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Photoreactions of 1-Acetylisatin with Alkynes: Regioselectivity in Oxetene Formation and Easy Access to 3-Alkylideneoxindoles and Dispiro[oxindole[3,2′]furan[3′,3″]oxindole]s

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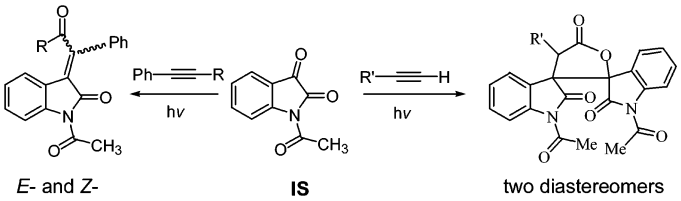
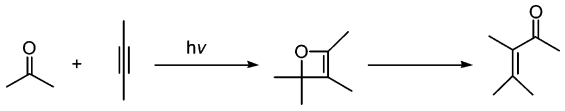


Photoinduced reactions of 1-acetylisatin (IS) with diphenylacetylenes **1a**−**c**, 1-(*p*-methoxyphenyl)-propyne **2**, and 1,4-diphenyl-1,3-butadiyne **3** gave *β*,*β*-disubstituted 3-alkylidene oxindoles **6**−**12** respectively via [2+2] cycloaddition of ^{3}IS* with the alkyne and subsequent oxetene ring opening. Photoreactions of IS with phenylacetylenes **4a**−**d** and cyclopropylacetylene **5** furnished the dispiroindole[3,2′]furan[3′,3″]indoles **13** and **14**. Compounds **13** and **14** are formed in tandem reactions initiated by [2+2] cycloaddition of ^{3}IS* with the alkynes to give spirooxetenes **Va** and **Vb**, which upon spontaneous ring opening gave the α,*β*-unsaturated aldehydes **IVa** and **IVb**. It is proposed that hydrogen abstraction of ^{3}IS* from the C(O)−H functionality in **IV** followed by dissociation of the triplet isatin ketyl (**A**)−aldehyde acyl (**B**) radical pair and an oxygenphilic attack of the acyl radical **B** at the C3 carbonyl oxygen atom of a neutral IS gave the 2:1 (IS:**4**) radical **C**, which took part in an intramolecular radical cyclization to give the dispiroindole[3,2′]furan[3′,3″]-indoles **13** and **14**. The regioselectivity in the [2+2] photocycloadditions of IS with **4** to afford the oxetene **Va** depends on the intervening of the more stable 1,4-diradical intermediates **VI**, which have a linear α-phenyl-substituted vinyl radical where the phenyl provides spin delocalization of the radical center at the sp carbon atom.

Introduction

Photoinduced reactions of nπ^* excited state carbonyl compounds with alkynes take place via [2+2] cycloaddition to give the thermally labile oxetenes,[1]which undergo spontaneous electrocyclic ring opening at ambient temperature to afford α,*β*-unsaturated carbonyl compounds as final products (Scheme 1).[2−4] Despite the inherent mechanistic ingenuity and synthetic utility, these reactions are not as widely investigated as the photocycloadditions of carbonyl compounds with alkenes (the Paterno−Büchi reaction[5]). Mechanistic issues, such as structure of the 1,4-diradical intermediate and regioselectivity in the oxetene formation, and the scope and synthetic applications of these reactions need to be further inves-

SCHEME 1



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tigated. 1,2-Disubstituted acetylenes and diarylacetylenes have been found to undergo photocycloadditions with a variety of carbonyl addends, including aldehydes,[2] quinones,[3] and aromatic ketones.[4] In sharp contrast, photocycloadditions of carbonyl compounds with the more electron deficient terminal alkynes such as phenylacetylenes are scarcely reported.[4,6] Photoinduced cycloadditions of the C=O bond of (nπ^*) carbonyl compounds with alkenes and alkynes are initiated by orbital interaction between the low-lying half-occupied n orbital of the carbonyl addends with the highest occupied π orbital in the alkenes and alkynes.[7] As a result, the presence of a high-lying π orbital in the alkyne (as manifested by a low ionization potential or oxidation potential) is necessary. Therefore, only a few quinones[4,6] and electron-deficient ketones[4] have been reported to engage in photoreactions with phenylacetylene.

Isatin derivatives are important precursors in the synthesis of many naturally occurring oxindole alkaloids and their unnatural analogues of various biological activity.[8] With an electron-withdrawing acetyl at the nitrogen atom, 1-acetylisatin (IS) has a nπ^* triplet state (T_1)[9] with a E_T of 64 kcal·mol^{-1} and a reduction potential of -0.75 V (SCE).[10,11] This combination of a rather high E_T and a small negative $E^{red}_{1/2}$ makes it a strong electron-acceptor compound and enables it to take part in photocycloadditions with rather electron-deficient alkenes.[10] We have shown that these Paterno–Büchi reactions of IS with alkenes and further chemical transformations of the spirooxetane products provide an efficient and versatile synthetic approach for the oxindole structural elaboration at the C3 atom. We have further found that photoexcited IS could react not only with diphenylacetylene, but also with the more electron-deficient phenylacetylene.[11] These reactions lead to the formation of a series of β,β-disubstituted 3-alkylidene oxindoles and dispirocyclic butyrolactone fused oxindole derivatives in high yields, respectively. Since both the two types of C3 derivatized oxindoles are important classes of compounds not only on their own for having a diversity of biological activity,[12–14] but also because they are basic building blocks in the synthesis of different spiroxindole alkaloids and their analogues,[15–20] we have further investigated the scope and the mechanism of these reactions by studying the photoreactions of IS with the alkynes **1**–**5**. The results are reported here.

