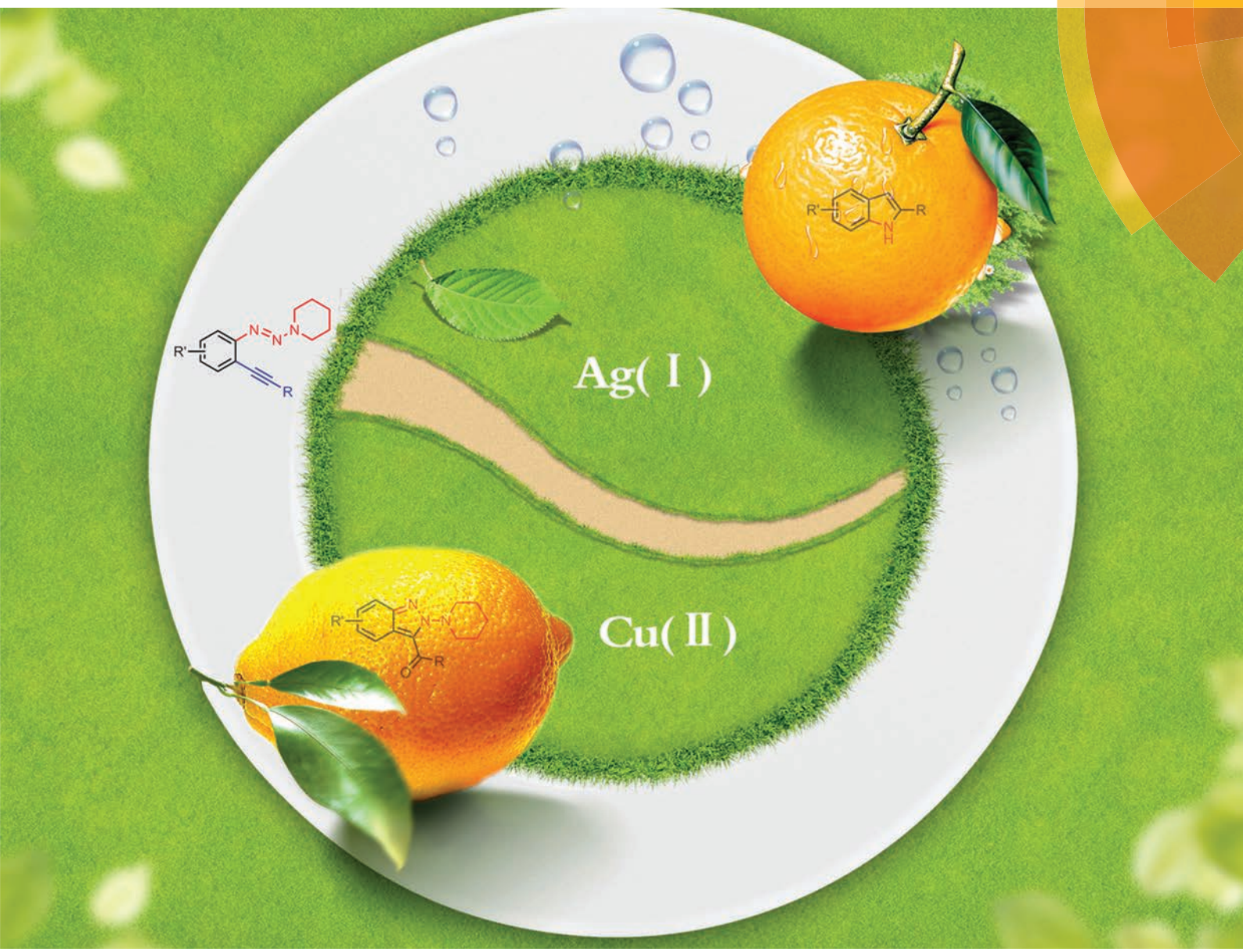

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Selective synthesis of indazoles and indoles *via* triazene–alkyne cyclization switched by different metals†

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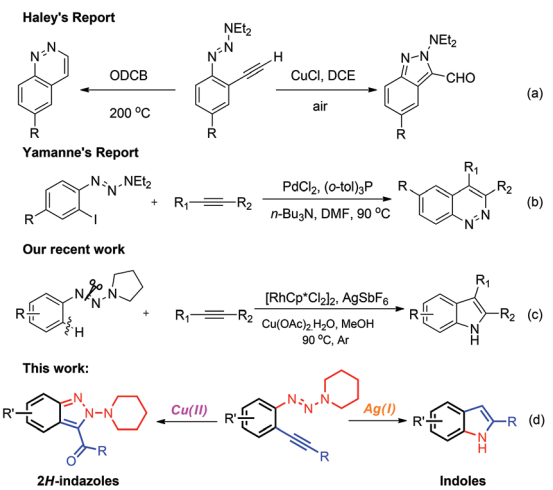
We described two orthogonal heterocycle syntheses, where an arene bearing both an alkyne and a triazene functionality underwent two distinct cyclization pathways mediated by different transition metals. Starting from the same substrates, a synthesis of 2*H*-indazole was accomplished by a Cu(II) salt promoted oxidative cyclization, while 2-substituted indoles could be accessed *via* a Ag(I) salt mediated N–N bond cleavage. This method represents the first synthesis of indoles from alkynyl triazenes. Computational analysis was performed for both reaction pathways, supporting a Lewis acid role for Cu and a π-acid catalysis for Ag.

The chemistry of triazenes dates back to 1875.[1] Readily prepared from commercially abundant anilines, triazenes have been used as linkers to solid supports,[2] as protecting groups for amines and amides,[3] as versatile precursors to a number of functionalities,[4] *etc.* In particular, triazenes were often employed as masked diazonium salts,[5] owing to their favorable chemical stability and safety profiles compared to the latter. Recently, we demonstrated that triazenes are also a class of highly versatile directing groups for selective C–H activation reactions.[6] Significantly, this particular directing group could either be conveniently removed under ambient conditions or participate in versatile synthetic manipulations following the pivotal C–H functionalization step.[6b,c]

In addition, utilization of triazenes for the synthesis of heterocycles also emerged recently. Several aromatic heterocycles containing 2 or 3 nitrogen atoms were synthesized by metal mediated cyclization of *ortho*-alkynyl triazenes. In 2000, Haley reported the first synthesis of cinnolines and 2*H*-indazoles using this strategy.[7] Heating an aryltriazene bearing an *ortho*-terminal alkyne group in *o*-dichlorobenzene (ODCB) at 170 °C resulted in a 2*H*-indazole aldehyde and a cinnoline product in 95% combined yield unselectively. Excellent chemoselectivity was subsequently accomplished for both syntheses of cinnolines (heating at 200 °C) and 4-substituted indazoles (excess CuCl, Scheme 1a).[8] In 2011, Yamane *et al.* reported a synthesis of cinnolines *via* a Pd-catalyzed annulation of 2-iodophenyltriazenes and internal alkynes (Scheme 1b).[9] Synthesis of related cinnolines and indazoles was also reported by Flynn using triazenes as masked diazonium salts in Ritter reactions.[10] Among these exercises, at least two out of the three nitrogen atoms from the triazene remained in the product framework. *In situ* removal of two nitrogen atoms is unprecedented. Recently, our group reported a general synthesis of 2,3-disubstituted indoles *via* triazene directed C–H annulation with various internal alkynes (Scheme 1c).[6a] However, our method was unable to access 2-substituted indoles, due to the low reactivity of terminal alkynes for organometallic addition



Scheme 1 Triazene mediated synthesis of heterocycles.

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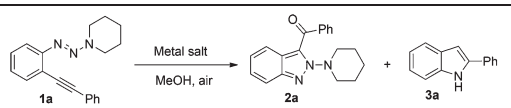
reactions. Herein, we report two distinct heterocyclization pathways of *o*-alkynyl aryltriazenes mediated by two different transition metals, respectively (Scheme 1d). Significantly, two nitrogen atoms of the triazene were concurrently removed for the reaction promoted by Ag salts. 2-Substituted indoles were synthesized exclusively. To the best of our knowledge, this is the first indole synthesis using alkyne substituted aryltriazenes.

Inspired by the above-mentioned Haley's report and our own work on the triazene chemistry, we decided to explore the opportunities for heterocycle synthesis using readily accessible *o*-alkynyl aryltriazenes. Our initial efforts began with investigating reactions of 2-phenylethynyl triazene **1a** using various transition metal salts. Following our protocol for Rh(III) catalyzed C–H activation reactions, we found that 2*H*-indazole **2a** was isolated in 44% yield as the sole product, using catalytic $[RhCp^*Cl_2]_2$ and stoichiometric copper acetate (Table 1, entry 1). The structure of the product was confirmed by X-ray. Upon further examination, we found that Rh was not necessary for this transformation, and copper acetate alone promoted this oxidative heterocyclization reaction in high yield (Table 1, entry 4). Other metal salts were examined, most of which only resulted in substrate decomposition. Gratifyingly, a 2-phenyl indole product **3a** was isolated exclusively when silver salts were introduced (Table 1, entries 19 and 20). After a careful reaction parameter survey (please see ESI† for a comprehensive condition investigation), the best reaction conditions for the synthesis of both heterocycles were identified: 2 equiv. $Cu(OAc)_2{\cdot}H_2O$ (for 2*H*-indazoles) or AgOAc (for indoles) in methanol under air at 90 °C. It was remarkable that under otherwise identical conditions including the counter ion, switching between Cu and Ag cations led to two structurally distinct heterocycles with complete chemoselectivity.

