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Formation of anti-Bredt-type Azabicyclo[4.2.0]octene Frameworks through Photochemical Intramolecular [2+2] Cycloaddition between Indole and a Distal Double Bond of Allene

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Abstract. Irradiation of 1-(penta-3,4-dienoyl)indole derivatives in the presence of an aromatic ketone by a high-pressure mercury lamp through Pyrex glass gave two types of cyclized products stereoselectively in high combined yields. The major product was a tetracyclic indoline derivative containing anti-Bredt-type azabicyclo[4.2.0]octene moiety produced via photo [2+2] cycloaddition between indole and a distal double bond of allene, accompanied by a small amount of proximal [2+2] adduct. Among a range of aromatic ketones screened, 3',4'-methylenedioxyacetophenone was found to sensitize the substrate most effectively.

Abstract Text----Continued

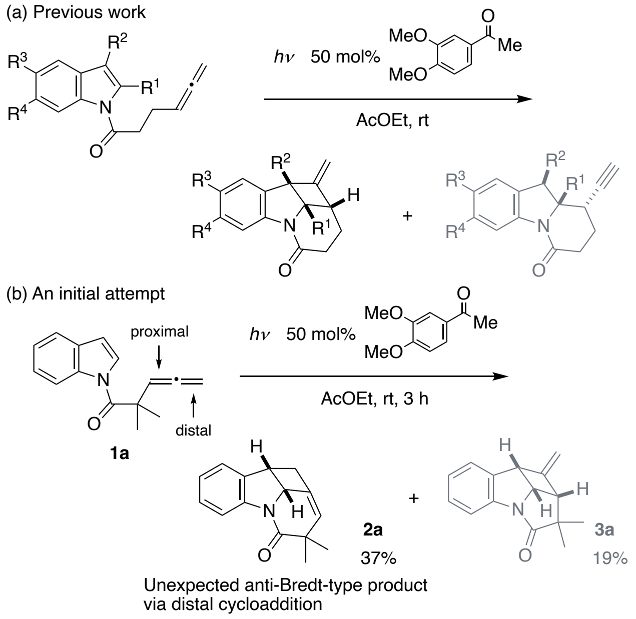
Keywords: Photochemistry; Indole; Indoline; Allene; [2+2] Cycloaddition

1. Introduction

Indoline-fused ring systems are common structural motifs in a number of indole alkaloids, which form an important class of biologically active compounds, such as pharmaceuticals, agrochemical, and so on.[1–3] In addition to known natural compounds, unprecedented fused cyclic indoline frameworks are of interest in bioactive screening for new pharmaceutical candidates.[4–7] Therefore, many efforts have been dedicated to the preparation of this particular molecular frameworks so far.[8–10] Whereas the preparative method for indolines fused with 5- or 6-membered ring has wide variety among these traditional processes,[8] those for cyclobutane-fused indolines have been much less explored.[11–17]

The photochemical cycloaddition is an attractive method for the construction of cyclic frameworks, because a complex ring system that is hardly achievable via thermochemical reaction can be easily obtained from a relatively simple molecule.[18,19] Especially, the intramolecular photo-cycloaddition allows to easily increase the *molecular complexity*, a concept introduced to evaluate the intrinsic structural complexity of compounds.[20–22] From a synthetic point of view, a dearomative [2+2] cycloaddition of indole derivatives seems to be the most straightforward method to construct the cyclobutane-fused indolines. Inter- or intramolecular [2+2] cycloaddition reactions between indole C2,C3 moiety and an alkene under UV irradiation have been extensively investigated.[23,24] More recently, several research groups reported intramolecular dearomative [2+2] cycloadditions of indole derivatives via visible-light-promoted energy transfer mechanism.[25–30] This elegant method provides a rare example of indole functionalization by exploiting visible-light-induced reactivity, though the reaction requires sufficiently low $\Delta G(T_1\text{-}S_0)$ values of substrates appropriate for the visible-light-excited energy transfer system.

In our ongoing study on the photochemistry of 5-membered heteroaromatic compounds,[31] we recently disclosed that irradiation of 1-(hexa-4,5-dienoyl)indole derivatives in the presence of an aromatic ketone, particularly 3',4'-dimethoxyacetophenone, by a high-pressure mercury lamp through Pyrex glass gave all-cis-fused methylenecyclobutane-containing indolines through [2+2] cycloaddition (Scheme 1a).[32] Prompted by this result, a reaction was attempted by using 1-(penta-3,4-dienoyl)indole derivative **1a**, which has one carbon between the amide carbonyl and allene moiety, in order to examine the effect of the tether length on the reaction. In this substrate **1a**, the dimethyl substitution is desirable to avoid the isomerization to conjugated compounds. Unexpectedly, it was found that an anti-Bredt-type azabicyclo[4.2.0]octene derivative **2a** was mainly produced via the regioselectivity alternation (Scheme 1b).[33,34] It is known that the proximal 2π component of the allene moiety participates in the cycloaddition to form bicyclic products in most reported intramolecular [2+2] cycloaddition reactions of simple unactivated allenes.[35–37] The detail of the study is described herein.

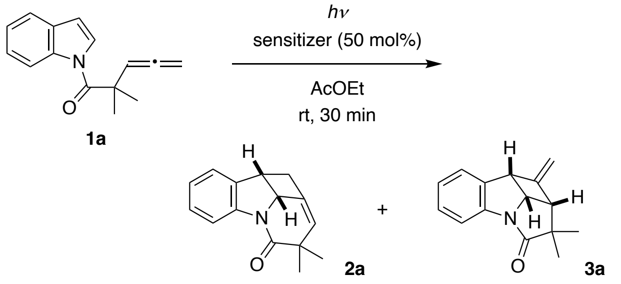


Scheme 1. An Initial Attempt.

2. Results and Discussion

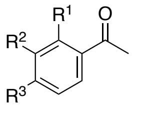
The study began with screening photosensitizers (Table 1). The reaction was discontinued in 30 min regardless of the conversion for comparison. Whereas 3,4-dimethoxyacetophenone (**S1**) nicely sensitized the reaction, the reaction was slowed in the presence of acetophenone (**S2**) or 4'-substituted derivatives **S3**–**S5**, resulting in a much lower yield of the photocycloadducts **2a** and **3a** (Entries 1–5). On the other hand, acetophenone derivatives **S6**, **S7** that have two alkoxy substituents on the benzene ring worked as well as **S1** (Entries 6 and 7). The structure of **2a** was unambiguously determined by X-ray crystallographic analysis (Figure 1). This kind of 2-azabicyclo[4.2.0]oct-5-ene framework was previously synthesized via interception of 1-azacyclohexa-2,3-diene with styrene, but a quite rare structure.[38] When isolated **2a** or **3a** was irradiated under the reaction conditions of Entry 7, it was recovered almost unchanged respectively. Benzophenone (**S8**), xanthone (**S9**), and thioxanthone (**S10**), which are also known as triplet sensitizers, showed sufficient conversion but the yields of **2a** and **3a** were low accompanied by unidentifiable messy byproducts (Entries 8–10). While arylketones that have an E_{T} of nearly 70 kcal/mol sensitized **1a** well, 2-acetonaphthone (**S11**) that has much smaller E_{T} (59 kcal/mol) did not give the product (**2a**, **3a**) at all (Entry 11). The triplet energy (E_{T}) of **1a** is not known, but those of 1-benzoylindole and 1-methylindole are reported as 68 and 69.3 kcal/mol in the literatures.[39,40] The reaction hardly proceeded in the absence of the sensitizer, resulting in a much lower yield of the photoadducts with decomposition of **1a** (Entry 12). The amounts of the sensitizer could be reduced to 20 mol%, without sacrifice of the product yield but somewhat inferior yields were obtained with 10 mol% sensitizer (Entries 13 and 14). Though the difference between **S1** and **S7** was little, **S7** was chosen for further investigations.