Results and Discussion

I. Photoinduced Reactions of IS with 1,2-Disubstituted Acetylenes 1–3. Irradiation of IS with diphenylacetylene **1a** gave the (*Z*)-3-(1,2-diphenyl-2-oxoethylidene)oxindole **6a** (43%) and its *E*-isomer **8a** (37%). These two isomers could not be fully separated by column chromatography, and the ratio was determined by ^{1}H NMR measurement of the product mixture. Photoinduced reactions of IS with the monosubstituted diphenylacetyl-

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CHART 1

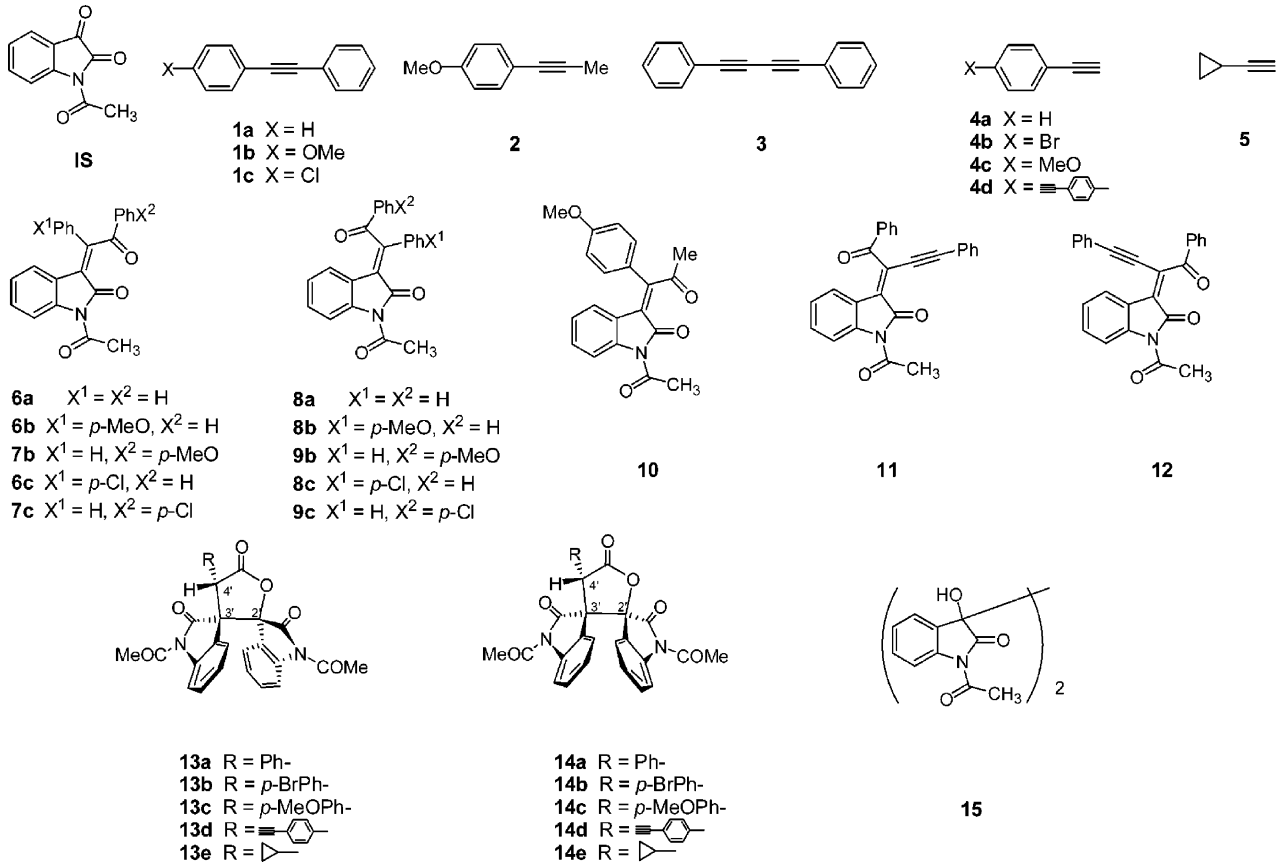


TABLE 1. Photoreactions of IS with the Alkynes[a]

entry	alkyne	irrd time, h	conv, %	products (yield, %)[b]
1	**1a**	24	100	**6a** (43), **8a** (37)[11]
2	**1b**	24	63	**6b**(48), **7b** (27), **8b** (6), **9b** (9)[11]
3	**1c**	24	50	**6c** (21), **7c** (41), **8c** (14), **9c** (8)[11]
4	**2**	24	100	**10** (93)
5	**3**	24	48	**11** (44), **12** (48)
6	**4a**	20	100	**13a** (52), **14a**(27)[11]
7	**4b**	48	100	**13b** (46), **14b** (23), **15** (25)
8	**4c**	72	75	**13c** (53), **14c** (28), **15** (15)
9	**4d**	48	70	**13d** (56), **14d** (23), **15** (14)
10	**5**	48	62	**13e** (47), **14e** (23), **15** (21)