Table 1 Optimization of the reaction conditions[a]



Entry	Catalyst	Oxidant (2.0 eq.)	Yield[b] (%) 2a	3a
1	$[RhCp^*Cl_2]_2$	$Cu(OAc)_2{\cdot}H_2O$	44	—
2	—	$Cu(OAc)_2{\cdot}H_2O$	94	—
3	—	$Cu(OAc)_2{\cdot}H_2O$ (1.0 eq.)	70	—
4	—	$Cu(OAc)_2{\cdot}H_2O$ (3.0 eq.)	68	—
5[c]	—	$Cu(OAc)_2{\cdot}H_2O$	20	—
6	—	$Ni(OAc)_2{\cdot}H_2O$	—	
7	$Pd(OAc)_2$	—	—	—
8	—	$Cu(OTf)_2$	—	—
9	—	CuO	—	—
10	—	CuCN	—	—
11	—	$Fe(OAc)_2$	—	—
12	—	$Mn(OAc)_2{\cdot}4H_2O$	—	—
13	—	AgOOCPh	—	—
14	—	$Co(OAc)_2{\cdot}4H_2O$	—	—
15	—	$Ni(OAc)_2$	—	—
16	—	$Zn(OAc)_2$	—	—
17	—	$AgNO_3$	—	—
18	—	Ag_2CO_3	—	—
19	—	AgOAc (1.0 eq.)	—	50
20	—	AgOAc	—	80

[a] The reactions were performed by stirring **1a** (0.30 mmol) and a metal salt (2.0 eq.) in methanol (3.0 mL) at 90 °C for 9 h under air. An additional metal catalyst (5 mol%) was used for entries 1 and 7. [b] Isolated yield. [c] The reaction was done in acetonitrile.

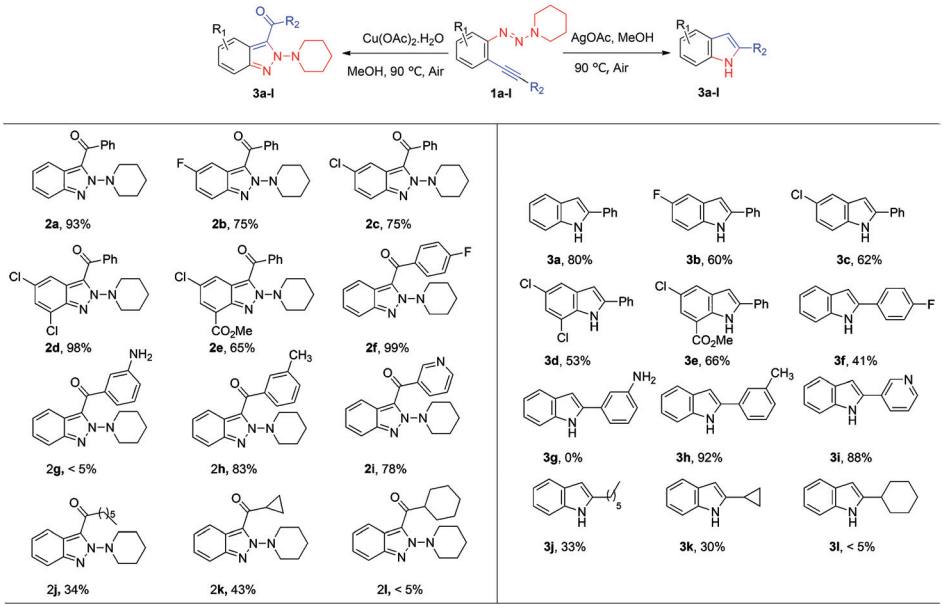
With the optimized reaction conditions in hand, we next explored the scope and generality of the synthesis of both heterocycles (Table 2). A number of substituted *o*-alkynyl aryltriazenes were prepared following literature procedures.[8c,10] Substituted triazenyl arenes were well tolerated and the yields for both the corresponding 2*H*-indazoles and indoles were high. Halogens did not interfere with the heterocyclization. The appending substituent for the alkynes was examined in detail as it delivers more structural diversity of the products. Aryl, including heteroaryl, substituted alkyne substrates were the most effective, with the exception of aminophenyl. The free NH_2 group resulted in the decomposition of the substrate rapidly. Reactions of alkynes bearing an aliphatic group were significantly slower and were sensitive to the steric effects of the substituent. While a pentyl substituted alkyne afforded both heterocycles in 33% and 34% yields, respectively, the corresponding cyclohexyl substrate yielded only trace amounts of the desired products (<5% yields) under both reaction conditions (Table 2, products **2j**, **2l**, **3j**, **3l**).

The synthesis of 2-substituted indoles enabled quick access to a number of functional molecules using the C–H functionalization strategy (Scheme 2). The dehydrogenative dimerization of 2-phenyl indole using copper and molecular oxygen yielded a structurally sophisticated hexacyclic scaffold.[11] Cyanation of the C3 of indole **3a** was accomplished *via* the copper mediated Me–N bond cleavage of DMF.[12] 2-Phenyl indole underwent chemo-selective C–H annulations with diphenyl acetylene. When the indole nitrogen was protected by a methyl group, a selective [C,C] annulation occurred in the presence of Pd(II) to provide **4b**.[13a] In contrast, NH free 2-phenylindole (**3a**) underwent a [C,N] annulation catalyzed by Rh(III) to afford **4d**.[13b] In addition, the Vilsmeier oxime synthesis led to a NF-κB inhibitor **4c**.[14] The Ag mediated indole synthesis was challenged with a methyl ynoate substrate. Gratifyingly, the corresponding methyl 1*H*-indole-2-carboxylate (**3m**) was obtained in 40% yield, providing easy access to libraries of histone deacetylase inhibitors (Scheme 2).[15]

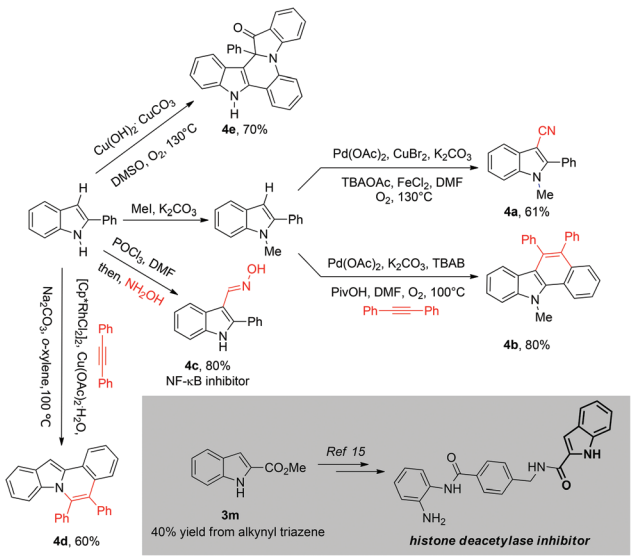
Various conditions were examined in an attempt to remove the piperidinyl group off the 2*H*-indazole product. The substrate was very stable against a wide range of acidic and reductive conditions. Finally, an oxidative protocol was identified for convenient deprotection (Scheme 3).[16] 3-Benzoyl substituted NH free 2*H*-indazole **5** was obtained in quantitative yield. This process enables further functionalization of the 2*H*-indazole nitrogens.[17]

Mechanistic studies by Haley suggested that the Cu promoted 2*H*-indazole formation of terminal alkynyl substrates proceeded through a pseudocoarctate rearrangement.[8a,c] Presumably, a carbene intermediate is generated and stabilized by Cu, which is further oxidized by molecular oxygen to give the

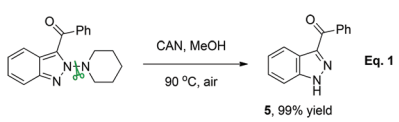
Table 2 Selective indole and 2*H*-indazole synthesis *via* transition metal mediated triazene alkyne cyclization[a]



[a] Condition: the reactions were performed by stirring **1** (0.30 mmol) and the corresponding Cu or Ag salts (0.60 mmol, 2.0 eq.) in methanol (3.0 mL) at 90 °C for 15 hours under air; isolated yield.

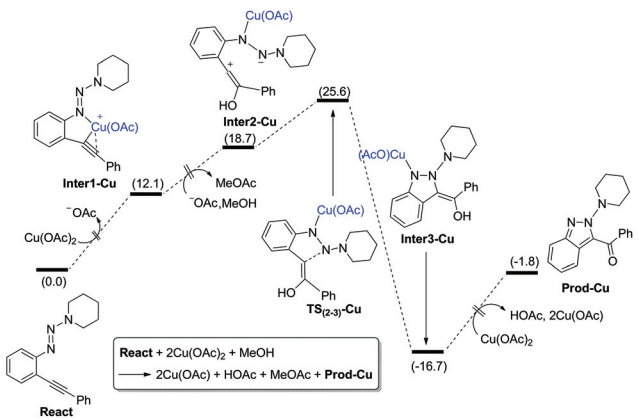


Scheme 2 Derivatization of 2-substituted indoles using the C–H functionalization strategy.