Table 1. Optimization of reaction conditions: Sensitizer.[a)]

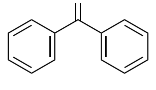


Entry	Sensitizer	E_{T} (kcal/mol)	Conv. (%)[b)]	**2a** (%)[b)]	**3a** (%)[b)]	**2a**/(**2a**+**3a**) (%)
1	**S1**	67.3[c)]	100	65	20	76
2	**S2**	73.6[d)]	76	34	9.5	78
3	**S3**	72.8[e)]	40	20	5.7	78
4	**S4**	71.7[c)]	80	48	14	77
5	**S5**	70.1[c)]	57	28	8.0	78
6	**S6**		94	59	19	76
7	**S7**	65.8[f)]	100	66	20	77
8	**S8**	68.5[d)]	100	42	18	70
9	**S9**	74.2[d)]	98	32	19	63
10	**S10**	65.5[d)]	84	33	16	67
11	**S11**	59.3[d)]	7	0	0	–
12	none		34	3.1	<1	76
13[g,i,j)]	**S7**	65.8[f)]	95	65	19	77
14[h,i,j)]	**S7**	65.8[f)]	85	47	13	78

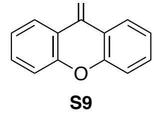
[a)] All reactions were carried out using 0.1 mmol of the substrate in a Pyrex test tube by external irradiation with a high-pressure Hg lamp at a concentration of 10 mM. [b)] Determined by the ^{1}H NMR integral ratio using 1,1,2,2-tetrachloroethane as an internal standard. [c)] Ref 41. [d)] Ref 42. [e)] Ref 43. [f)] Ref 44. [g)] Sensitizer, 20 mol%. [h)] Sensitizer, 10 mol%. [i)] The sensitizer was recrystallized from *n*-



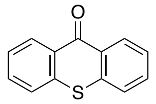
S1: R^1=H, R^2=R^3=MeO
S2: R^1=R^2=R^3=H
S3: R^1=R^2=H, R^3=F
S4: R^1=R^2=H, R^3=Cl
S5: R^1=R^2=H, R^3=MeO
S6: R^1=R^3=MeO, R^2=H
S7: R^1=H, R^2,R^3= $-(OCH_2O)-$



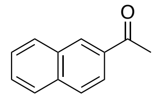
S8



S9



S10



S11

heptane–AcOEt (5:1) before use. [j] Reaction time, 1 h.

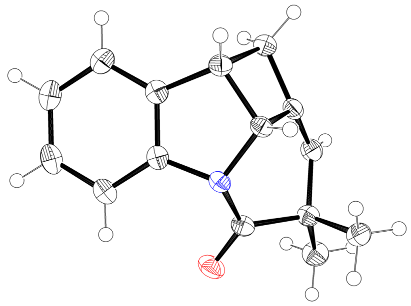
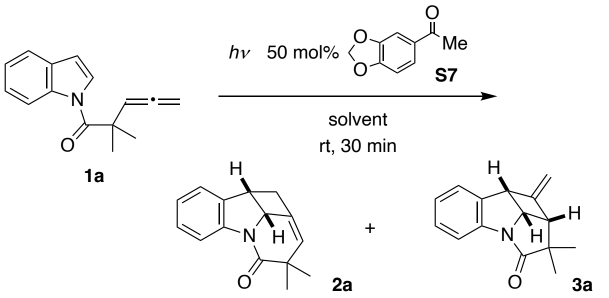


Figure 1. ORTEP drawing of **2a**.

Next, the reaction of **1a** with **S7** was attempted in a range of solvents (Table 2). The reaction proceeded in slightly polar or non-polar solvents, such as MTBE, benzene, cyclohexane as well as in ethyl acetate (Entries 1–4). The reactions in halogenated solvent and highly polar solvents gave inferior conversion and product yields (Entries 5–7). This solvent effect on the reaction would be interpreted as the change of the excited triplet state character. It is known that the ππ* state is more stabilized than the nπ* state with increasing solvent polarity.[45] Thus T_1 state of alkoxy-substituted acetophenone that has ππ* character is lowered in polar solvents, causing the decrease of sensitizing ability. Concentration of the substrate little affected the reaction (Entries 8 and 9). Although benzene gave the best yield of **2a**, ethyl acetate was chosen as the standard solvent in the further studies because of the carcinogenicity of benzene.

Table 2. Optimization of reaction conditions: Solvent.[a,b]

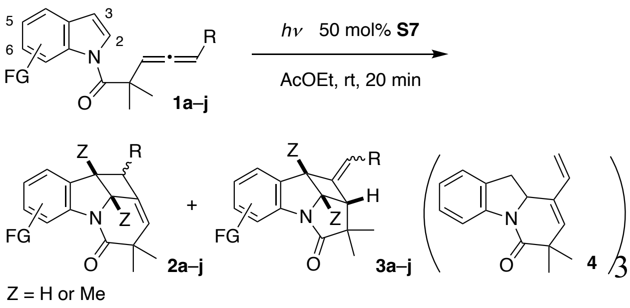


Entry	Solvent	Conv. (%)[c]	**2a** (%)[c]	**3a** (%)[c]	**2a**/(**2a**+**3a**) (%)
1	AcOEt	91	69	19	78
2	MTBE	99	69	19	78
3	Benzene	97	72	19	79
4	Cyclohexane	94	63	14	82
5	CH_2Cl_2	81	50	13	79
6	MeCN	58	35	11	76
7	MeOH	41	21	6.4	77
8[d]	AcOEt	100	66	19	78
9[e]	AcOEt	94	66	19	78

[a] All reactions were carried out using 0.1 mmol of the substrate in a Pyrex test tube by external irradiation with a high-pressure Hg lamp at a concentration of 10 mM. [b] The sensitizer was recrystallized from *n*-heptane–AcOEt (5:1) before use. [c] Determined by the ^1H NMR integral ratio using 1,1,2,2-tetrachloroethane as an internal standard. [d] 5 mM. [e] 20 mM.

Using optimized conditions as described above, the reaction was explored with a variety of indole derivatives (Table 3). The reactions shown in Table 3 were carried out in a photochemical reaction vessel for internal irradiation. The result of the reaction with **1a** was almost same as that by external irradiation, giving isolated **2a** and **3a** with only a slight loss of the yields (Entry 1). It should be noted that ring junctures were created diastereoselectively, showing the potential of this reaction for the stereoselective synthesis of ring-fused indolines. The reaction could be carried out in 1 mmol scale without significant loss of the yields (Entry 2). The substituents at the benzene ring of indole showed significant influence on the reaction. The reactions of halogenated indole derivatives **1b–d** gave yields of the cyclized products comparable to that of **1a** (Entries 3–5). While methyl-substituted derivative **1e** also afforded a nice result, a somewhat lower yield was obtained in the case of 5-MeO-substituted **1f** (Entries 6 and 7). Introduction of 5-CO_2Me group (**1g**) retarded the reaction, giving the products in moderate yields (Entry 8). Whereas irradiation of 3-Me-substituted substrate **1h** afforded the photoadducts with a quaternary carbon in good yield, 2-Me derivative **1i** gave a messy mixture, from which only a small amount of **2i** could be isolated (Entries 9 and 10). In Entries 7, 8, and 10, the low yields of the products were likely attributed to undesirable side reactions, such as deacylation and acylmigration of the indole substrates (photo-Fries rearrangement),[46] which are common pathways in the photochemical reaction of 1-acylated indoles. The reaction with **1j**, which has a methyl group at the allene moiety, was also possible, giving the cycloadducts in moderate yields, though the diastereoselectivity at the methyl group was not satisfactory (Entry 11).

Table 3. Substrate scope.[a]



Entry	Indole core and allene substitution	2 (%)[b]	3 (%)[b]
1	none, R=H (**1a**)	63	20
2[c]	none, R=H (**1a**)	60	19
3	5-F, R=H (**1b**)	65	23
4	6-Cl, R=H (**1c**)	67	19
5	5-Br, R=H (**1d**)	57	20
6	5-Me, R=H (**1e**)	68	20
7	5-OMe, R=H (**1f**)	44	15[d]
8[e]	5-CO_2Me, R=H (**1g**)	34	12
9	3-Me, R=H(**1h**)	53	20
10[f]	2-Me, R=H (**1i**)	5	21
11[g]	none, R=Me (**1j**)	40[h]	28[i]

[a] All reactions were carried out using 0.2 mmol of the substrate in a Pyrex reaction vessel for photochemical reaction by internal irradiation with a high-pressure Hg lamp at a concentration of 10 mM. The conversion was 97–100%, unless otherwise noted. [b] Yield of isolated product. [c] 1 mmol scale reaction. [d] The product contained a small amount of an inseparable impurity. [e] Irradiation time, 40 min. Conversion, 75%. [f] Irradiation time, 40 min. Conversion, 95%. [g] 1,3-Diene **4** was obtained in 6%. [h] (all cis):(cis-trans)=1:3 [i] *Z*:*E*=2:3.