[a] All the reactions were carried out in benzene solution. For reaction scale, see the Experimental Section. [b] Yields of isolated products based on consumed IS. For entries 1−3, the product ratio is determined by ^{1}H NMR measurement of the product mixture.

enes **1b** and **1c** similarly gave the quinone methides **6b** (48%), **7b** (27%), **8b** (6%), **9b** (9%) and **6c** (21%), **7c** (41%), **8c** (14%), **9c** (8%) respectively, each as two pairs of regioisomeric geometric isomers (Table 1). All these 3-alkylideneoxindoles have a more extended π-system than in IS to show strong absorptions in the wavelength region used for irradiation, and are subjected to photoinduced *E*-,*Z*-isomerizations during the reactions. The *E*-/*Z*-product ratio, therefore, likely does not represent the ratio when they are initially formed.

Photoreactions of IS with 1-(4-methoxyphenyl)propyne **2** afforded the (*Z*)-1-acetyl-3-[1-(*p*-methoxyphenyl)-2-oxopropylidene]oxindole **10** (93%) as the only product, while photolysis of IS with 1,4-diphenyl-1,3-butadiyne **3** furnished the corresponding 3-alkylideneoxindoles ***E*-11** (44%) and *Z*-**12** (48%). The steric configurations of these products are established by X-ray crystallographic analysis of **10** and **11** (Figure 1). It is seen that the cycloadditions of ^{3}IS* with **2** and **3** are regiospecific, the products **10**, **11**, and **12** are formed from the ring opening of the oxetenes **Ia** and **Ib** (Chart 2), respectively, which in turn are derived from the thermodynamically more stable 1,4-diradical intermediates **IIa** and **IIb**, respectively (vide infra).

Products **6**−**12** are 3-alkylideneoxindoles with different substitution patterns at the 3-methylene position. 3-Alkylideneoxindoles are known to have biological activities,[12−14] and are important synthetic precursors for the synthesis of a wide range of polycyclic oxindole alkaloids as represented by spirotryprostatins[15a,b] and alstonisine[15c]

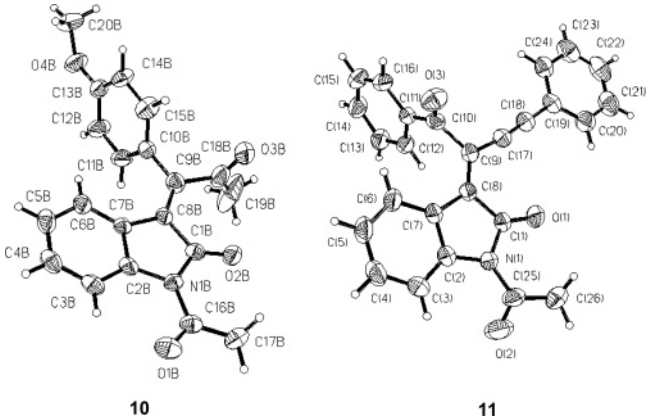
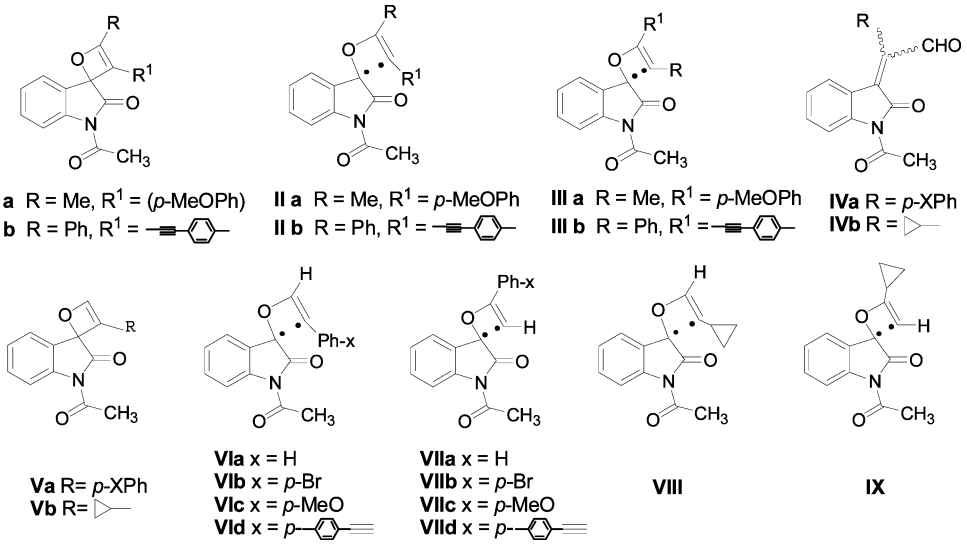


FIGURE 1. ORTEP drawing of **10** and **11**.