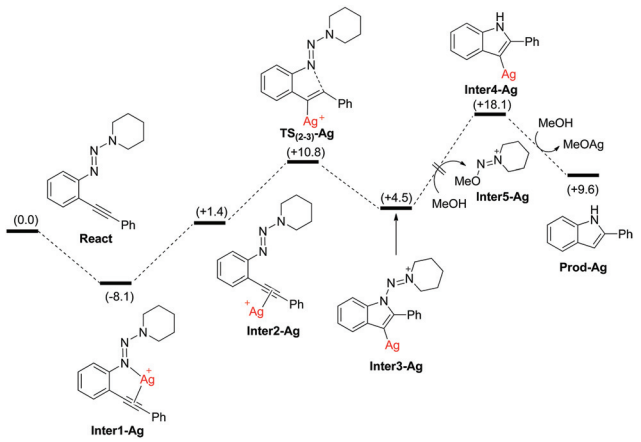


Scheme 3 Removal of the piperidine protecting group.

corresponding 3-formal-2*H*-indazole product. A control experiment performed in a glovebox revealed that the formation of the 3-keto-2*H*-indazole occurred in the absence of oxygen. No isotope incorporation was observed using either $^{18}O_2$, anhydrous $Cu(OAc)_2$, or ^{18}O labeled water in the absence of O_2. Therefore, we concluded that the oxygen atom in the product originated from either MeOH or OAc. In this context, we suggested an alternative reaction pathway for the synthesis of 3-keto-2*H*-indazoles. Copper might initially function as a Lewis acid to tether the triazene and alkyne in proximity. According to our DFT calculations at the SMD:M06-L/GEN1(LanL2DZ:6-31+G(d))//B3LYP/GEN2(LanL2DZ:6-31+G(d) level,[18,19] the coordination is endergonic by 12.1 kcal mol^{-1} and resulted in the formation of **Inter1-Cu** (Scheme 4). Thereafter, the coordination of the HO^- (**Inter1-Cu** → **Inter2-Cu**, Scheme 4) and the C–N bond formation step (**Inter2-Cu** → **TS$_{(2\text{-}3)}$-Cu** → **Inter3-Cu**) occurs subsequently to form the enol intermediate **Inter3-Cu**.



Scheme 4 Mechanism for copper-mediated formation of 3-keto-2*H*-indazoles based on DFT calculations.



Scheme 5 Proposed mechanism for the indole synthesis promoted by silver.

Finally, tautomerzation and deprotonation of **Inter3-Cu** might occur with the aid of $Cu(OAc)_2$ and yield the final product **Prod-Cu** (Scheme 4). According to the calculation results, the Cu center was formally +2 valence along the overall mechanism, and therefore it is understandable that no oxidant (O_2) is required for these Cu(II) mediated reactions. Nonetheless, the detailed transformation for some steps in Scheme 4 might be complicated (such as the coordination and the deprotonation steps), and in-depth studies are currently underway to fully elucidate the details.

By contrast, Ag activates alkynes and olefins most probably through a π-acid mechanism.[20] For the indole formation, a 5-*endo-dig* cyclization (**$TS_{(2\text{-}3)}$-Ag**) takes place between the activated triple bond and the N1 atom of the triazene (Scheme 5), with a free energy barrier of 18.9 kcal mol^{-1}. Subsequent solvolysis of the formed intermediate **Inter3-Ag** by MeOH leads to the intermediate **Inter4-Ag**, from which a final solvolysis can occur to release the 3-benzoyl 2*H*-indazole product and AgOMe. Herein, the cleaved 2 nitrogens were proposed to form the cationic compound **Inter5-Ag**. The lack of silver turnover is probably attributed to the decomposition of AgOMe, as a Ag mirror was observed during the reaction.

In summary, we developed a practical method to synthesize substituted 2*H*-indazoles and indoles. Two orthogonal reaction pathways were conveniently distinguished by switching metal ions. The change of cyclization mechanism was believed to be attributed to the intrinsic characteristics of the metals: Cu acts as a Lewis acid and the Ag functions as a π-acid. Significantly, two out of the three nitrogens of the triazene were *in situ* removed during the indole synthesis, representing an unprecedented N–N cleavage pathway for alkynyl triazenes.

Experimental section

General information

Dichloro(η^5-pentamethylcyclopentadienyl)rhodium(III) dimer (99%) was purchased from Sinocompound Technology Co., Ltd. Cupric acetate and silver acetate were purchased from Sinopharm Chemical Reagent Co., Ltd and used directly. All other reagents were purchased and used without further purification unless specified otherwise. Solvents for chromatography were of technical grade. All compounds that were purified by flash chromatography used silica gel (200–300 mesh) with the indicated solvent system according to standard techniques. Analytical thin layer chromatography (TLC) was performed on pre-coated 0.25 mm thick silica gel 60-F254 plates (*Whatman PE SILG/UV*) and visualized using UV light (254 nm). ^{1}H NMR and ^{13}C NMR data were recorded on 400 MHz nuclear resonance spectrometers. Chemical shifts (δ) in ppm are reported as quoted relative to the residual signals of chloroform (^{1}H 7.268 ppm or ^{13}C 77.16 ppm). Multiplicities are described as: s (singlet), bs (broad singlet), d (doublet), t (triplet), q (quartet), m (multiplet); and coupling constants (J) are reported in hertz (Hz). ^{13}C NMR spectra were recorded with total proton decoupling. HRMS (ESI) analysis with a quadrupole time-of-205 flight (QqTOF) mass spectrometer yielded ion mass/charge (m/z) ratios in atomic mass units. IR spectra were measured as dry films (KBr) and are reported in terms of frequency (cm^{-1}) and intensity of absorption.

General procedures for the preparation of *ortho*-alkynyl triazene substrate 1

The iodoaryl triazene starting materials were prepared through the corresponding diazonium salts, according to a reported protocol.[1] The *o*-iodoaniline (23 mmol, 1.0 eq.) was dissolved in a 2 : 1 mixture of acetonitrile–water (30 mL) and cooled to 0 °C (ice bath). Concentrated aqueous HCl (7.6 mL, 91 mmol, 4.0 eq.) was added dropwise. The reaction mixture was further cooled to −5 °C (salt ice bath) and aqueous solution of $NaNO_2$ (2.4 g, 34 mmol in 30 mL water, 1.5 eq.) was introduced slowly, while maintaining the reaction temperature below 0 °C. After the addition was complete, the reaction mixture was stirred at between −5 °C and 0 °C for 30 minutes and was added slowly to a stirred solution of piperidine (5.6 mL, 57 mmol, 2.5 eq.) and potassium carbonate (16 g, 119 mmol, 5.2 eq.) in a 2 : 1 mixture of acetonitrile and water (120 mL) at 0 °C (ice bath). The reaction mixture was allowed to warm to room temperature and was stirred at that temperature for 1 hour. The resulting solution was extracted three times using ethyl acetate (20 mL × 3). The combined organic layer was washed with brine, dried over Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by flash silica gel column chromatography (petroleum ether–ethyl acetate = 30 : 1) to give the corresponding *ortho*-iodo triazene substrates.

(*E*)-1-((2-Iodophenyl)diazenyl)piperidine (S_{1a}).[10] 23 mmol scale, 6.75 g, 95% yield, red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (dd, J = 7.9, 1.0 Hz, 1H), 7.41 (dd, J = 8.0, 1.2 Hz, 1H), 7.30 (td, J = 7.8, 1.3 Hz, 1H), 6.88 (td, J = 7.8, 1.6 Hz, 1H), 3.87 (s, 4H), 1.73 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.0, 139.1, 128.8, 127.0, 117.6, 96.8, 52.8, 44.4, 26.2, 24.4; HRMS (ESI): found: 316.0306, calcd for $C_{11}H_{15}IN_3$ ($[M + H]^+$): 316.0311; IR

(KBr) 3059, 2937, 1651, 1573, 1447, 1099, 1014, 752, 557, 441, 419.

(*E*)-1-((5-Fluoro-2-iodophenyl)diazenyl)piperidine (S_{1b}). 2 mmol scale, 0.67 g, 99% yield, brown solid, mp 52–54 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (dd, J = 8.7, 6.0 Hz, 1H), 7.17 (dd, J = 10.5, 3.0 Hz, 1H), 6.64 (ddd, J = 8.6, 7.8, 3.0 Hz, 1H), 3.88 (s, 4H), 1.74 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8 (d, J_{CF} = 245 Hz), 151.6 (d, J_{CF} = 7 Hz), 139.6 (d, J_{CF} = 9 Hz), 114.0 (d, J_{CF} = 23 Hz), 104.6 (d, J_{CF} = 24 Hz), 89.6 (d, J_{CF} = 3 Hz), 53.2, 44.5, 26.0, 24.4; HRMS (ESI): found: 334.0209, calcd for $C_{11}H_{14}FIN_3$ ($[M + H]^+$): 334.0216; IR (KBr) 3064, 2937, 1633, 1589, 1463, 1248, 1098, 1018, 871, 603, 462.

(*E*)-1-((4-Chloro-2-iodophenyl)diazenyl)piperidine (S_{1c}).[8c] 10 mmol scale, 3.39 g, 97% yield, light brown solid, mp 46–48 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, J = 2.2 Hz, 1H), 7.28 (dt, J = 8.7, 5.4 Hz, 2H), 3.85 (s, 4H), 1.73 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.9, 138.3, 131.1, 128.9, 117.9, 96.6, 53.0, 44.5, 26.3, 24.4; HRMS (ESI): found: 349.9908, calcd for $C_{11}H_{14}ClIN_3$ ($[M + H]^+$): 349.9921; IR (KBr) 3360, 2937, 1630, 1552, 1456, 1186, 1030, 1001, 820, 723, 572, 519, 447.

(*E*)-1-((2,4-Dichloro-6-iodophenyl)diazenyl)piperidine (S_{1d}). 10 mmol scale, 2.94 g, 77% yield, orange oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, J = 2.2 Hz, 1H), 7.40–7.39 (m, 1H), 3.85 (s, 4H), 1.72 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.7, 136.9, 130.4, 130.1, 126.5, 93.7, 53.0, 43.9, 26.6, 24.3; HRMS (ESI): found: 383.9509, calcd for $C_{11}H_{13}Cl_2IN_3$ ($[M + H]^+$): 383.9531; IR (KBr) 3360, 2940, 1634, 1533, 1418, 1298, 1107, 986, 856, 721, 570, 518, 419.