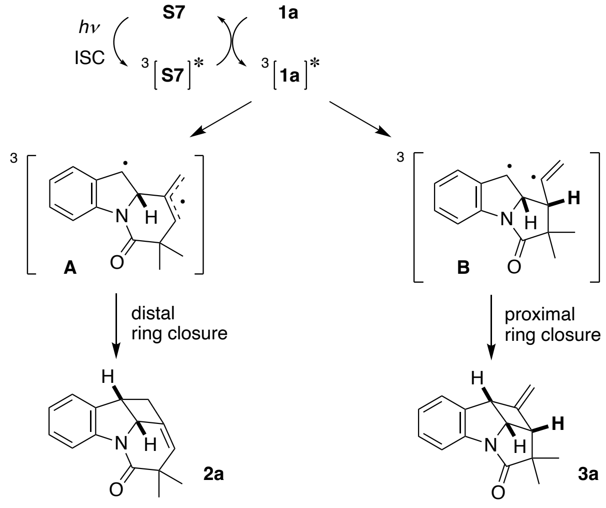
To obtain information on the reaction mechanism, several reactions were performed. When the reaction was carried out in the presence of *p*-terphenyl, which is known as a triplet quencher (E_T=58 kcal/mol),[47] the formation of **2a** and **3a** was significantly disturbed. Taking the influence of competitive absorption of *p*-terphenyl into account, the reaction was also performed in O_2 (E_T=23 kcal/mol)[47] saturated ethyl acetate under O_2, resulting in a complete inhibition of the reaction (Scheme 2). These results strongly suggested that the reaction occurred via a triplet intermediate.

$$\mathbf{1a} \xrightarrow[\text{AcOEt, rt, 30 min}]{h\nu \text{ 50 mol\% } \mathbf{S7}} \mathbf{2a} + \mathbf{3a} + \text{recovery of } \mathbf{1a}$$

	2a	**3a**	recovery of **1a**
with *p*-terphenyl (100 mol%)	9.5%	2.7%	80%
in O_2 satd. AcOEt under O_2	0%	0%	70%

Scheme 2. Mechanistic investigation.

Though the mechanism underlying this reaction is not clear in detail at this stage, the reaction pathway is surmised as shown in Scheme 3 based on the results shown in Scheme 2 and information from the literature.[39,48] Triplet **1a**, which is generated by energy transfer from triplet **S7**, forms a carbon-carbon bond between the 2-position of indole and the center carbon of the allene moiety to give the tricyclic biradical intermediate **A**. This type of radicalic bond formation of allenes is known to occur as a minor pathway in many cases.[35–37] After ring closure of **A** accompanied with intersystem crossing (ISC), the distal [2+2] adduct **2a** that has an anti-Bredt-type azabicyclo[4.2.0] framework is produced. The formation of 1,3-diene **4** in the reaction of **1j** is rationally explained by hydrogen transposition from the terminal methyl group to indole 3-position of the **A**-type intermediate. On the other hand, the proximal [2+2] adduct **3a** is formed via near-side ring closure of ^{3}[**1a**]* via intermediate **B**. The formation of **2a** and **3a** through direct excitation of **1a** seems inefficient, because the photoabsorption of **1a** in the range of Pyrex-filtered UV is much less effective than that of **S7** (see, Supporting Information). It is well known that a five-membered ring is preferentially formed in the initial bond forming step in an intramolecular [2+2] photocycloaddition (the Rule of Five).[49,50] According to this rule, **3a** should be formed in preference to **2a**, but the result was opposite. The result is interpreted that the thermodynamic stability of allylic radical **A** over vinylic radical **B** would overcome the geometrical advantage in five-membered ring formation.[51]



Scheme 3. Plausible reaction pathway.

3. Conclusion

In conclusion, a [2+2] photochemical cycloaddition reaction of 1-(penta-3,4-dienoyl)indole derivatives was investigated and it was found that the cycloaddition occurred mainly between indole C2–C3 bond and a distal double bond of allene. 3',4'-Methylenedioxyacetophenone works effectively as a photosensitizer in this reaction. In many cases, the reaction completes within half an hour to afford the indolines that possess anti-Bredt-type azabicyclo[4.2.0]octene frameworks accompanied by methylenecyclobutane-fused indolines in high combined yield. The excellent diastereoselection in this reaction is noteworthy. A plausible reaction pathway is proposed based on mechanistic experiments.

4. Experimental Section

4.1 General remarks

NMR spectra were obtained on a JEOL JNM-ECS400 spectrometer. Chemical shifts were reported in ppm (δ) by using following compounds as internal standards: ^{1}H NMR, $CHCl_3$ (7.26); ^{13}C NMR, $CDCl_3$ (77.0); ^{19}F NMR, C_6F_6 (–162.9).[52] Carbon multiplicity was assigned by a DEPT experiment and described as follows: methyl, CH_3; methylene, CH_2; methine, CH; quaternary, C. IR spectra were recorded on a JASCO FT/IR-4100 spectrophotometer. UV spectra were obtained on a JASCO UV/Vis spectrophotometer Ubest-30. Silica gel column chromatography was performed with Fuji Silysia PSQ60B or FL60D. Preparative thin-layer chromatography (TLC) was carried out with Wako Gel B-5F (FUJIFILM Wako Pure Chemical Corporation). Gel permeation chromatography (GPC) was performed using an LC-5060 recycling preparative HPLC equipped with JAIGEL-1H and -2H columns in series (Japan Analytical Industry Co., Ltd.). Solvents and reagents were used as received unless otherwise noted. Mass spectrometry and elemental analysis were carried out at the Instrumental Analysis Division, Global Facility Center, Creative Research Institution, Hokkaido University.

4.2 Preparation and physical data of the starting materials

The starting materials were prepared by acylation of indole derivatives by 2,2-dimethylpenta-3,4-dienoyl chloride[53] based on the method for 2,2-diethylbutanoylation reported in the literature.[54] The physical data of new compounds are as follows:

4.2.1 1-(1*H*-Indol-1-yl)-2,2-dimethylpenta-3,4-dien-1-one (**1a**)

Faintly yellow oil. UV-vis (1.7×10^{-4} mol/L, ethyl acetate) λ_{max} 302 nm (ε 6.5×10^3). IR (KBr) 3170, 2981, 1955, 1696, 1538, 1448, 1390, 1308, 1207, 1154, 1077, 901, 852, 757, 719 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.51 (d, J=8.3 Hz, 1H), 7.88 (d, J=3.9 Hz, 1H), 7.54 (d, J=7.7 Hz, 1H), 7.37–7.33 (m, 1H), 7.29–7.25 (m, 1H), 6.57 (d, J=3.9 Hz, 1H), 5.56 (t, J=6.8 Hz, 1H), 4.97 (d, J=6.8 Hz, 2H), 1.56 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.5 (C), 174.6 (C), 136.5 (C), 129.6 (C), 126.3 (CH), 125.1 (CH), 123.7 (CH), 120.5 (CH), 117.2 (CH), 108.2 (CH), 97.7 (CH), 79.1 (CH_2), 44.6 (C), 27.2 (CH_3). HRMS (ESI$^+$) m/z 248.1041 (M+Na$^+$), calcd for $C_{15}H_{15}NNaO$: 248.1046.

4.2.2 1-(5-Fluoro-1*H*-indol-1-yl)-2,2-dimethylpenta-3,4-dien-1-one (**1b**)

Colorless oil. IR (KBr) 2983, 1955, 1699, 1592, 1465, 1444, 1314, 1254, 1205, 1141, 1079, 988, 903, 851 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.45 (dd, J=9.1, 4.8 Hz, 1H), 7.92 (d, J=3.9 Hz, 1H), 7.19 (dd, J=8.7, 2.6 Hz, 1H), 7.06 (dt, J_d=2.6, J_t=9.1 Hz, 1H), 6.53 (d, J=3.9 Hz, 1H), 5.55 (t, J=6.7 Hz, 1H), 4.98 (d, J=6.7 Hz, 2H), 1.55 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.5 (C), 174.4 (C), 159.6 (d, $^1J_{C\text{–}F}$=240.1 Hz, C), 132.8 (C), 130.6 (d, $^3J_{C\text{–}F}$=9.8 Hz, C), 127.8 (CH), 118.1 (d, $^3J_{C\text{–}F}$=8.9 Hz, CH), 112.5 (d, $^2J_{C\text{–}F}$=24.4 Hz, CH), 107.8 (d, $^4J_{C\text{–}F}$=3.8 Hz, CH), 106.0 (d, $^2J_{C\text{–}F}$=23.7 Hz, CH), 97.6 (CH), 79.1 (CH_2), 44.5 (C), 27.2 (CH_3). ^{19}F NMR (377 MHz, $CDCl_3$) δ –120.7– –120.8 (m). HRMS (ESI$^+$) m/z 266.0949 (M+Na$^+$), calcd for $C_{15}H_{14}FNNaO$: 266.0952.