CHART 2



by 1,3-dipolar cycloadditions[16] and Diels−Alder reactions.[17,18] Therefore, the syntheses of 3-alkylideneoxindoles have drawn much recent attention.[21] The results in photoreactions of IS with the disubstituted acetylenes **1**−**3** showed that these reactions provide a convenient access to *β*,*β*-disubstituted 3-alkylidene oxindoles.

II. Photoinduced Reactions of IS with the Monosubstituted Acetylenes 4 and 5. IS can also react with the more electron-deficient terminal acetylenes. Therefore, photoreactions of IS with phenylacetylenes **4a**−**d** gave pairs of diastereomeric dispiroindole[3,2′]furan-[3′,3″]indoles **13a**−**13d** and **14a**−**14d**, respectively. Small amounts of isatide (**15**) were also formed in these reactions (Table 1). The steric structures of these 2:1 (IS**:** 4) adducts **13** and **14** are based on the X-ray crystallographic structure measurement of **13c** and **14b** (Figure 2). In the major isomer **13**, the three stereogenic carbon atoms 2′, 3′, and 4′ (C(20), C(10), and C(11) in **13c**, respectively, in Figure 2,) have *R*, *S*, *S* configurations, and the two oxindole rings are anti to each other, while in the minor isomer **14**, these stereogenic atoms (C(1), C(19), and C(17), respectively, in **14b** in Figure 2) are of *S*, *S*, *R* configurations, respectively, with the two oxindole rings syn to each other. Similar to the reactions with the phenylacetylenes **4a**−**d**, photoreactions of IS with cyclopropylacetylene **5** gave the corresponding 2:1 adducts **13e** and **14e**.

These 2:1 (IS:**4**) adducts **13** and **14** are obviously not directly formed in photoreactions of IS with **4**, but are formed by secondary photoreactions of IS with the primary products **IV**, which are in turn derived from electrocyclic ring opening of the oxetene **V** formed by regioselective [2+2] photocycloadditions of IS with **4** and **5**. This regioselectivity in the formation of **Va** is similar to that found in the oxetenes **Ia** and **Ib** from photoreactions of IS with **2** and **3**. In each oxetene (**I** and **V**), the phenyl is at the C(3′) atom of the oxetene ring. We envision that this regioselectivity results from the intervening of the more stable 1,4-diradical intermediate in these "Paterno−Büchi"-type reactions,[22] and suggests a greater thermodynamic stability of the 1,4-diradical intermediates **II** and **VI** than the corresponding regioisomeric diradicals **III** and **VII**. We have carried out a DFT calculation of the structures of the triplet 1,4-diradicals **VIa** and **VIIa** at the UB3LYP/6-31G* level[23] and it turns out that in **VIa**, the α-phenyl vinyl radical center has a linear structure (phenyl to C=C bond angle: 177°) as shown in Figure 3, with the spin bearing carbon atom having an sp hybridization so that the phenyl π system is orthogonal with the vinyl C=C π orbital but is parallel with the singly occupied p-orbital at the sp-hybridized carbon atom, resulting in unpaired electron delocalization to the phenyl. In contrast, in **VIIa** (Figure 3), the *β*-phenyl-substituted vinyl radical is a σ radical with a bent configuration (H to C=C bond angle: 136°) (Figure 3) and the radical center is sp^2 hybridized, with the phenyl π system being parallel and conjugated with the vinyl π system, but orthogonal to the lone pair sp^2 orbital at the radical center. Therefore, diradical **VI** (and **II)** with a spin delocalized vinyl radical is 11.32 kcal·mol^{-1} more stable than **VII** (and **III)** with a localized *β*-phenyl vinyl radical. This result is in accord with recent computational[24] and ESR experimental investigation[25] on the structure of simple vinyl radicals which showed that the *β*-unsubstituted α-phenyl vinyl radical ($H_2C{=}C(^{\bullet})Ph$) has a linear structure with an sp radical center carbon

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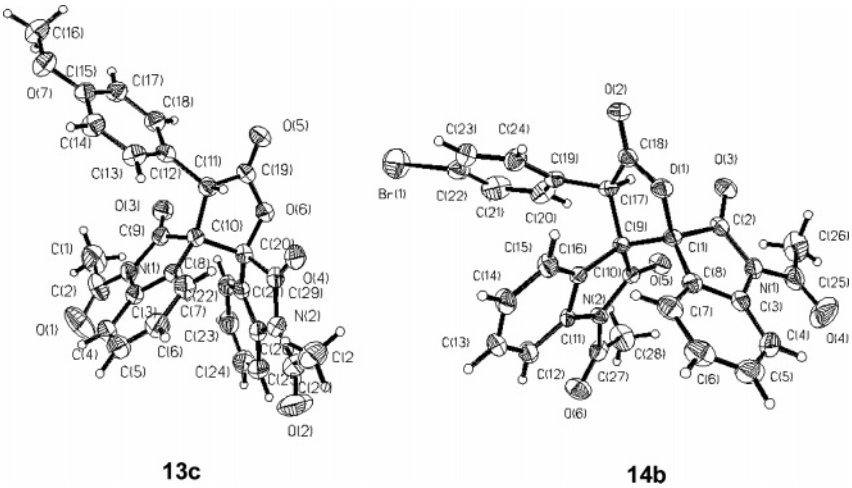

FIGURE 2. ORTEP drawing of **13c** and **14b**.