(*E*)-Methyl 5-chloro-3-iodo-2-(piperidin-1-yldiazenyl)benzoate (S_{1e}). 6 mmol scale, 2.06 g, 85% yield, light yellow solid, mp 105–106 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, J = 2.3 Hz, 1H), 7.49 (d, J = 2.3 Hz, 1H), 3.92 (*S*, 3H), 3.78 (s, 4H), 1.74 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.9, 148.3, 140.3, 130.3, 129.6, 125.0, 96.3, 53.0, 52.1, 44.4, 26.5, 24.2; HRMS (ESI): found: 407.9961, calcd for $C_{13}H_{16}ClIN_3O_2$ ($[M + H]^+$): 407.9976; IR (KBr) 3360, 2938, 1715, 1600, 1493, 1418, 1354, 1182, 1091, 1001, 754, 691, 592, 518, 419.

The iodoaryl piperidine triazene (1 mmol, 1.0 eq.) was dissolved in pyrrolidine (5 mL) and Ar was bubbled through for 5 min. $Pd(PPh_3)_4$ (4 mmol%) was added and the reaction was heated to 60 °C (oil bath). A solution of appropriate alkyne (2 mmol, 2.0 eq.) in pyrrolidine (4 mL) was added *via* a syringe in small portions over 0.5 h. After the addition was completed, the mixture was stirred for 10 hours at 60 °C and extracted three times using ethyl acetate (20 mL × 3) and water. The combined organic layer was washed with brine, dried over Na_2SO_4, filtered, and concentrated under reduced pressure. The residue was purified by flash silica gel column chromatography (petroleum ether–ethyl acetate = 100 : 1) to give the corresponding alkynyl triazene substrate **1**.

(*E*)-1-((2-(Phenylethynyl)phenyl)diazenyl)piperidine (1a).[10] 5 mmol scale, 1.41 g, 93% yield, yellow solid, mp 56–58 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57–7.51 (m, 3H), 7.48–7.45 (m, 1H), 7.37–7.28 (m, 4H), 7.13 (d, J = 1.1 Hz, 1H), 3.89 (s, 4H), 1.74 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.0, 133.0, 131.7, 129.1, 128.4, 128.0, 125.3, 124.2, 118.3, 117.2, 93.7, 88.1, 52.5, 44.5, 25.4, 24.5; HRMS (ESI): found: 290.1651, calcd for $C_{19}H_{20}N_3$ ($[M + H]^+$): 290.1657; IR (KBr) 3360, 3059, 2938, 1600, 1492, 1418, 1354, 1182, 1091, 754, 690, 592, 518, 419.

(*E*)-1-((5-Fluoro-2-(phenylethynyl)phenyl)diazenyl)piperidine (1b). 1.6 mmol scale, 0.45 g, 90% yield, orange yellow solid, mp 92–94 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (ddd, J = 10.2, 6.8, 4.1 Hz, 3H), 7.40–7.29 (m, 3H), 7.27–7.22 (m, 1H), 6.84 (td, J = 8.2, 2.6 Hz, 1H), 3.92 (s, 4H), 1.75 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.2 (d, J_{CF} = 248 Hz), 153.9 (d, J_{CF} = 7 Hz), 134.2 (d, J_{CF} = 10 Hz), 131.6, 128.2 (d, J_{CF} = 38 Hz), 124.1, 114.5 (d, J_{CF} = 3 Hz), 112.4 (d, J_{CF} = 23 Hz), 103.9 (d, J_{CF} = 24 Hz), 93.3, 87.2, 53.2, 44.0, 26.3, 24.4; HRMS (ESI): found: 308.1554, calcd for $C_{19}H_{19}FN_3$ ($[M + H]^+$): 308.1563; IR (KBr) 3360, 3078, 2938, 1634, 1593, 1501, 1427, 1181, 1088, 1002, 756, 496, 445.

(*E*)-1-((4-Chloro-2-(phenylethynyl)phenyl)diazenyl)piperidine (1c). 4 mmol scale, 1.23 g, 95% yield, yellow solid, mp 62–63 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (dd, J = 5.8, 3.0 Hz, 3H), 7.45 (d, J = 8.7 Hz, 1H), 7.40–7.31 (m, 3H), 7.25 (dd, J = 8.9, 2.5 Hz, 1H), 3.90 (s, 4H), 1.74 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.6, 132.2, 131.7, 130.2, 129.1, 128.4, 128.3, 123.7, 119.7, 118.3, 94.7, 86.8, 52.7, 43.9, 25.3, 24.4; HRMS (ESI): found: 324.1266, calcd for $C_{19}H_{19}ClN_3$ ($[M + H]^+$): 324.1268; IR (KBr) 3360, 3061, 2938, 1599, 1491, 1427, 1296, 1182, 1101, 819, 756, 691, 527, 453.

(*E*)-1-((2,4-Dichloro-6-(phenylethynyl)phenyl)diazenyl)piperidine (1d). 4 mmol, 0.90 g, 63% yield, yellow solid, mp 72–74 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46–7.42 (m, 3H), 7.38 (d, J = 2.3 Hz, 1H), 7.36–7.32 (m, 3H), 3.87 (s, 4H), 1.73 (t, J = 4.7 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.3, 131.6, 131.6, 129.8, 129.7, 129.4, 128.6, 128.5, 123.3, 117.9, 93.3, 86.8, 52.9, 43.7, 25.7, 24.4; HRMS (ESI): found: 358.0870, calcd for $C_{19}H_{18}Cl_2N_3$ ($[M + H]^+$): 358.0878; IR (KBr) 3360, 3057, 2940, 1600, 1541, 1418, 1180, 1105, 935, 853, 756, 690, 525, 419.

(*E*)-Methyl 5-chloro-3-(phenylethynyl)-2-(piperidin-1-yldiazenyl)benzoate (1e). 3.8 mmol scale, 1.34 g, 92% yield, light yellow solid, mp 77–78 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (d, J = 2.4 Hz, 1H), 7.51–7.47 (m, 3H), 7.37–7.32 (m, 3H), 3.85 (s, 3H), 3.81 (s, 4H), 1.73 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.08, 150.21, 134.60, 131.65, 129.58, 129.50, 128.55, 128.45, 125.92, 123.33, 120.13, 94.87, 86.16, 53.01, 52.17, 44.06, 25.61, 24.32; HRMS (ESI): found: 382.1318, calcd for $C_{21}H_{21}ClN_3O_2$ ($[M + H]^+$): 382.1322; IR (KBr) 3360, 3050, 2920, 1732, 1715, 1456, 1420, 1319, 1107, 988, 756, 690, 527, 419.

(*E*)-1-((2-((4-Fluorophenyl)ethynyl)phenyl)diazenyl)piperidine (1f). 1 mmol scale, 0.25 g, 82% yield, light yellow solid, mp 95–97 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56–7.45 (m, 4H), 7.29 (dt, J = 11.1, 2.0 Hz, 1H), 7.13 (t, J = 7.5 Hz, 1H), 7.04 (t, J = 8.7 Hz, 2H), 3.89 (s, 4H), 1.74 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.4 (d, J_{CF} = 247 Hz), 152.0, 133.5 (d, J_{CF} = 8 Hz), 132.9, 129.2, 125.3, 120.3 (d, J_{CF} = 4 Hz), 118.1, 117.3, 115.66 (d, J_{CF} = 22 Hz), 92.6, 87.8, 52.3, 44.3, 25.3, 24.5; HRMS (ESI): found: 308.1560, calcd for $C_{19}H_{19}FN_3$ ($[M + H]^+$): 308.1563; IR (KBr) 3360, 3203, 2922, 2359, 1634, 1558, 1506, 1418, 1182, 1091, 835, 756, 669, 527, 419.

(*E*)-3-((2-(Piperidin-1-yldiazenyl)phenyl)ethynyl)aniline (1g). 1 mmol scale, 0.31 g, 100% yield, dark red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (dd, J = 7.7, 1.3 Hz, 1H), 7.47 (dd, J = 8.2, 0.8 Hz, 1H), 7.29–7.24 (m, 1H), 7.12–7.07 (m, 2H), 6.95–6.92 (m, 1H), 6.84–6.82 (m, 1H), 6.59 (ddd, J = 8.0, 2.4, 1.0 Hz, 1H), 3.87 (s, 4H), 3.68 (d, J = 16.9 Hz, 2H), 1.71 (dd, J = 22.4, 7.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.8, 146.3, 132.9, 129.1, 128.9, 125.1, 124.6, 121.9, 118.3, 117.7, 117.1, 115.1, 93.9, 87.3, 52.4, 44.7, 25.2, 24.3; HRMS (ESI): found: 305.1763, calcd for $C_{19}H_{21}N_4$ ($[M + H]^+$): 305.1766; IR (KBr) 3373, 3217, 2938, 1620, 1599, 1418, 1182, 1092, 993, 758, 687, 592, 457, 419.

(*E*)-1-((2-(*m*-Tolylethynyl)phenyl)diazenyl)piperidine (1h). 2 mmol scale, 0.56 g, 93% yield, light yellow solid, mp 41–43 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, J = 7.6 Hz, 1H), 7.51 (d, J = 8.1 Hz, 1H), 7.41–7.36 (m, 2H), 7.34–7.29 (m, 1H), 7.26 (dd, J = 9.5, 5.7 Hz, 1H), 7.18–7.12 (m, 2H), 3.91 (s, 4H), 2.38 (s, 3H), 1.75 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.0, 137.9, 132.9, 132.2, 129.0, 128.9, 128.7, 128.2, 125.3, 124.0, 118.4, 117.2, 93.9, 87.8, 52.5, 44.6, 25.3, 24.5, 21.4; HRMS (ESI): found: 304.1807, calcd for $C_{20}H_{22}N_3$ ($[M + H]^+$): 304.1814; IR (KBr) 3360, 3055, 2922, 1634, 1489, 1420, 1356, 1180, 1094, 1001, 852, 756, 691, 594, 442, 419.