4.2.3 1-(6-Chloro-1*H*-indol-1-yl)-2,2-dimethylpenta-3,4-dien-1-one (**1c**)

Faintly yellow oil. IR (KBr) 2982, 1955, 1699, 1533, 1453, 1425, 1314, 1235, 1203, 1181, 1140, 1112, 1078, 895, 852, 812 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.57 (d, J=1.9 Hz, 1H), 7.86 (d, J=3.9 Hz, 1H), 7.44 (d, J=8.3 Hz, 1H), 7.24 (dd, J=8.3, 1.9 Hz, 1H), 6.54 (dd, J=3.9, 0.6 Hz, 1H), 5.54 (t, J=6.7 Hz, 1H), 4.97 (d, J=6.7 Hz, 2H), 1.55 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.5 (C), 174.6 (C), 136.8 (C), 131.0 (C), 128.0 (C), 126.9 (CH), 124.1 (CH), 121.1 (CH), 117.4 (CH), 107.8 (CH), 97.5 (CH), 79.2 (CH_2), 44.6 (C), 27.1 (CH_3). HRMS (ESI$^+$) m/z 282.0651 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{35}ClNNaO$: 282.0656.

4.2.4 1-(5-Bromo-1*H*-indol-1-yl)-2,2-dimethylpenta-3,4-dien-1-one (**1d**)

Colorless oil. IR (KBr) 3170, 2982, 1955, 1698, 1575, 1443, 1304, 1229, 1183, 1080, 893, 854, 810, 761, 718 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.38 (d, J=8.8 Hz, 1H), 7.88 (d, J=3.9 Hz, 1H), 7.67 (d, J=2.0 Hz, 1H), 7.43 (dd, J=8.8, 2.0 Hz, 1H), 6.51 (d, J=3.9 Hz, 1H), 5.54 (t, J=6.7 Hz, 1H), 4.97 (d, J=6.7 Hz, 2H), 1.55 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.5 (C), 174.5 (C), 135.2 (C), 131.3 (C), 127.8 (CH), 127.4 (CH), 123.1 (CH), 118.5 (CH), 116.9 (C), 107.3 (CH), 97.5 (CH), 79.2 (CH_2), 44.6 (C), 27.2 (CH_3). HRMS (ESI$^+$) m/z 326.0144 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{79}BrNNaO$: 326.0151.

4.2.5 2,2-Dimethyl-1-(5-methyl-1*H*-indol-1-yl)penta-3,4-dien-1-one (**1e**)

Pale yellow oil. IR (KBr) 2981, 1955, 1697, 1542, 1466, 1389, 1362, 1310, 1211, 1188, 1080, 903, 851, 810 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.41 (d, J=8.5 Hz, 1H), 7.86 (d, J=3.9 Hz, 1H), 7.354–7.350 (br m, 1H), 7.19 (dd, J=8.5, 1.7 Hz, 1H), 6.52 (dd, J=3.9, 0.6 Hz, 1H), 5.57 (t, J=6.7 Hz, 1H), 4.98 (d, J=6.8 Hz, 2H), 2.46 (s, 3H), 1.57 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.4 (C), 174.4 (C), 134.6 (C), 133.2 (C), 129.8 (C), 126.35 (CH), 126.29 (CH), 120.4 (CH), 116.8 (CH), 108.0 (CH), 97.8 (CH), 79.0

(CH_2), 44.4 (C), 27.2 (CH_3), 21.3 (CH_3). HRMS (ESI^+) m/z 262.1199 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.2.6 2,2-Dimethyl-1-(5-methoxyl-1*H*-indol-1-yl)penta-3,4-dien-1-one (**1f**)

Colorless oil. IR (KBr) 2983, 2936, 1955, 1693, 1613, 1587, 1471, 1444, 1390, 1365, 1315, 1264, 1186, 1154, 1098, 1080, 1033, 903, 849, 816, 717 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 8.41 (d, *J*=9.0 Hz, 1H), 7.85 (d, *J*=3.8 Hz, 1H), 7.02 (d, *J*=2.6 Hz, 1H), 6.95 (dd, *J*=9.0, 2.6 Hz, 1H), 6.51 (d, *J*=3.8, 0.7 Hz, 1H), 5.56 (t, *J*=6.7 Hz, 1H), 4.97 (d, *J*=6.7 Hz, 2H), 3.85 (s, 3H), 1.55 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.4 (C), 174.2 (C), 156.4 (C), 131.1 (C), 130.5 (C), 127.0 (CH), 117.9 (CH), 113.2 (CH), 108.0 (CH), 103.3 (CH), 97.8 (CH), 79.0 (CH_2), 55.6 (CH_3), 44.4 (C), 27.2 (CH_3). HRMS (ESI^+) m/z 278.1146 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO_2$: 278.1152.

4.2.7 1-(2,2-Dimethyl-1-oxopenta-3,4-dien-1-yl)-1*H*-indole-5-carboxylic acid methyl ester (**1g**)

Colorless oil. IR (KBr) 3165, 2987, 2941, 1947, 1710, 1694, 1441, 1306, 1287, 1271, 1224, 1183, 1151, 1082, 908, 863, 758 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 8.53 (d, *J*=8.8 Hz, 1H), 8.27 (dd, *J*=1.7, 0.6 Hz, 1H), 8.03 (dd, *J*=8.8, 1.7 Hz, 1H), 7.94 (d, *J*=3.9 Hz, 1H), 6.63 (dd, *J*=3.9, 0.6 Hz, 1H), 5.54 (t, *J*=6.6 Hz, 1H), 4.97 (d, *J*=6.6 Hz, 2H), 3.93 (s, 3H), 1.55 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.5 (C), 174.7 (C), 167.3 (C), 139.1 (C), 129.4 (C), 127.6 (CH), 126.3 (CH), 125.4 (C), 122.7 (CH), 116.8 (CH), 108.5 (CH), 97.4 (CH), 79.2 (CH_2), 52.0 (CH_3), 44.7 (C), 27.1 (CH_3). HRMS (ESI^+) m/z 306.1096 ($M+Na^+$), calcd for $C_{17}H_{17}NNaO_3$: 306.1101.

4.2.8 2,2-Dimethyl-1-(3-methyl-1*H*-indol-1-yl)penta-3,4-dien-1-one (**1h**)

Pale yellow oil. IR (KBr) 2981, 2935, 1955, 1688, 1608, 1449, 1389, 1344, 1240, 1217, 1180, 1063, 896, 850, 756 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 8.51 (d, *J*=8.3 Hz, 1H), 7.623–7.621 (br m, 1H), 7.50–7.48 (m, 1H), 7.38–7.34 (m, 1H), 7.32–7.28 (m, 1H), 5.56 (t, *J*=6.7 Hz, 1H), 4.98 (d, *J*=6.7 Hz, 2H), 2.28 (d, *J*=1.3 Hz, 3H), 1.56 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.6 (C), 174.2 (C), 136.9 (C), 130.6 (C), 125.1 (CH), 123.4 (CH), 123.2 (CH), 118.4 (CH), 117.24 (CH), 117.20 (CH), 97.9 (CH), 78.9 (CH_2), 44.4 (C), 27.2 (CH_3), 9.8 (CH_3). HRMS (ESI^+) m/z 262.1198 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.2.9 2,2-Dimethyl-1-(2-methyl-1*H*-indol-1-yl)penta-3,4-dien-1-one (**1i**)