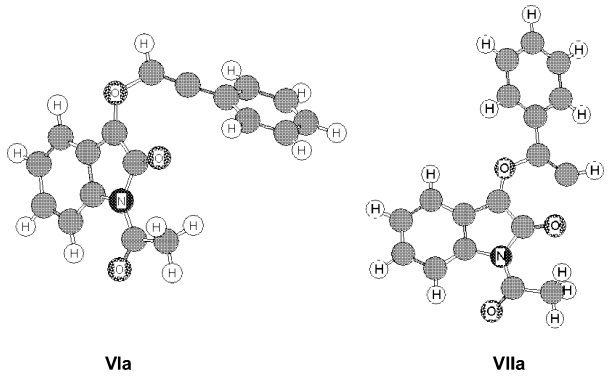

FIGURE 3. Structures of diradical intermediates **VIa** and **VIIa**.

atom and the phenyl is orthogonal with the vinyl π system but parallel with the lone pair p orbital at the radical center to allow efficient spin delocalization to the phenyl. In the case of formation of oxetene **Vb** by photoreactions of IS with **5**, DFT UB3LYP/6-31G* calculation of the triplet diradicals **VIII** and **IX** showed that the α-cyclopropylvinyl radical in **VIII** and the β-cyclopropylvinyl radical in **IX** are all σ radicals with the unpaired electron in a sp^2 orbital. However, diradical **VIII** is 4.77 kcal·mol^{-1} more stable than **IX**. ISC in **VIII** followed by cyclization gave **Vb**.

We propose that the formation of **13** and **14** from the photoreactions of **IS** with **4** is initiated by hydrogen abstraction of the triplet excited IS (^{3}IS*) from **IV**. Aldehydes have a weak C(O)−H bond with a dissociation enthalpy of 86 kcal·mol^{-1},[26] close to that for benzylic (88 kcal·mol^{-1}) and allylic C−H (86 kcal·mol^{-1}) bonds. Therefore, the aldehydic C(O)−H functionality could serve as a good hydrogen atom donor for nπ^* triplet excited *p*-[27] and *o*-quinones.[28]

Hydrogen abstraction of **IV** by ^{3}**IS*** leads to the triplet radical pair [**AB**] (Scheme 2), from which two possible reaction pathways can be envisaged to lead to the formation of products **13** and **14**. In pathway 1, escaping out of the cage of the triplet radical pairs gives the isatin ketyl radicals and the acyl radicals. Encounter and recombination of the isatin ketyl radicals leads to the formation of isatide **15**. On the other hand, acyl radicals are known to be electrophilic and display special "oxygenphilic" reactivity,[29,30] being apt to add to the oxygen atom of a carbonyl group in α-dicarbonyl compounds and *o*-quinones. An oxygenphilic attack of the ketyl radical derived from **IV** to the oxygen atom of the C(3) carbonyl in IS furnishes radical **C**. An intramolecular radical cyclization in **C** followed by hydrogen abstraction results in the formation of **13** and **14**. Alternatively, radical pair **A** may undergo an in-cage radical pair recombination after intersystem crossing to give the ketene product **E** (pathway 2 in Scheme 2). Intramolecular nucleophilic attack of the hydroxy group at the ketene functionality in **E** then furnishes products **13** and **14**.

Photoinduced hydrogen abstraction reactions of *o*-quinones (1,2-naphthoquinone[28d,e] and 9,10-phenanthraquinone[28a−c]) from aldehydes have been reported. Following the initial hydrogen abstraction event, the triplet (quinone ketyl−aldehyde acyl) radical pair may follow an in-cage reaction pathway via intersystem