(*E*)-3-((2-(Piperidin-1-yldiazenyl)phenyl)ethynyl)pyridine (1i). 2 mmol scale, 0.52 g, 90% yield, brown solid, mp 57–58 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.76 (d, J = 1.3 Hz, 1H), 8.52 (dd, J = 4.9, 1.5 Hz, 1H), 7.79 (dt, J = 7.9, 1.8 Hz, 1H), 7.55 (dd, J = 7.7, 1.2 Hz, 1H), 7.48 (dd, J = 8.2, 0.7 Hz, 1H), 7.36–7.30 (m, 1H), 7.30–7.24 (m, 1H), 7.13 (dd, J = 10.8, 4.2 Hz, 1H), 3.88 (s, 4H), 1.73 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.3, 152.1, 148.2, 138.2, 132.9, 129.6, 125.2, 123.1, 121.3, 117.5, 117.2, 91.5, 90.1, 52.5, 44.1, 25.4, 24.4; HRMS (ESI): found: 291.1603, calcd for $C_{18}H_{19}N_4$ ($[M + H]^+$): 291.1610; IR (KBr) 3360, 3028, 2938, 1632, 1560, 1485, 1418, 1354, 1182, 1093, 1001, 758, 625, 520, 443, 419.

(*E*)-1-((2-(Oct-1-yn-1-yl)phenyl)diazenyl)piperidine (1j). 2 mmol scale, 0.56 g, 89% yield, dark red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45–7.41 (m, 2H), 7.25–7.20 (m, 1H), 7.07 (td, J = 7.6, 1.1 Hz, 1H), 3.83 (d, J = 5.2 Hz, 4H), 2.48 (t, J = 7.0 Hz, 2H), 1.71 (s, 6H), 1.68–1.60 (m, 2H), 1.56–1.47 (m, 2H), 1.39–1.28 (m, 4H), 0.93 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.8, 133.0, 128.1, 125.1, 119.2, 117.0, 94.6, 78.6, 48.1, 31.5, 29.0, 28.7, 25.3, 24.5, 22.6, 19.9, 14.2; HRMS (ESI): found: 298.2281, calcd for $C_{19}H_{28}N_3$ ($[M + H]^+$): 298.2283; IR (KBr) 3360, 3065, 2932, 1640, 1477, 1427, 1296, 1178, 1096, 1001, 853, 756, 592, 501, 425, 419.

(*E*)-1-((2-(Cyclopropylethynyl)phenyl)diazenyl)piperidine (1k). 2 mmol scale, 0.46 g, 92% yield, red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (ddd, J = 8.1, 3.9, 1.2 Hz, 2H), 7.23–7.18 (m, 1H), 7.05 (td, J = 7.5, 1.2 Hz, 1H), 3.82 (d, J = 5.5 Hz, 4H), 1.72 (d, J = 7.2 Hz, 6H), 1.50 (tt, J = 8.2, 5.1 Hz, 1H), 0.90–0.78 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.9, 132.9, 128.0, 125.1, 118.9, 117.0, 97.8, 73.7, 52.4, 44.6, 25.3, 24.4, 14.2, 8.8; HRMS (ESI): found: 254.1653, calcd for $C_{16}H_{20}N_3$ ($[M + H]^+$): 254.1657; IR (KBr) 3360, 3008, 2922, 1634, 1479, 1418, 1340, 1178, 1087, 955, 853, 756, 590, 515, 417.

(*E*)-1-((2-(Cyclohexylethynyl)phenyl)diazenyl)piperidine (1l). 2 mmol scale, 0.56 g, 95% yield, red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43–7.39 (m, 2H), 7.24–7.19 (m, 1H), 7.06 (td, J = 7.5, 1.2 Hz, 1H), 3.84 (s, 4H), 2.72–2.65 (m, 1H) 1.92–1.77 (m, 6H), 1.71 (s, 6H), 1.40–1.34 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.8, 133.0, 128.1, 125.2, 119.3, 117.0, 98.7, 78.7, 52.3, 44.3, 32.9, 30.0, 26.2, 24.8, 24.6; HRMS (ESI): found: 296.2121, calcd for $C_{19}H_{26}N_3$ ($[M + H]^+$): 296.2127; IR (KBr) 3360, 3064, 2928, 1687, 1633, 1506, 1479, 1423, 1298, 1180, 1096, 756, 592, 547, 418.

General procedure for the cyclization of alkynyl triazene substrates

To a solution of triazene substrate **1** (0.3 mmol, 1.0 eq.) in methanol (3 mL) in an oven dried Schlenk tube was added $Cu(OAc)_2{\cdot}H_2O$ (120 mg, 0.6 mmol, 2.0 eq.) or AgOAc (100 mg, 0.6 mmol, 2.0 eq.). The reaction was stirred under an air atmosphere at 90 °C and the progress of the cyclization was monitored by TLC. Upon complete consumption of **1**, the reaction was cooled to room temperature. Volatile solvent was removed by rotary evaporation and the residue was purified by silica gel flash chromatography (petroleum ether–ethyl acetate) to afford product **2** or **3**, respectively.

Phenyl(2-(piperidin-1-yl)-2*H*-indazol-3-yl)methanone (2a). 85.9 mg, 94% yield, colorless solid, mp 101–103 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80–7.76 (m, 3H), 7.63–7.58 (m, 1H), 7.56 (d, J = 8.5 Hz, 1H), 7.48 (dd, J = 10.5, 4.7 Hz, 2H), 7.37 (ddd, J = 8.7, 6.7, 1.0 Hz, 1H), 7.19 (ddd, J = 8.4, 6.7, 0.8 Hz, 1H), 3.30–3.24 (m, 4H), 1.58–1.50 (m, 4H), 1.45 (dd, J = 10.7, 5.5 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.5, 145.5, 139.2, 132.8, 130.0, 129.3, 128.4, 126.6, 124.6, 121.5, 120.8, 118.0, 56.8, 25.7, 23.3; HRMS (ESI): found: 306.1602, calcd for $C_{19}H_{20}N_3O$ ($[M + H]^+$): 306.1606; IR (KBr) 3564, 3059, 2939, 2359, 1715, 1645, 1598, 1456, 1273, 912, 750, 694, 515, 443, 419.

(6-Fluoro-2-(piperidin-1-yl)-2*H*-indazol-3-yl)(phenyl)methanone (2b). 73.0 mg, 75% yield, white solid, mp 104–106 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79–7.74 (m, 2H), 7.66–7.60 (m, 1H), 7.56 (dd, J = 9.2, 5.3 Hz, 1H), 7.49 (dd, J = 10.6, 4.7 Hz, 2H), 7.37 (dd, J = 9.6, 1.8 Hz, 1H), 7.00 (td, J = 9.2, 2.2 Hz, 1H), 3.28–3.19 (m, 4H), 1.52 (dd, J = 10.5, 5.6 Hz, 4H), 1.44 (d, J = 5.1 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.4, 162.0 (d, J_{CF} = 244 Hz), 145.5 (d, J_{CF} = 13 Hz), 139.0, 133.1, 130.6, 129.2, 128.5, 122.8 (d, J_{CF} = 11 Hz), 118.4, 115.9 (d, J_{CF} = 27 Hz), 101.4 (d, J_{CF} = 23 Hz), 56.8, 25.7, 23.3; HRMS (ESI): found: 324.1505, calcd for $C_{19}H_{19}FN_3O$ ($[M + H]^+$): 324.1512; IR (KBr) 3566, 3065, 2940, 2359, 1715, 1635, 1599, 1516, 1456, 1307, 1227, 1151, 906, 694, 516, 419.

(5-Chloro-2-(piperidin-1-yl)-2*H*-indazol-3-yl)(phenyl)methanone (2c). 76.2 mg, 75% yield, brown solid, mp 122–124 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 (dd, J = 5.1, 3.3 Hz, 2H), 7.71 (dd, J = 9.1, 0.5 Hz, 1H), 7.66–7.60 (m, 1H), 7.58 (dd, J = 1.9, 0.6 Hz, 1H), 7.50 (dd, J = 10.6, 4.7 Hz, 2H), 7.31 (dd, J = 9.1, 2.0 Hz, 1H), 3.28–3.21 (m, 4H), 1.60–1.39 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.2, 143.9, 138.9, 133.1, 130.6, 129.8, 129.2, 128.5, 128.2, 121.9, 119.7, 119.6, 56.9, 25.7, 23.3; HRMS (ESI): found: 340.1213, calcd for $C_{19}H_{19}ClN_3O$ ($[M + H]^+$):

340.1217; IR (KBr) 3335, 3065, 2920, 2361, 1716, 1647, 1599, 1505, 1456, 1234, 1175, 1069, 930, 745, 692, 516, 418.

(5,7-Dichloro-2-(piperidin-1-yl)-2*H*-indazol-3-yl)(phenyl)methanone (2d). 109.6 mg, 98% yield, white solid, mp 110–112 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76–7.73 (m, 2H), 7.64 (d, J = 7.4 Hz, 1H), 7.51 (q, J = 6.9 Hz, 3H), 7.39 (d, J = 1.7 Hz, 1H), 3.34–3.24 (m, 4H), 1.51 (d, J = 5.1 Hz, 4H), 1.45 (d, J = 5.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.0, 141.9, 138.5, 133.3, 130.9, 129.9, 129.2, 128.6, 127.2, 122.4, 118.6, 56.8, 25.6, 23.1; HRMS (ESI): found: 374.0820, calcd for $C_{19}H_{18}Cl_2N_3O$ ($[M + H]^+$): 374.0827; IR (KBr) 3360, 3063, 2922, 2359, 1717, 1647, 1597, 1500, 1456, 1240, 1194, 1012, 900, 777, 719, 584, 516, 418.