Colorless oil. IR (KBr) 2975, 1956, 1704, 1456, 1384, 1294, 1207, 1108, 850, 742 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.48–7.45 (m, 2H), 7.18–7.11 (m, 2H), 6.35–6.34 (br m, 1H), 5.42 (t, *J*=6.7 Hz, 1H), 4.90 (d, *J*=6.7 Hz, 2H), 2.43 (d, *J*=0.9 Hz, 3H), 1.53 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.2 (C), 182.0 (C), 137.0 (C), 135.8 (C), 128.8 (C), 121.9 (CH), 121.4 (CH), 119.8 (CH), 113.3 (CH), 105.9 (CH), 96.8 (CH), 78.6 (CH_2), 46.6 (C), 27.2 (CH_3), 14.7 (CH_3). HRMS (ESI^+) m/z 262.1197 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.2.10 1-(1*H*-Indol-1-yl)-2,2-dimethylhexa-3,4-dien-1-one (**1j**)

Colorless oil. IR (KBr) 2981, 2932, 1963, 1697, 1537, 1449, 1386, 1314, 1207, 1183, 1153, 1077, 914, 884, 756, 720 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 8.51 (d, *J*=8.4 Hz, 1H), 7.93 (d, *J*=3.9 Hz, 1H), 7.54 (d, *J*=7.7 Hz, 1H), 7.36–7.32 (m, 1H), 7.28–7.24 (m, 1H), 6.56 (d, *J*=3.9 Hz, 1H), 5.50–5.46 (m, 1H), 5.39–5.32 (m, 1H), 1.68 (dd, *J*=7.1, 3.2 Hz, 3H), 1.54 (s, 3H), 1.53 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.8 (C), 174.9 (C), 136.5 (C), 129.6 (C), 126.6 (CH), 125.0 (CH), 123.5 (CH), 120.4 (CH), 117.1 (CH), 107.8 (CH), 98.0 (CH), 90.1 (CH), 45.2 (C), 27.6 (CH_3), 27.2 (CH_3), 13.7 (CH_3). HRMS (ESI^+) m/z 262.1200 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.3 General procedure for the photocycloaddition and physical data of the products: A small scale reaction for screening of the sensitizers or solvents (Table 1, Entry 7)

The reaction of **1a** is representative.

In a Pyrex test tube, **1a** (24.1 mg, 0.107 mmol) and 3',4'-methylenedioxyacetophenone (**S7**) (8.8 mg, 0.054 mmol) were charged. Air present in the tube was replaced with argon by several rapid evacuations/Ar introduction cycles. Ethyl acetate (11 mL) that had been degassed by three freeze-thaw cycles was transferred into the tube by a syringe. The solution was homogenized by sonication for a few seconds. The solution was externally irradiated by a 100 W high-pressure mercury lamp (UVL-100HA; Riko) for 30 min. After removal of the solvent, 1,1,2,2-tetrachloroethane (10.7 mg, 0.0637 mmol) was added to the mixture as an internal standard. The yields of **2a** and **3a**, and the recovery of **1a** were estimated by ^1H NMR integrals.

4.4 General procedure for the photocycloaddition and physical data of the products: A preparative scale reaction (Table 3, Entry 1)

The reaction of **1a** is representative.

In a Pyrex 50 mL photoreactor (UVL-100HA-50P-type; Riko), **1a** (44.9 mg, 0.199 mmol) and 3',4'-methylenedioxyacetophenone (**S7**) (16.4 mg, 0.0999 mmol) were charged, and air present in the vessel was replaced with argon by several rapid evacuations/Ar introduction cycles. Ethyl acetate (20 mL) that had been degassed by three freeze-thaw cycles was transferred into the vessel by a syringe. After homogenization by sonication, the solution was irradiated by a 100 W high-pressure mercury lamp internally for 20 min. The solution was concentrated under a reduced pressure. The crude material was purified by silica-gel thin layer chromatography to give the product **2a** (28.1 mg, 0.125 mmol, 63%) and **3a** (8.9 mg, 0.040 mmol, 20%) as a colorless solid.

4.4.1 *rac*-(9b*R*,9c*S*)-3,3-Dimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2a**)

Colorless solid. UV-vis (1.2×10^{-4} mol/L, ethyl acetate) $\lambda_{\max}$ 280 nm (shoulder, ε 3.5×10^{3}). IR (KBr) 2980, 2958, 1686, 1598, 1471, 1458, 1331, 1277, 1155, 1099, 835, 772, 760 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.71 (d, J=7.9 Hz, 1H), 7.24–7.20 (m, 2H), 7.04 (dt, J_d=1.1, J_t=7.4 Hz, 1H), 5.56–5.54 (m, 1H), 5.24 (dt, J_d=9.0, J_t=2.3 Hz, 1H), 3.93 (dt, J_d=3.5, J_t=9.0 Hz, 1H), 3.45 (ddd, J=15.3, 9.0, 2.4 Hz, 1H), 2.87–2.81 (m, 1H), 1.46 (s, 3H), 1.32 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 182.7 (C), 148.0 (C), 143.6 (C), 133.3 (C), 131.6 (CH), 128.1 (CH), 125.5 (CH), 124.0 (CH), 116.6 (CH), 64.4 (CH), 46.9 (C), 37.0 (CH), 36.4 (CH$_2$), 25.2 (CH$_3$), 22.9 (CH$_3$). HRMS (ESI$^+$) *m*/*z* 248.1041 (M+Na$^+$), calcd for $C_{15}H_{15}NNaO$: 248.1046. Anal. Calcd for $C_{15}H_{15}NO$: C, 79.97; H, 6.71; N, 6.22. Found: C, 79.86; H, 6.73; N, 6.19.

4.4.2 *rac*-(1a*R*,8b*S*,8c*R*)-2,2-Dimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3a**)

Colorless solid. UV-vis (3.7×10^{-4} mol/L, ethyl acetate) $\lambda_{\max}$ 283 nm (ε 1.6×10^{3}). IR (KBr) 2967, 2937, 1721, 1601, 1469, 1339, 1309, 1280, 1268, 1236, 1212, 1113, 1086, 909, 771, 749, 736 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.42 (d, J=7.7 Hz, 1H), 7.24–7.19 (m, 2H), 7.09 (dt, J_d=1.0, J_t=7.5 Hz, 1H), 5.17–5.12 (m, 2H), 4.87 (t, J=4.8 Hz, 1H), 3.99–3.97 (m, 1H), 3.39–3.37 (m, 1H), 1.32 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 186.1 (C), 149.6 (C), 146.9 (C), 137.1 (C), 127.6 (CH), 125.4 (CH), 123.6 (CH), 118.3 (CH), 116.7 (CH$_2$), 62.6 (CH), 54.1 (CH), 49.2 (CH), 48.0 (C), 23.8 (CH$_3$), 20.2 (CH$_3$). HRMS (ESI$^+$) *m*/*z* 248.1041 (M+Na$^+$), calcd for $C_{15}H_{15}NNaO$: 248.1046.

4.4.3 *rac*-(9b*R*,9c*S*)-8-Fluoro-3,3-dimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2b**)

Colorless solid (35.5 mg, 65%). IR (KBr) 2979, 2925, 1693, 1477, 1279, 1251, 1226, 1194, 1149, 1098, 858, 829 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.65–7.62 (m, 1H), 6.90–6.86 (m, 2H), 5.56 (dd, J=3.9, 2.3 Hz, 1H), 5.26 (dt, J_d=9.0, J_t=2.3 Hz, 1H), 3.89 (dt, J_d=3.5, J_t=9.0 Hz, 1H), 3.45 (ddd, J=15.3, 9.0, 2.4 Hz, 1H), 2.87–2.81 (m, 1H), 1.44 (s, 3H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 182.6 (C), 159.8 (d, $^{1}J_{C\text{–}F}$=241.5 Hz, C), 144.1 (C), 143.2 (C), 135.2 (d, $^{3}J_{C\text{–}F}$=7.7 Hz, C), 131.7 (CH), 117.2 (d, $^{3}J_{C\text{–}F}$=7.7 Hz, CH), 114.3 (d, $^{2}J_{C\text{–}F}$=23.0 Hz, CH), 112.7 (d, $^{2}J_{C\text{–}F}$=24.0 Hz, CH), 65.0 (CH), 46.8 (C), 36.9 (CH), 36.2 (CH$_2$), 25.2 (CH$_3$), 22.7 (CH$_3$). ^{19}F NMR (377 MHz, CDCl$_3$) δ −120.77– −120.82 (m). HRMS (ESI$^+$) *m*/*z* 266.0946 (M+Na$^+$), calcd for $C_{15}H_{14}FNNaO$: 266.0952.