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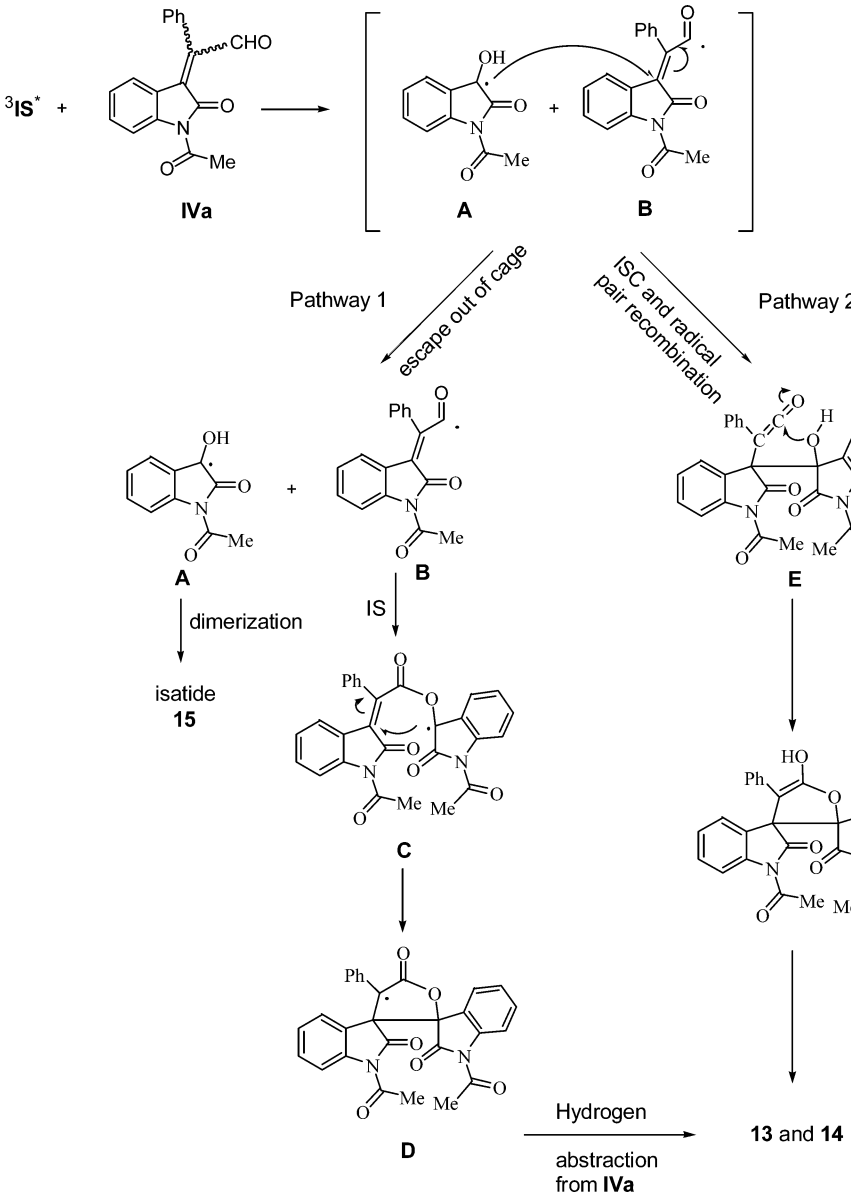
SCHEME 2



crossing and radical pair recombination or an out-of-cage pathway by escaping out of the cage of the two radicals and their taking part in subsequent reactions respectively in bulk solution. For phenanthraquinone−aldehyde photoreactions, both out-of-cage[28a] and in-cage[28b,c] mechanisms have been suggested by different authors to account for the formation of the cross coupling products between the semiquinone and the aldehyde acyl radicals. In our recent investigation on photoinduced reactions of IS with a series of aliphatic and aromatic aldehydes,[30] we have shown that in these reactions, dissociation of the triplet (isatin ketyl−aldehyde acyl) radical pair prevails and an out-of-cage mechanism similar to pathway 1 in Scheme 2 is predominant, leading to a range of homo and cross radical coupling products derived from the isatin ketyl and aldehyde acyl radicals. In the present case of photoreactions of IS with the alkynes **4** and **5**, the formation of isatide **15** suggests that these reactions also follow pathway 1, although pathway 2 could not be entirely ruled out. Furthermore, it is noteworthy that the yield of isatide **15** is much less than would be required should all the acyl radicals **B** be formed by hydrogen abstraction from **IVa** with ^{3}IS* as the only hydrogen abstractor. This fact further suggests that radicals **D** also serve as a hydrogen abstractor from **IVa** to initiate a chain process as shown in pathway 1 of Scheme 2.

The transformation of **C** to **13** and **14** is by a 5-*endo-trig* radical cyclization. This kind of process was regarded as unfavorable based on stereoelectronic consideration,[31] and it was not until recently that an increasing number of 5-*endo-trig* cyclizations, both homolytic and heterolytic, have been reported.[32]A very recent work[33] investigating the 5-*endo-trig* reactions computationally and experimentally has shown that this process is feasible thermo-

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dynamically as well as kinetically as compared with the corresponding 4-*exo-trig* process for a wide range of 4-pentenyl and heteropentenyl radical systems. This type of cyclization has been found in 4-pentenyl, carbamoylmethyl, α-amidoyl, δ-unsaturated acyl, and δ-unsaturated vinyl radical systems,[32] leading to the formation of five-membered carbocycles and nitrogen-containing heterocycles. The radical cyclization in **C** leading to **13** and **14** is in a vinylcarboxymethyl radical system, which gives γ-lactones. Synthesis of γ-lactones by radical cyclization reactions has only been previously achieved by 5-*exo-trig* cyclizations in haloacetal systems (the Ueno−Stork cyclization[34,35]). This result may furnish further support to the feasibility of the 5-*endo-trig* process and substantiate that this process is especially favorable when the radical center before cyclization is highly substituted (as in **C**, Scheme 2), and the newly formed radical center in the cyclization can be stabilized by spin delocalization to a neighboring π-system[32] (as in **D**, Scheme 2).