Methyl 3-benzoyl-5-chloro-2-(piperidin-1-yl)-2*H*-indazole-7-carboxylate (2e). 77.8 mg, 65% yield, yellow solid, mp 114–116 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, J = 2.0 Hz, 1H), 7.86 (d, J = 2.0 Hz, 1H), 7.76–7.71 (m, 2H), 7.64 (dd, J = 10.5, 4.4 Hz, 1H), 7.51 (t, J = 7.7 Hz, 2H), 4.04 (s, 3H), 3.33–3.26 (m, 4H), 1.52–1.38 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.3, 165.1, 141.5, 138.6, 133.3, 131.9, 130.2, 129.5, 129.2, 128.5, 125.0, 123.4, 121.3, 56.8, 52.6, 25.6, 23.1; HRMS (ESI): found: 398.1262, calcd for $C_{21}H_{21}N_3O_3Cl$ ($[M + H]^+$): 398.1271; IR (KBr) 3334, 3100, 2924, 2360, 1717, 1651, 1580, 1456, 1234, 1175, 1068, 930, 744, 692, 517, 419.

(4-Fluorophenyl)(2-(piperidin-1-yl)-2*H*-indazol-3-yl)methanone (2f). 96.3 mg, 99% yield, dark red solid, mp 85–87 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87–7.81 (m, 2H), 7.78 (d, J = 8.7 Hz, 1H), 7.54 (d, J = 8.5 Hz, 1H), 7.40–7.34 (m, 1H), 7.19 (dt, J = 12.2, 8.3 Hz, 3H), 3.32–3.25 (m, 4H), 1.59 (dd, J = 11.3, 5.9 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.8, 165.8 (d, J_{CF} = 253 Hz), 145.6, 135.4 (d, J_{CF} = 3 Hz), 132.0 (d, J_{CF} = 9 Hz), 129.7, 126.7, 124.7, 121.5, 120.6, 118.1, 115.6 (d, J_{CF} = 22 Hz), 56.9, 25.8, 23.3; HRMS (ESI): found: 324.1499, calcd for $C_{19}H_{19}FN_3O$ ($[M + H]^+$): 324.1512; IR (KBr) 3362, 3196, 2924, 2361, 1732, 1645, 1598, 1506, 1456, 1232, 1153, 914, 756, 603, 515, 419.

(3-Aminophenyl)(2-(piperidin-1-yl)-2*H*-indazol-3-yl)methanone (2g). <5% yield. HRMS (ESI): found: 321.1713, calcd for $C_{19}H_{21}N_4O$ ($[M + H]^+$): 321.1715.

(2-(Piperidin-1-yl)-2*H*-indazol-3-yl)(*m*-tolyl)methanone (2h). 79.0 mg, 83% yield, light yellow solid, mp 127–129 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (d, J = 8.7 Hz, 1H), 7.58 (dd, J = 16.3, 8.3 Hz, 3H), 7.43 (d, J = 7.5 Hz, 1H), 7.36 (dd, J = 12.8, 4.2 Hz, 2H), 7.19 (dd, J = 7.9, 7.3 Hz, 1H), 3.32–3.24 (m, 4H), 2.41 (s, 3H), 1.56 (dd, J = 10.6, 5.4 Hz, 4H), 1.49–1.42 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.6, 145.5, 139.1, 138.2, 133.6, 130.2, 129.8, 128.3, 126.6, 124.5, 121.4, 120.8, 117.9, 56.8, 25.7, 23.4, 21.4; HRMS (ESI): found: 320.1756, calcd for $C_{20}H_{22}N_3O$ ($[M + H]^+$): 320.1763; IR (KBr) 3360, 3055, 2924, 2358, 1942, 1732, 1715, 1653, 1456, 1147, 943, 752, 677, 570, 473, 419.

(2-(Piperidin-1-yl)-2*H*-indazol-3-yl)(pyridin-3-yl)methanone (2i). 72.1 mg, 78% yield, yellow solid, mp 77–79 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.92 (s, 1H), 8.81 (d, J = 3.9 Hz, 1H), 8.06 (dt, J = 7.8, 1.7 Hz, 1H), 7.79 (t, J = 9.5 Hz, 2H), 7.46 (dt, J = 10.9, 5.4 Hz, 1H), 7.41 (dd, J = 11.2, 4.2 Hz, 1H), 7.30 (d, J = 7.8 Hz, 1H), 3.23 (d, J = 5.2 Hz, 4H), 1.43 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.6, 152.5, 150.0, 145.7, 136.0, 135.2, 129.2, 127.0, 125.7, 123.3, 122.2, 120.8, 118.3, 56.8, 25.7, 23.2; HRMS (ESI): found: 307.1544, calcd for $C_{18}H_{19}N_4O$ ($[M + H]^+$): 307.1559; IR (KBr) 3360, 3053, 2938, 2359, 1715, 1645, 1585, 1471, 1427, 1274, 1205, 980, 889, 754, 709, 619, 557, 443, 419.

1-(2-(Piperidin-1-yl)-2*H*-indazol-3-yl)heptan-1-one (2j). 26.7 mg, 34% yield, claybank oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, J = 8.5 Hz, 1H), 7.67 (d, J = 8.7 Hz, 1H), 7.32–7.28 (m, 1H), 7.12–7.06 (m, 1H), 6.87 (dt, J = 16.4, 1.4 Hz, 1H), 6.61 (dt, J = 16.4, 7.0 Hz, 1H), 3.26–3.24 (m, 4H), 2.38–2.32 (m, 2H), 1.90–1.80 (m, 4H), 1.67 (s, 2H), 1.57 (m, 4H), 1.42–1.39 (M, 6H), 1.38–1.27 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.9, 134.7, 130.5, 126.1, 121.6, 120.9, 117.6, 117.6, 56.2, 42.4, 34.0, 31.6, 29.2, 26.2, 23.6, 22.7, 14.2; HRMS (ESI): found: 314.2213, calcd for $C_{19}H_{28}N_3O$ ($[M + H]^+$): 314.2232; IR (KBr) 3360, 3055, 2975, 1732, 1715, 1660, 1550, 1510, 1456, 1375, 1265, 1205, 1147, 1033, 966, 854, 743, 555, 443, 419.

Cyclopropyl(2-(piperidin-1-yl)-2*H*-indazol-3-yl)methanone (2k). 34.3 mg, 43% yield, claybank solid, mp 81–83 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.17 (d, J = 8.4 Hz, 1H), 7.74 (d, J = 8.6 Hz, 1H), 7.40–7.34 (m, 1H), 7.31–7.28 (m, 1H), 3.49–3.44 (m, 1H), 3.43–3.39 (m, 4H), 1.86 (dd, J = 11.3, 5.7 Hz, 4H), 1.64 (s, 2H), 1.37–1.33 (m, 2H), 1.10–1.06 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.0, 145.3, 126.8, 125.5, 122.2, 121.6, 117.8, 100.2, 57.1, 26.2, 23.5, 19.9, 11.8; HRMS (ESI): found: 270.1595, calcd for $C_{16}H_{20}N_3O$ ($[M + H]^+$): 270.1606; IR (KBr) 3360, 3055, 3007, 2926, 2358, 1942, 1716, 1645, 1622, 1550, 1508, 1471, 1427, 1354, 1205, 1006, 939, 752, 698, 557, 443, 419.

Cyclohexyl(2-(piperidin-1-yl)-2*H*-indazol-3-yl)methanone (2l). <5% yield. HRMS (ESI): found: 312.2068, calcd for $C_{19}H_{26}N_3O$ ($[M + H]^+$): 312.2076; IR (KBr) 3360, 3296, 3064, 2937, 2852, 2358, 2105, 1715, 1645, 1475, 1417, 1354, 1192, 1093, 1001, 852, 758, 651, 592, 507, 419.

2-Phenyl-3a,7a-dihydro-1*H*-indole (3a).[20] 46.2 mg, 80%, white solid, mp 187–188 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.36 (s, 1H), 7.70–7.63 (m, 3H), 7.44 (ddd, J = 12.7, 7.8, 1.3 Hz, 3H), 7.34 (dd, J = 10.5, 4.3 Hz, 1H), 7.23–7.18 (m, 1H), 7.16–7.10 (m, 1H), 6.86–6.83 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.0, 137.0, 132.6, 129.4, 129.2, 127.9, 125.3, 122.5, 120.8, 120.4, 111.0, 100.2; HRMS (ESI): found: 194.0956, calcd for $C_{14}H_{12}N$ ($[M + H]^+$): 194.0970; IR (KBr) 3427, 2918, 2359, 1942, 1867, 1630, 1558, 1500, 1456, 1410, 1339, 1145, 1074, 797, 744, 689.

6-Fluoro-2-phenyl-1*H*-indole (3b).[21] 38.1 mg, 60% yield, white solid, mp 166–168 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.40 (s, 1H), 7.66–7.62 (m, 2H), 7.54 (dd, J = 8.6, 5.4 Hz, 1H), 7.48–7.42 (m, 2H), 7.36–7.31 (m, 1H), 7.09 (dd, J = 9.5, 2.0 Hz, 1H), 6.91 (ddd, J = 9.7, 8.7, 2.3 Hz, 1H), 6.80 (dd, J = 2.1, 0.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.2 (d, J_{CF} = 237 Hz), 138.6 (d, J_{CF} = 4 Hz), 136.9 (d, J_{CF} = 13 Hz), 132.3, 129.2, 127.9, 125.9, 125.1, 121.5 (d, J_{CF} = 10 Hz), 109.2 (d, J_{CF} = 24 Hz), 100.0, 97.5 (d, J_{CF} = 26 Hz); HRMS (ESI): found: 212.0866, calcd for $C_{14}H_{11}NF$ ($[M + H]^+$): 212.0876; IR (KBr) 3435, 3078, 2920, 2850, 2358, 1869, 1600, 1533, 1356, 1224, 1141, 962, 812, 758, 689, 611, 510, 435, 419.