4.4.4 *rac*-(1a*R*,8b*S*,8c*R*)-7-Fluoro-2,2-dimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3b**)

Colorless solid (12.3 mg, 23%). IR (KBr) 2976, 2961, 2933, 1725, 1472, 1307, 1270, 1197, 1082, 922, 816 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (dd, J=8.3, 4.6 Hz, 1H), 6.92–6.86 (m, 2H), 5.19–5.14 (m, 2H), 4.88 (dd, J=5.1, 4.6 Hz, 1H), 3.97–3.94 (m, 1H), 3.40–3.37 (m, 1H), 1.31 (s, 3H), 1.19 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 186.1 (C), 160.8 (d, $^{1}J_{C\text{–}F}$=243.0 Hz, C), 148.8 (C), 142.9 (C), 139.0 (d, $^{3}J_{C\text{–}F}$=8.6 Hz, C), 118.8 (d, $^{3}J_{C\text{–}F}$=8.9 Hz, CH), 117.2 (CH$_2$), 113.5 (d, $^{2}J_{C\text{–}F}$=23.5 Hz, CH), 111.4 (d, $^{2}J_{C\text{–}F}$=24.4 Hz, CH), 63.1 (CH), 54.2 (CH), 49.1 (CH), 47.8 (C), 23.8 (CH$_3$), 20.1 (CH$_3$). ^{19}F NMR (377 MHz, CDCl$_3$) δ −118.95– −119.01 (m). HRMS (ESI$^+$) *m*/*z* 266.0945 (M+Na$^+$), calcd for $C_{15}H_{14}FNNaO$: 266.0952.

4.4.5 *rac*-(9b*R*,9c*S*)-7-Chloro-3,3-dimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2c**)

Colorless solid (35.7 mg, 67%). IR (KBr) 2993, 2962, 1672, 1470, 1412, 1334, 1293, 1229, 1108, 862, 831, 813 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.71 (d, J=2.0 Hz, 1H), 7.09 (dd, J=7.9, 0.7 Hz, 1H), 6.99 (dd, J=7.9, 2.0 Hz, 1H), 5.55–5.54 (m, 1H), 5.25 (dt, J_d=8.9, J_t=2.3 Hz, 1H), 3.88 (dt, J_d=3.6, J_t=8.9 Hz, 1H), 3.44 (ddd, J=15.3, 9.0, 2.5 Hz, 1H), 2.83–2.77 (m, 1H), 1.44 (s, 3H), 1.32 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 182.6 (C), 149.0 (C), 143.3 (C), 133.7 (C), 131.9 (C), 131.5 (CH), 126.1 (CH), 124.0 (CH), 116.9 (CH), 65.0 (CH), 47.0 (C), 36.5 (CH), 36.5 (CH$_2$), 25.1 (CH$_3$), 22.7 (CH$_3$). HRMS (ESI$^+$) *m*/*z* 282.0653 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{35}ClNNaO$: 282.0656.

4.4.6 *rac*-(1a*R*,8b*S*,8c*R*)-6-Chloro-2,2-dimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3c**)

Colorless solid (10.1 mg, 19%). IR (KBr) 3084, 2973, 1721, 1600, 1469, 1415, 1384, 1332, 1303, 1281, 1238, 1212, 1144, 1087, 898 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.40 (d, J=1.8 Hz, 1H), 7.09 (d, J=7.9 Hz, 1H), 7.05 (dd, J=7.9, 1.8 Hz, 1H), 5.18–5.11 (m, 2H), 4.87 (dd, J=5.1, 4.6 Hz, 1H), 3.96–3.94 (m, 1H), 3.40–3.37 (m, 1H), 1.31 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (100 MHz, CDCl$_3$) δ 185.8 (C), 149.1 (C), 148.0 (C), 135.8 (C), 133.1 (C), 125.3 (CH), 124.1

(CH), 118.9 (CH), 117.1 (CH_2), 63.1 (CH), 54.2 (CH), 48.7 (CH), 47.9 (C), 23.7 (CH_3), 20.1 (CH_3). HRMS (ESI$^+$) *m*/*z* 282.0652 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{35}ClNNaO$: 282.0656.

4.4.7 *rac*-(9b*R*,9c*S*)-8-Bromo-3,3-dimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2d**)

Colorless solid (35.7 mg, 57%). IR (KBr) 2969, 2930, 1687, 1592, 1463, 1386, 1305, 1283, 1250, 1227, 1180, 1157, 1100, 819 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59–7.56 (m, 1H), 7.32–7.29 (m, 2H), 5.56–5.54 (m, 1H), 5.24 (dt, J_d=9.0, J_t=2.3 Hz, 1H), 3.89 (dt, J_d=3.5, J_t=9.0 Hz, 1H), 3.45 (ddd, *J*=15.3, 9.0, 2.5 Hz, 1H), 2.87–2.81 (m, 1H), 1.44 (s, 3H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.6 (C), 147.1 (C), 143.2 (C), 135.6 (C), 131.6 (CH), 130.9 (CH), 128.6 (CH), 117.9 (CH), 116.4 (C), 64.7 (CH), 47.0 (C), 36.8 (CH), 36.4 (CH_2), 25.2 (CH_3), 22.7 (CH_3). HRMS (ESI$^+$) *m*/*z* 326.0146 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{79}BrNNaO$: 326.0151.

4.4.8 *rac*-(1a*R*,8b*S*,8c*R*)-7-Bromo-2,2-dimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3d**)

Colorless solid (12.5 mg, 20%). IR (KBr) 2969, 2936, 1727, 1601, 1462, 1318, 1305, 1281, 1265, 1238, 1212, 1164, 903, 817 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34–7.30 (m, 2H), 7.27 (d, *J*=8.2 Hz, 1H), 5.19–5.15 (m, 2H), 4.86 (dd, *J*=5.0, 4.6 Hz, 1H), 3.98–3.95 (m, 1H), 3.40–3.37 (m, 1H), 1.31 (s, 3H), 1.19 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.8 (C), 148.7 (C), 146.1 (C), 139.4 (C), 130.4 (CH), 126.8 (CH), 119.6 (CH), 118.2 (C), 117.3 (CH_2), 62.8 (CH), 54.2 (CH), 49.0 (CH), 47.9 (C), 23.7 (CH_3), 20.1 (CH_3). HRMS (ESI$^+$) *m*/*z* 326.0150 (M+Na$^+$), calcd for $C_{15}H_{14}{}^{79}BrNNaO$: 326.0151.

4.4.9 *rac*-(9b*R*,9c*S*)-3,3,8-Trimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2e**)

Colorless solid (33.0 mg, 68%). IR (KBr) 2983, 2925, 1681, 1472, 1384, 1320, 1286, 1279, 1224, 1162, 821 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61–7.59 (m, 1H), 7.03–7.01 (m, 2H), 5.54–5.52 (m, 1H), 5.22 (dt, J_d=8.9, J_t=2.4 Hz, 1H), 3.88 (dt, J_d=3.5, J_t=8.9 Hz, 1H), 3.43 (ddd, *J*=15.3, 9.0, 2.5 Hz, 1H), 2.84–2.79 (m, 1H), 2.30 (s, 3H), 1.45 (s, 3H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.7 (C), 145.7 (C), 143.6 (C), 133.6 (C), 133.3 (C), 131.5 (CH), 128.5 (CH), 126.1 (CH), 116.2 (CH), 64.6 (CH), 46.8 (C), 36.9 (CH), 36.2 (CH_2), 25.2 (CH_3), 22.8 (CH_3), 20.9 (CH_3). HRMS (ESI$^+$) *m*/*z* 262.1196 (M+Na$^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.10 *rac*-(1a*R*,8b*S*,8c*R*)-2,2,7-Trimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3e**)