Products **13** and **14** are dispiro[oxindole[3,2′]furano-[3,3″]oxindole] derivatives which contain a spirofurano-[2,3′]oxindole structure. These spirocyclic butyrolactone oxindoles are basic structural units and synthetic precursors in the naturally occurring tryptoquivalines of mycotoxin metablites, [19] and their synthesis has been actively investigated.[20]

Conclusions

In summary, photoinduced reactions of 1-acetylisatin with 1,2-disubstituted acetylenes **1**−**3** gave β,β-disubstituted 3-alkylideneoxindoles via [2+2] photocycloaddition of ^{3}IS* with the alkyne and subsequent oxetene ring opening. On the other hand, photoreactions of IS with monosubstituted acetylenes **4** and **5** afforded the dispiro-[oxindole[3,2′]furano[3′,3″]oxindole] derivatives **13** and **14** via one-pot tandem reactions initiated by [2+2] photocycloadditions of ^{3}IS* with the alkyne to give the spirooxetenes **V**. Oxetene ring opening furnishing the aldehyde **IV** was followed by hydrogen abstraction of a second ^{3}IS* from **IV** to give the triplet (isatin ketyl−aldehyde acyl) radical pairs. It is proposed that dissociation of the triplet radical pairs and an oxygenphilic attack of the acyl radical **B** at the C(3) carbonyl oxygen of a neutral IS gave radical **C**, which could undergo a 5-*endo-trig* cyclization and hydrogen abstraction to give **13** and **14**. The regioselectivity in the oxetene (**I** and **V**) formation is determined by the formation of the most stable 1,4-diradicals (**II** and **VI**) which have a linear α-phenylvinyl radical center with spin delocalization to the phenyl. These photoreactions of IS with alkynes provided convenient access to 3-alkylidene oxindoles and spirocyclic butyrolactone oxindoles.

Experimental Section

General Procedures for the Preparative Photolysis of 1-Acetylisatin with Alkynes. The light source was a medium-pressure mercury lamp (500 W) in a cooling water jacket that was further surrounded by a layer of filter solution (1 cm thick, 20% aqueous sodium nitrite) to cut off light of wavelength shorter than 400 nm. The solution of 1-acetylisatin (IS) and an excess amount of alkyne in benzene was purged with dry argon for 15 min and then irradiated under continuous argon purging. The reaction course was monitored by TLC. At the end of the reaction, the solvent was removed under reduced pressure and the residue was separated by flash chromatography on a silica gel column with petroleum ether (bp 60−90 °C)/ethyl acetate as eluents.

Photolysis of IS with 1a. A solution of IS (756 mg, 4 mmol) and **1a** (1.424 g, 8 mmol) in benzene (80 mL) was photolyzed for 24 h to reach a complete conversion of IS. Workup as described above gave the products **6a** and **8a** as a mixture. The ratio of the two products was determined by ^{1}HNMR integration of the corresponding protons in the product mixture. Repeated crystallization from chloroform afforded a pure analytical sample of **6a**.

6a [(3*Z*)-1-acetyl-1,3-dihydro-3-(2-oxo-1,2-diphenylethylidene)-2*H*-indol-2-one]: yellow crystals from chloroform, mp 228−230 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.61 (s, 3H), 6.95−7.01 (m, 2H), 7.31−7.62 (m, 9H), 8.07 (dd, 2H, J = 7.2 and 1.4 Hz), 8.32 (d, 1H, J = 8.1 Hz); IR 3050, 1740, 1700, 1660, 1600, 1580, 1450, 1370, 1340, 1290, 1240, 1180, 1100, 1050, 940, 900, 840, 790, 760, 700 cm^{-1}; MS *m/z* (% base) 367 (M^+, 23), 325 (38), 296 (26), 248 (13), 220 (13), 190 (10), 165 (12), 105 (100), 77 (54), 43(32). Anal. Calcd for $C_{24}H_{17}NO_3$: C, 78.47; H, 4.63; N, 3.81; Found: C, 78.30; H, 4.60; N, 3.79.

8a [(3*E*)-1-acetyl-1,3-dihydro-3-(2-oxo-1,2-diphenylethylidene)-2*H*-indol-2-one]: not fully separated from **6a**.

Photolysis of IS with 1b. A solution of IS (567 mg, 3 mmol) and **1b** (1.248 g, 6 mmol) in benzene (60 mL) was photolyzed for 24 h to reach a 63% conversion of IS. Workup as described above gave a mixture of **6b**, **7b**, **8b**, and **9b.** The product ratio was determined by ^{1}H NMR integration of the corresponding protons in the product mixture. Recrystallization from ethyl acetate gave **6b** as a pure product.