5-Chloro-2-phenyl-3a,7a-dihydro-1*H*-indole (3c).[22] 42.5 mg, 62% yield, white solid, mp 170–172 °C. ^{1}H NMR (400 MHz,

$CDCl_3$) δ 8.39 (s, 1H), 7.66 (dd, J = 5.2, 3.3 Hz, 2H), 7.60 (d, J = 1.9 Hz, 1H), 7.47 (dd, J = 10.4, 4.8 Hz, 2H), 7.36 (ddd, J = 7.4, 3.9, 1.1 Hz, 1H), 7.31 (d, J = 8.6 Hz, 1H), 7.15 (dd, J = 8.6, 2.0 Hz, 1H), 6.78–6.76 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.5, 135.3, 132.0, 130.5, 129.2, 128.3, 126.0, 125.4, 122.7, 120.1, 112.0, 99.7; HRMS (ESI): found: 228.0571, calcd for $C_{14}H_{11}ClN$ ($[M + H]^+$): 228.0580: 228.0502; IR (KBr) 3435, 2920, 2359, 1867, 1700, 1558, 1506, 1454, 1284, 1124, 1062, 758, 686.

5,7-Dichloro-2-phenyl-3a,7a-dihydro-1*H*-indole (3d).[23] 41.6 mg, 53% yield, white solid, mp 137–139 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.52 (s, 1H), 7.72–7.66 (m, 2H), 7.49 (dd, J = 12.3, 4.7 Hz, 3H), 7.39 (t, J = 7.4 Hz, 1H), 7.20 (d, J = 1.7 Hz, 1H), 6.80 (d, J = 2.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.1, 132.7, 131.4, 131.0, 129.3, 128.7, 125.9, 125.5, 121.8, 118.9, 116.8, 100.5; IR (KBr) 3431, 2918, 2848, 2360, 1869, 1653, 1558, 1506, 1452, 1417, 1195, 1078, 843, 727, 682, 580, 526, 489, 419.

Methyl 5-chloro-2-phenyl-3a,7a-dihydro-1*H*-indole-7-carboxylate (3e). 57.2 mg, 66% yield, light yellow solid, mp 102–104 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.05 (s, 1H), 7.80 (d, J = 1.9 Hz, 1H), 7.75 (d, J = 1.7 Hz, 1H), 7.72–7.68 (m, 2H), 7.47 (dd, J = 10.4, 4.7 Hz, 2H), 7.40–7.35 (m, 1H), 6.77 (d, J = 2.4 Hz, 1H), 4.00 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.2, 140.5, 135.5, 131.5, 131.5, 129.2, 128.6, 125.6, 125.4, 125.1, 124.0, 113.1, 99.1, 52.3; HRMS (ESI): found: 286.0628, calcd for $C_{16}H_{13}ClNO_2$ ($[M + H]^+$): 286.0635; IR (KBr) 3444, 3034, 2951, 2924, 2852, 2358, 1867, 1699, 1608, 1588, 1489, 1456, 1394, 1340, 1296, 1249, 1174, 1033, 941, 871, 758, 734, 544, 503, 419.

2-(4-Fluorophenyl)-3a,7a-dihydro-1*H*-indole (3f).[20] 25.9 mg, 41% yield, white solid, mp 185 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.29 (s, 1H), 7.66–7.60 (m, 3H), 7.43–7.38 (m, 1H), 7.23–7.19 (m, 1H), 7.18–7.13 (m, 3H), 6.77 (d, J = 1.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.92, 163.8, 161.3, 137.1 (d, J_{CF} = 19 Hz), 129.4, 128.9, 127.0 (d, J_{CF} = 8 Hz), 122.6, 120.7 (d, J_{CF} = 26 Hz), 116.2 (d, J_{CF} = 22 Hz), 111.0, 100.1; HRMS (ESI): found: 212.0867, calcd for $C_{14}H_{11}NF$ ($[M + H]^+$): 212.0876; IR (KBr) 3435, 3417, 3064, 2920, 2850, 2358, 1716, 1645, 1541, 1456, 1427, 1273, 1099, 964, 870, 794, 752, 736, 657.

2-(*m*-Tolyl)-3a,7a-dihydro-1*H*-indole (3h).[22] 57.8 mg, 92% yield, white solid, mp 123–124 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (s, 1H), 7.64 (d, J = 7.8 Hz, 1H), 7.49 (d, J = 11.8 Hz, 2H), 7.41 (d, J = 8.0 Hz, 1H), 7.35 (t, J = 7.6 Hz, 1H), 7.17 (ddd, J = 21.7, 14.9, 7.1 Hz, 3H), 6.84–6.82 (m, 1H), 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.8, 138.2, 136.9, 132.5, 129.5, 129.1, 128.7, 126.0, 122.5, 122.4, 120.8, 120.4, 111.0, 100.0, 21.7; HRMS (ESI): found: 208.1118, calcd for $C_{15}H_{14}N$ ($[M + H]^+$): 208.1126; IR (KBr) 3431, 3364, 3103, 2920, 2850, 1633, 1607, 1303, 1232, 785, 748, 689.

2-(Pyridin-3-yl)-3a,7a-dihydro-1*H*-indole (3i).[24] 51.6 mg, 88% yield, yellow solid, mp 175–177 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.67 (d, J = 75.6 Hz, 2H), 7.79–7.71 (m, 1H), 7.70–7.64 (m, 2H), 7.58 (s, 1H), 7.30 (ddd, J = 11.2, 4.5, 1.6 Hz, 3H), 7.13–7.07 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.7, 149.8, 148.8, 146.1, 134.8, 129.7, 126.4, 122.5, 122.1, 120.9, 120.1, 117.9, 56.4; IR (KBr) 3325, 3176, 3055, 2922, 2667, 2358, 2135, 1940, 1747, 1714, 1680, 1575, 1516, 1417, 1373, 1261, 1147, 1024, 858, 796, 713, 617, 556, 443.

2-Hexyl-3a,7a-dihydro-1*H*-indole (3j).[20] 20.0 mg, 33% yield, white solid, mp 39–41 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (s, 1H), 7.54 (d, J = 7.5 Hz, 1H), 7.34–7.26 (m, 1H), 7.16–7.05 (m, 2H), 6.25 (d, J = 0.8 Hz, 1H), 2.76 (t, J = 7.6 Hz, 2H), 1.73 (dt, J = 15.3, 7.5 Hz, 2H), 1.45–1.37 (m, 2H), 1.37–1.30 (m, 6H), 1.28 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.2, 135.9, 129.0, 121.0, 119.9, 119.7, 110.4, 99.6, 31.8, 29.3, 29.2, 28.4, 22.7, 14.2; HRMS (ESI): found: 202.1589, calcd for $C_{14}H_{20}N$ ($[M + H]^+$): 202.1596; IR (KBr) 3406, 3360, 3055, 2922, 2852, 2351, 1907, 1616, 1585, 1552, 1489, 1456, 1012, 972, 779, 748.

2-Cyclopropyl-3a,7a-dihydro-1*H*-indole (3k).[25] 14.2 mg, 30% yield, light yellow solid, mp 65–67 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (s, 1H), 7.52–7.48 (m, 1H), 7.28 (dd, J = 5.1, 4.3 Hz, 1H), 7.12–7.03 (m, 2H), 6.18–6.14 (m, 1H), 2.02–1.93 (m, 1H), 0.97 (ddd, J = 8.4, 6.4, 4.3 Hz, 2H), 0.79 (dt, J = 6.6, 4.5 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.8, 135.9, 128.9, 125.9, 121.2, 119.9, 119.8, 110.3, 97.9, 9.0, 7.4; HRMS (ESI): found: 158.0962, calcd for $C_{11}H_{12}N$ ($[M + H]^+$): 158.0970; IR (KBr) 3584, 3402, 3385, 3065, 3005, 2922, 2850, 2359, 1869, 1558, 1508, 1458, 1417.

Substrate **3a** (0.2 mmol), $Pd(OAc)_2$ (4.5 mg, 10 mol%), $FeCl_2$ (2.6 mg, 10 mol%), $CuBr_2$ (49.3 mg, 1.1 eq.), K_2CO_3 (30.4 mg, 1.1 eq.), and TBAOAc (66.3 mg, 1.1 eq.) were added to a 20 mL Schlenk tube and the reaction vessel was vacuumed and purged with O_2 for three times, followed by the addition of DMF (2.0 mL). The reaction mixture was stirred at 130 °C under an O_2 balloon for 24 hours and was monitored by TLC. The reaction was then cooled to r.t., diluted with ethyl acetate (15 mL), washed with brine (10 mL × 3), dried over Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by column chromatography on silica gel (hexane–ethyl acetate = 50 : 1) to afford the desired compound **4a**.

1-Methyl-2-phenyl-1*H*-indole-3-carbonitrile (4a).[12] 28.4 mg, 61% yield, white solid, mp 114–115 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81–7.78 (m, 1H), 7.63–7.53 (m, 5H), 7.45 (d, J = 7.9 Hz, 1H), 7.40 (dd, J = 6.9, 1.2 Hz, 1H), 7.38–7.32 (m, 1H), 3.78 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.3, 137.0, 130.1, 130.0, 129.2, 128.9, 127.7, 124.0, 122.6, 119.8, 116.8, 110.6, 85.7, 31.9; HRMS (ESI): found: 233.1059, calcd for $C_{16}H_{13}N_2$ ($[M + H]^+$): 233.1079; IR (KBr) 3356, 3061, 2926, 2360, 2214, 1768, 1647, 1608, 1587, 1537, 1469, 1398, 1357, 1251, 1159, 1132, 1012, 968, 849, 812, 745, 700, 658.