Faintly brown solid (9.9 mg, 20%). IR (KBr) 2963, 1725, 1479, 1325, 1308, 1279, 1241, 1208, 1154, 1115, 1082, 897, 815 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31–7.29 (m, 1H), 7.02–7.01 (m, 2H), 5.16–5.13 (m, 2H), 4.84 (dd, *J*=5.1, 4.6 Hz, 1H), 3.95–3.92 (m, 1H), 3.38–3.35 (m, 1H), 2.31 (s, 3H), 1.31 (s, 3H), 1.19 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.2 (C), 149.6 (C), 144.5 (C), 137.1 (C), 135.1 (C), 127.9 (CH), 124.5 (CH), 117.8 (CH), 116.6 (CH_2), 62.7 (CH), 54.0 (CH), 49.2 (CH), 47.9 (C), 23.9 (CH_3), 21.1 (CH_3), 20.1 (CH_3). HRMS (ESI$^+$) *m*/*z* 262.1195 (M+Na$^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.11 *rac*-(9b*R*,9c*S*)-8-Methoxy-3,3-dimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2f**)

Pale yellow solid (24.3 mg, 44%). IR (KBr) 2934, 1680, 1589, 1480, 1286, 1257, 1227, 1202, 1165, 1099, 1032, 852, 818 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 (d, *J*=8.7 Hz, 1H), 6.77–6.72 (m, 2H), 5.55–5.53 (m, 1H), 5.24 (dt, J_d=8.9, J_t=2.4 Hz, 1H), 3.89 (dt, J_d=3.5, J_t=8.9 Hz, 1H), 3.76 (s, 3H), 3.43 (ddd, *J*=15.3, 9.1, 2.4 Hz, 1H), 2.86–2.80 (m, 1H), 1.44 (s, 3H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.7 (C), 156.7 (C), 143.5 (C), 141.7 (C), 134.7 (C), 131.6 (CH), 117.0 (CH), 112.3 (CH), 111.8 (CH), 64.9 (CH), 55.6 (CH_3), 46.7 (C), 37.0 (CH), 36.0 (CH_2), 25.2 (CH_3), 22.8 (CH_3). HRMS (ESI$^+$) *m*/*z* 278.1146 (M+Na$^+$), calcd for $C_{16}H_{17}NNaO_2$: 278.1152.

4.4.12 *rac*-(1a*R*,8b*S*,8c*R*)-7-Methoxy-2,2-dimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3f**)

Colorless solid (9.2 mg, 15%). IR (KBr) 2962, 1723, 1593, 1477, 1311, 1276, 1234, 1208, 1083, 1030, 815 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (d, *J*=8.5 Hz, 1H), 6.78 (d, *J*=2.6 Hz, 1H), 6.71 (dd, *J*=8.5, 2.6 Hz, 1H), 5.17–5.13 (m, 2H), 4.85 (dd, *J*=5.1, 4.6 Hz, 1H), 3.95–3.92 (m, 1H), 3.77 (s, 3H), 3.37–3.35 (m, 1H), 1.31 (s, 3H), 1.19 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.3 (C), 157.8 (C), 149.3 (C), 140.2 (C), 138.6 (C), 118.4 (CH), 116.8 (CH_2), 111.02 (CH), 110.97 (CH), 63.0 (CH), 55.7 (CH_3), 54.0 (CH), 49.4 (CH), 47.8 (C), 23.9 (CH_3), 20.1 (CH_3). HRMS (ESI$^+$) *m*/*z* 278.1145 (M+Na$^+$), calcd for $C_{16}H_{17}NNaO_2$: 278.1152.

4.4.13 *rac*-(9b*R*,9c*S*)-3,3-Dimethyl-4-oxo-3,4,9b,9c-tetrahydro-1*H*-benzo[*b*]cyclobuta[*hi*]indolizine-8-carboxylic acid methyl ester (**2g**)

Pale yellow solid (19.1 mg, 34%). IR (KBr) 2951, 1716, 1692, 1605, 1475, 1440, 1333, 1283, 1257, 1192, 1176, 1162, 1106, 1094, 775 cm^{-1}. ^{1}H NMR

(400 MHz, $CDCl_3$) δ 7.93 (ddd, J=8.5, 1.7, 0.3 Hz, 1H), 7.88–7.87 (m, 1H), 7.72 (d, J=8.5 Hz, 1H), 5.56–5.55 (m, 1H), 5.27 (dt, J_d=8.9, J_t=2.3 Hz, 1H), 3.94 (dt, J_d=3.5, J_t=8.9 Hz, 1H), 3.87 (s, 3H), 3.48 (ddd, J=15.4, 9.0, 2.4 Hz, 1H), 2.87–2.82 (m, 1H), 1.45 (s, 3H), 1.32 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.6 (C), 166.7 (C), 151.8 (C), 143.4 (C), 133.6 (C), 131.5 (CH), 130.7 (CH), 127.1 (CH), 125.9 (C), 115.8 (CH), 64.8 (CH), 52.0 (CH_3), 47.2 (C), 36.7 (CH_2), 36.6 (CH), 25.2 (CH_3), 22.8 (CH_3). HRMS (ESI^+) m/z 306.1095 ($M+Na^+$), calcd for $C_{17}H_{17}NNaO_3$: 306.1101.

4.4.14 *rac*-(1a*R*,8b*S*,8c*R*)-2,2-Dimethyl-1-methylene-3-oxo-1,1a,2,3,8b,8c-hexahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizine-7-carboxylic acid methyl ester (**3g**)

Colorless solid (6.8 mg, 12%). IR (KBr) 2972, 2958, 1715, 1606, 1442, 1282, 1262, 1163, 902 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.95 (dd, J=8.1, 1.7 Hz, 1H), 7.87–7.86 (m, 1H), 7.44 (d, J=8.1 Hz, 1H), 5.18–5.15 (m, 2H), 4.90 (dd, J=5.1, 4.6 Hz, 1H), 4.04–4.02 (m, 1H), 3.89 (s, 3H), 3.42–3.40 (m, 1H), 1.32 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.6 (C), 166.8 (C), 151.0 (C), 149.0 (C), 137.6 (C), 130.2 (CH), 127.3 (C), 124.9 (CH), 117.7 (CH), 117.3 (CH_2), 62.8 (CH), 54.3 (CH), 52.1 (CH_3), 48.7 (CH), 48.1 (C), 23.7 (CH_3), 20.1 (CH_3). HRMS (ESI^+) m/z 306.1094 ($M+Na^+$), calcd for $C_{17}H_{17}NNaO_3$: 306.1101.

4.4.15 *rac*-(9b*R*,9c*S*)-3,3,9b-Trimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2h**)

Colorless solid (26.0 mg, 53%). IR (KBr) 2978, 2965, 2931, 1684, 1597, 1470, 1449, 1326, 1294, 1275, 1257, 1188, 1159, 1099, 839, 763 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.72–7.70 (m, 1H), 7.24–7.18 (m, 2H), 7.07 (dt, J_d=1.1, J_t=7.4 Hz, 1H), 5.55–5.54 (m, 1H), 4.78 (t, J=2.3 Hz, 1H), 3.11 (dd, J=15.3, 2.4 Hz, 1H), 2.99 (ddd, J=15.3, 2.4, 1.7 Hz, 1H), 1.63 (s, 3H), 1.46 (s, 3H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.9 (C), 147.2 (C), 140.8 (C), 137.4 (C), 131.7 (CH), 128.2 (CH), 124.2 (CH), 123.7 (CH), 116.5 (CH), 70.2 (CH), 46.8 (C), 43.8 (C), 42.8 (CH_2), 26.2 (CH_3), 25.3 (CH_3), 22.8 (CH_3). HRMS (ESI^+) m/z 262.1197 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.16 *rac*-(1a*R*,8b*S*,8c*R*)-2,2,8b-Trimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3h**)

Colorless solid (9.9 mg, 20%). IR (KBr) 2960, 1727, 1602, 1469, 1277, 1247, 1117, 772, 743 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.41–7.39 (m, 1H), 7.24–7.19 (m, 1H), 7.15–7.10 (m, 2H), 5.10–5.08 (m, 2H), 4.49 (d, J=4.6 Hz, 1H), 3.42–3.40 (m, 1H), 1.57 (m, 3H), 1.33 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.8 (C), 154.7 (C), 146.6 (C), 140.9 (C), 127.5 (CH), 125.4 (CH), 121.8 (CH), 118.1 (CH), 114.9 (CH_2), 67.6 (CH), 54.6 (C), 52.0 (CH), 47.6 (C), 23.8 (CH_3), 20.4 (CH_3), 18.9 (CH_3). HRMS (ESI^+) m/z 262.1196 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.17 *rac*-(9b*R*,9c*S*)-3,3,9c-Trimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2i**)