To a 20 mL Schlenk tube was added $Pd(OAc)_2$ (6.8 mg, 0.1 eq.), K_2CO_3 (12.4 mg, 0.3 eq.), TBAB (48.4 mg, 0.5 eq.), PivOH (30.7 mg, 1.0 eq.), **3a** (63.0 mg, 0.30 mmol), diphenylaceylene (53.5 mg, 1.0 eq.). The reaction vessel was vacuumed and purged with O_2 for three times, followed by the addition of DMF (3.0 mL). The reaction mixture was stirred at 100 °C under an O_2 balloon for 12 hours and was monitored by TLC. The reaction was then cooled to r.t., diluted with ethyl acetate (40 mL), washed with H_2O (10 mL × 3), dried over Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by column chromatography on silica gel (eluent: petroleum ether–ethyl acetate = 50 : 1) to afford **4b**.

11-Methyl-5,6-diphenyl-11*H*-benzo[*a*]carbazole (4b).[13a] 92.0 mg, 80% yield, yellow solid, mp 169–171 °C. ^{1}H NMR (400 MHz,

$CDCl_3$) δ 8.86 (d, J = 8.5 Hz, 1H), 7.73 (d, J = 7.9 Hz, 1H), 7.65–7.60 (m, 1H), 7.55 (t, J = 10.4 Hz, 1H), 7.48–7.39 (m, 3H), 7.48–7.25 (m, 5H), 7.22 (d, J = 7.2 Hz, 4H), 6.95 (t, J = 7.6 Hz, 1H), 6.67 (d, J = 8.0 Hz, 1H), 4.51 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.4, 140.4, 139.7, 135.1, 132.9, 132.0, 131.2, 130.4, 128.5, 128.1, 127.7, 126.9, 126.4, 125.0, 124.9, 124.6, 123.3, 122.3, 122.2, 122.1, 119.4, 117.9, 108.9, 34.6; IR (KBr) 1471, 1445, 1390, 1330, 1260, 1070, 1026, 764, 743, 700, 668.

Phosphorous oxychloride (30.0 mmol, 4.6 mL) was added dropwise to DMF (4.2 mL) at 0 °C and the reaction mixture was stirred at that temperature for 1 hour. A solution of compound **3a** (1.0 mmol, 193.2 mg) in DMF (2.2 mL) was added dropwise and kept at r.t. for 2 h. The mixture was then poured into ice cold water and neutralized with dilute ammonia solution. The formed precipitate was collected by vacuum filtration and crystallized from absolute ethanol to give the hydroxylamine hydrochloride as greenish brown crystals. The hydroxylamine hydrochloride (0.34 mmol, 75.0 mg) was added to a solution of 2-phenylindole-3-carboxaldehyde (0.5 mmol, 34.8 mg) and sodium hydroxide (20.0 mg, 0.5 mmol) in methanol (3 mL). The reaction mixture was stirred at r.t. until no starting material was detected by TLC (about 3 h). The reaction mixture was evaporated *in vacuo* and EtOAc was added to the residue. The solution was washed with water, and the organic layer was dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was purified by flash column chromatography on silica gel (eluent: petroleum ether–ethyl acetate = 20 : 1) to give **4c**.

2-Phenyl-1*H*-indole-3-carbaldehyde oxime (4c).[14] 94.5 mg, 80% yield, white solid, mp 183–185 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.46 (s, 1H), 8.34 (s, 1H), 8.23 (d, J = 7.5 Hz, 1H), 7.59–7.46 (m, 5H), 7.42 (d, J = 7.5 Hz, 1H), 7.33–7.24 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.0, 140.7, 136.1, 131.4, 129.3, 129.0, 126.1, 123.8, 122.8, 121.8, 111.0, 106.8; HRMS (ESI): found: 237.1023, calcd for $C_{15}H_{13}N_2O$ ($[M + H]^+$): 237.1028; IR (KBr) 3418, 2963, 2849, 2359, 2208, 1714, 1610, 1454, 1261, 1093, 1018, 959, 800, 769, 698, 635, 517, 469.

To a 20 mL two-necked flask charged with a refluxing condenser and a rubber septum were added **3a** (0.3 mmol, 58.0 mg), diphenylacetylene (0.3 mmol, 53.5 mg), $[(Cp^*RhCl_2)_2]$ (0.003 mmol, 0.2 mg), $Cu(OAc)_2{\cdot}H_2O$ (0.015 mmol, 3.0 mg), Na_2CO_3 (0.3 mmol, 31.8 mg) and *o*-xylene (3 mL). The mixture was stirred under air at 100 °C for 10 hours and was monitored by TLC. The reaction mixture was then cooled to r.t., diluted with ethyl acetate (20 mL), washed with saturated brine (5 mL × 2), dried over Na_2SO_4, filtered, and evaporated under vacuum. The crude product was purified by column chromatography on silica gel (petroleum ether–ethyl acetate = 100 : 1) to afford **4d**.

5,6-Diphenylindolo[2,1-*a*]isoquinoline (4d).[13b] 66.6 mg, 60% yield, yellow solid, mp 222–224 °C. ^{1}H NMR (400 MHz, CDCl3) δ 8.32 (d, J = 8.0 Hz, 1H), 7.80 (d, J = 8.0 Hz, 1H), 7.55–7.49 (m, 1H), 7.43 (s, 1H), 7.38–7.31 (m, 6H), 7.26–7.14 (m, 7H), 6.82 (ddd, J = 8.4, 7.0, 1.1 Hz, 1H), 6.00 (d, J = 8.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.9, 136.2, 136.1, 135.5, 132.9, 132.0, 131.0, 130.4, 129.8, 128.9, 128.8, 128.0, 127.5, 127.2, 126.9, 126.3, 125.5, 123.4, 121.8, 121.6, 120.3, 120.2, 114.7, 94.3; HRMS (ESI): found: 370.1588, calcd for $C_{28}H_{20}N$ ($[M + H]^+$): 370.1596; IR (KBr) 3915, 3566, 2920, 2361, 1867, 1625, 1580, 1500, 1442, 1338, 1275, 1144, 787, 748, 696, 669, 519, 444, 419.

To an oven-dried Schlenk tube were sequentially added $Cu(OH)_2{\cdot}CuCO_3$ (13.3 mg, 0.06 mmol), 2-phenylindole (57.9 mg, 0.3 mmol), and DMSO (2 mL). The reaction vessel was immersed in an oil bath preheated to 130 °C and stirred for 48 hours. The mixture was then cooled to r.t., and saturated aqueous NaCl solution (10 mL) and EtOAc (10 mL) were added. The organic phase was separated, and the aqueous phase was further extracted with EtOAc (10 mL × 2). The combined organic layers were dried over anhydrous Na_2SO_4, filtered and concentrated. The residue was purified by silica gel column chromatography (eluent: petroleum ether–ethyl acetate = 100 : 1) to afford **4e**.

15a-Phenyl-5*H*-diindolo[1,2-*a*:3′,2′-*c*]quinolin-15(15a*H*)-one (4e).[11] 41.7 mg, 70% yield, yellow solid, mp 162–164 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 12.02 (s, 1H), 8.26 (d, J = 7.9 Hz, 1H), 7.82 (dd, J = 13.0, 5.0 Hz, 2H), 7.66–7.61 (m, 2H), 7.45 (t, J = 8.4 Hz, 3H), 7.33 (dt, J = 9.3, 4.8 Hz, 3H), 7.28–7.11 (m, 5H), 7.03 (d, J = 7.6 Hz, 1H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 195.1, 155.5, 137.5, 136.2, 135.0, 133.1, 129.7, 126.5, 126.4, 125.9, 124.1, 124.0, 123.1, 122.3, 120.9, 120.8, 120.4, 119.2, 118.9, 118.4, 115.9, 109.8, 107.8, 106.7, 72.1; HRMS (ESI): found: 399.1493, calcd for $C_{28}H_{19}N_2O$ ($[M + H]^+$): 399.1497; IR (KBr) 3381, 3208, 2922, 2850, 2359, 2135, 1712, 1693, 1601, 1580, 1506, 1456, 1350, 1323, 1288, 1049, 1024, 928, 746, 698, 669, 606, 515, 445, 419.

A round bottom flask equipped with a stirring bar was charged with **2a** (92 mg, 0.3 mmol), CAN (1.64 g, 3.0 mmol, 10.0 equiv.), and MeOH (5 mL). The solution was stirred for 1 hour and was concentrated under reduced pressure. The solid residue was purified by flash silica gel column chromatography (eluent: petroleum ether–ethyl acetate = 2 : 1) to afford the free indazole product **5**.

(1*H*-Indazol-3-yl)(phenyl)methanone (5). 65.8 mg, 99% yield, yellow solid, mp 185–187 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.74 (s, 1H), 8.48 (d, J = 8.0 Hz, 1H), 8.30 (d, J = 7.5 Hz, 2H), 7.66–7.46 (m, 5H), 7.40 (t, J = 7.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.3, 143.3, 140.9, 138.1, 132.7, 130.6, 128.4, 127.8, 124.0, 123.6, 123.1, 110.0. HRMS (ESI): found: 223.0864, calcd for $C_{14}H_{11}N_2O$ ($[M + H]^+$): 223.0871; IR (KBr) 3334, 3064, 2924, 2852, 2345, 1715, 1643, 1456, 1276, 1276, 1224, 1074, 921, 885, 748, 669, 491, 446, 419.

Calculation methods

All calculations were performed on Gaussian09 suit of programs.[21] The B3LYP functional[22] is used for geometry optimization in gas phase, with the LanL2DZ[23] basis on Cu/Ag atom and the 6-31+G(d) for all the other atoms. Frequency calculations were performed at the same level, to provide the thermal corrections of Gibbs free energy, and verify that the stationary point is local minimum (with zero imaginary

frequency) or transition state (with one imaginary frequency). The M06-L[24] solution phase single point calculations were carried out on the gas-phase optimized structures, and the self-consistent reaction field (SCRF) with the SMD solvation model[25] was used. MeOH was used as a solvent, corresponding to our experimental conditions. The detailed Cartesian coordinates, thermal correction to Gibbs free energy (TCG), and the electronic energies (au) in solution phase are given in the ESI.†

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