Colorless oil (2.5 mg, 5.0%). IR (KBr) 2965, 2928, 1685, 1599, 1471, 1457, 1269, 1136, 835, 768, 743 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, J=8.0 Hz, 1H), 7.23–7.18 (m, 2H), 7.04 (dt, J_d=1.0, J_t=7.4 Hz, 1H), 5.54–5.53 (m, 1H), 3.45–3.42 (m, 1H), 3.38 (dd, J=9.4, 2.3 Hz, 1H), 2.83–2.77 (m, 1H), 1.77 (s, 3H), 1.56 (s, 3H), 1.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.8 (C), 148.3 (C), 144.5 (C), 132.6 (C), 130.9 (CH), 128.2 (CH), 125.7 (CH), 123.9 (CH), 116.0 (CH), 71.2 (C), 46.9 (C), 44.5 (CH), 34.7 (CH_2), 28.8 (CH_3), 27.7 (CH_3), 24.4 (CH_3). HRMS (ESI^+) m/z 262.1198 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.18 *rac*-(1a*R*,8b*S*,8c*R*)-2,2,8c-Trimethyl-1-methylene-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3i**)

Faintly yellow solid (10.5 mg, 21%). IR (KBr) 2963, 2939, 1720, 1604, 1470, 1378, 1336, 1285, 1266, 1119, 1022, 917, 776, 752 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.42 (d, J=7.7 Hz, 1H), 7.25–7.19 (m, 2H), 7.10 (dt, J_d=1.0, J_t=7.4 Hz, 1H), 5.15–5.12 (m, 2H), 3.65 (t, J=2.4 Hz, 1H), 3.11 (t, J=2.4 Hz, 1H), 1.57 (s, 3H), 1.38 (s, 3H), 1.17 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.9 (C), 147.6 (C), 146.0 (C), 136.5 (C), 127.6 (CH), 125.5 (CH), 124.2 (CH), 118.6 (CH), 116.4 (CH_2), 70.4 (C), 57.7 (CH), 54.1 (CH), 48.3 (C), 25.3 (CH_3), 21.0 (CH_3), 20.9 (CH_3). HRMS (ESI^+) m/z 262.1195 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.19 1,3,3-Trimethyl-1,3,9b,9c-tetrahydro-4*H*-benzo[*b*]cyclobuta[*hi*]indolizin-4-one (**2j**)

rac-(1*R*,9b*R*,9c*S*):*rac*-(1*S*,9b*R*,9c*S*)=3:1. Faintly yellow oil (23.0 mg, 40%). IR (KBr) 2964, 1686, 1598, 1471, 1458, 1335, 1282, 1257, 1226, 1180, 1158, 1101, 768, 746 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.72–7.70 (m, 1H), 7.23–7.19 (m, 1H), 7.12–7.10 (m, 1H), 7.05–7.00 (m, 1H), 5.55 (dd, J= 2.2, 1.4 Hz, minor 1H), 5.52 (t, J= 2.3 Hz, major 1H), 5.27 (dt, J_d=9.0, J_t=2.3 Hz, minor 1H), 5.15 (dd, J=8.9, 2.1 Hz, major 1H), 3.97 (t, J= 8.9 Hz, major 1H), 3.71–3.63 (m, major 1H), 3.48 (dd, J=9.0, 3.1 Hz, minor 1H), 3.19–3.13 (m, minor 1H), 1.48 (d, J=7.4 Hz, minor 3H), 1.46 (s, major 3H), 1.45 (s, minor 3H), 1.32 (s, 3H), 0.98 (d, J=6.9 Hz, major 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.8 (C), 182.7 (minor, C), 151.4 (C), 148.8 (C), 147.83 (minor, C), 147.80 (minor, C), 132.9 (minor, C), 131.2 (CH), 130.1 (C), 129.1 (CH), 128.1 (CH), 126.5 (CH), 125.4 (minor, CH), 124.0 (minor, CH), 123.7 (CH), 117.0 (CH), 116.5 (minor, CH), 62.7 (minor, CH), 62.4 (CH), 46.8 (minor, C), 46.6 (C), 45.4 (minor, CH), 45.3 (minor, CH), 41.9 CH), 41.5 (CH), 25.23 (minor, CH_3), 25.19 (CH_3), 23.3 (CH_3), 22.8 (minor, CH_3), 20.5 (minor, CH_3), 15.0 (CH_3). HRMS (ESI^+) *m*/*z* 262.1197 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.20 *rac*-(1a*R*,8b*S*,8c*R*)-1-Ethylidene-2,2-dimethyl-1a,2,8b,8c-tetrahydrobenzo[*b*]cyclobuta[*gh*]pyrrolizin-3(1*H*)-one (**3j**)

E:*Z*=3:2. Colorless oil (18.1 mg, 32%). IR (KBr) 2964, 1726, 1602, 1469, 1281, 1269, 1239, 1212, 1089, 777, 761, 728 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 7.43–7.40 (m, 1H), 7.24–7.16 (m, 2H), 7.10–7.05 (m, 1H), 5.60–5.51 (m, 1H), 4.87–4.83 (m, 1H), 4.06–4.04 (m, major 1H), 3.93–3.90 (m, minor 1H), 3.49–3.47 (m, minor 1H), 3.31–3.27 (m, major 1H), 1.58 (dt, J_d=7.1, J_t=1.8 Hz, minor 3H), 1.54 (dt, J_d=6.7, J_t=1.8 Hz, major 3H), 1.34 (s, mior 3H), 1.30 (s, major 3H), 1.18 (s, minor 3H), 1.17 (s, major 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.44 (minor, C), 186.39 (C), 146.8 (C), 146.7 (minor, C), 139.8 (minor, C), 139.5 (C), 137.4 (minor, C), 136.8 (C), 127.44 (CH), 127.40 (minor, CH), 127.3 (CH), 127.2 (minor, CH), 125.3 (minor, CH), 125.1 (CH), 124.6 (CH), 123.6 (minor, CH), 118.4 (CH), 118.1 (minor, CH), 62.7 (minor, CH), 62.6 (CH), 53.7 (minor, CH), 53.2 (CH), 49.2 (minor, C), 48.6 (minor, CH), 47.8 (CH), 47.7 (C), 24.2 (minor, CH_3), 23.8 (CH_3), 22.3 (minor, CH_3), 20.3 (CH_3), 15.2 (minor, CH_3), 15.4 (CH_3). HRMS (ESI^+) *m*/*z* 262.1196 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

4.4.21 7,7-Dimethyl-9-vinyl-9a,10-dihydropyrido[1,2-*a*]indol-6(7*H*)-one (**4**)

Colorless solid (3.3 mg, 5.8%). IR (KBr) 2966, 1659, 1600, 1481, 1463, 1407, 1298, 1282, 760 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$) δ 8.13 (d, *J*=7.9 Hz, 1H), 7.26–7.23 (m, 2H), 7.07 (dt, J_d=1.0, J_t=7.4 Hz, 1H), 6.32 (ddt, J_d=17.8, 11.3, J_t=0.8 Hz, 1H), 5.78 (d, *J*=1.9, 1H), 5.30 (d, *J*=17.8 Hz, 1H), 5.19 (d, *J*=11.3 Hz, 1H), 5.06–5.01 (m, 1H), 3.40 (dd, *J*=15.1, 7.8 Hz, 1H), 3.09–3.02 (m, 1H), 1.39 (s, 3H), 1.34 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.3 (C), 142.2 (C), 134.9 (CH), 134.7 (CH), 132.6 (C), 130.9 (C), 127.5 (CH), 124.4 (CH), 124.3 (CH), 117.8 (CH), 114.7 (CH_2), 61.4 (CH), 40.6 (C), 35.6 (CH_2), 26.9 (CH_3), 26.3 (CH_3). HRMS (ESI^+) *m*/*z* 262.1198 ($M+Na^+$), calcd for $C_{16}H_{17}NNaO$: 262.1202.

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Conflict of Interest

I have no conflict of interest to declare.

Data Availability Statement

^1H NMR, ^{13}C NMR spectra for all new compounds, UV-vis spectral charts for **1a**, **2a**, **3a**, **S7**, and *p*-terphenyl, emission property of the photoreactor, and CIF for **2a** are available in the supplementary material for this article.

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