6b [(3*Z*)-1-acetyl-1,3-dihydro-3-[1-(4-methoxyphenyl)-2-oxo-2-phenylethylidene]-2*H*-indol-2-one]: yellow crystals from ethyl acetate, mp 178−181 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.60 (s, 3H), 3.87 (s, 3H), 6.97−7.58 (m, 10H), 8.02−8.46 (dd, 2H, J = 8.6 and 1.5 Hz), 8.31 (d, 1H, J = 7.9 Hz); IR 1730, 1700, 1670, 1600, 1580, 1500, 1450, 1380, 1340, 1300, 1250, 1170, 1050, 840, 780, 750, 680 cm^{-1}; MS *m/z* (% base) 397 (M^+, 67), 326 (34), 312 (6), 250 (51), 219 (9), 179 (6), 105 (100), 77 (52), 43 (64). Anal. Calcd for $C_{25}H_{19}NO_4$: C, 75.57; H, 4.79; N, 3.53. Found: C, 75.39; H, 5.00; N, 3.63.

7b [(3*Z*)-1-Acetyl-1,3-dihydro-3-[2-(4-methoxyphenyl)-2-oxo-1-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **6b**, **8b**, and **9b**.

8b [(3*E*)-1-acetyl-1,3-dihydro-3-[1-(4-methoxyphenyl)-2-oxo-2-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **6b**, **7b**, and **9b**.

9b [(3*E*)-1-acetyl-1,3-dihydro-3-[2-(4-methoxyphenyl)-2-oxo-1-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **6b**, **7b**, and **8b**.

Photolysis of IS with 1c. A solution of IS (567 mg, 3 mmol) and **1c** (1.275 g, 6 mmol) in benzene (60 mL) was photolyzed for 24 h to reach a 50% conversion of IS. Workup as described above gave a mixture of **6c**, **7c**, **8c**, and **9c**. The product ratio was determined by ^{1}H NMR integration of the corresponding protons in the product mixture. Recrystallization from petroleum ether−acetone gave **7c** as a pure product.

6c [(3*Z*)-1-acetyl-1,3-dihydro-3-[1-(4-chlorophenyl)-2-oxo-2-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **7c**, **8c**, and **9c**.

7c [(3*Z*)-1-acetyl-1,3-dihydro-3-[2-(4-chlorophenyl)-2-oxo-1-phenylethylidene]-2*H*-indol-2-one]: green needles from acetone−petroleum ether, mp 226−228 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.61 (s, 3H), 6.95−7.01 (m, 2H), 7.30−7.62 (m, 8H), 7.98−8.01 (m, 2H), 8.32 (d, 1H, J = 8.1 Hz); IR 3050, 1740, 1680,

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1580, 1450, 1360, 1340, 1310, 1280, 1240, 1200, 1080, 930, 840, 780, 720, 700, 620 cm^{-1}; MS *m/z* (% base) 401 (M^+, 30), 359 (57), 330 (35), 248 (8), 220 (24), 191 (12), 171 (14), 165 (24), 139 (100), 111 (42), 43 (59). Anal. Calcd for $C_{24}H_{16}NO_3Cl$: C, 71.73; H, 3.99; N, 3.49. Found: C, 71.78; H, 3.97; N, 3.39.

8c [(3*E*)-1-acetyl-1,3-dihydro-3-[1-(4-chlorophenyl)-2-oxo-2-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **6c**, **7c**, and **9c**.

9c [(3*E*)-1-acetyl-1,3-dihydro-3-[2-(4-chlorophenyl)-2-oxo-1-phenylethylidene]-2*H*-indol-2-one]: not fully separated from **6c**, **7c**, and **8c**.

Photolysis of IS with 2. A solution of IS (189 mg, 1 mmol) and **2** (292 mg, 2 mmol) in benzene (20 mL) was photolyzed for 24 h to reach a complete conversion of IS. Workup as described above gave **10** (310 mg, 93%) as the sole product.

10 [(*Z*)-1-acetyl-1,3-dihydro-3-[1-(4-methoxyphenyl)-2-oxo-1-propylidene]-2*H*-indol-2-one]: yellow blocks from petroleum ether−acetone, mp 150−152 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.45 (s, 3H), 2.72 (s, 3H), 3.90 (s, 3H), 6.95 (t, 1H, J = 7.5 Hz), 7.01−7.07 (m, 3H), 7.30 (td, 1H, J = 7.8 and 1.2 Hz), 7.44−7.49 (m, 2H), 8.28 (d, 1H, J = 8.1 Hz); IR 1738, 1712, 1640, 1600, 1507, 1459, 1371, 1344, 1283, 1176, 1027, 827, 791, 755, 595, 558 cm^{-1}; MS *m/z* (% base) 335 (M^+, 100), 293 (64), 251 (88), 223 (4), 208 (10), 178 (7), 108 (4), 43 (96). Anal. Calcd for $C_{20}H_{17}NO_4$: C, 71.64; H, 5.07; N, 4.18. Found: C, 71.57; H, 5.05; N, 4.09.

Photolysis of IS with 3. A solution of IS (378 mg, 2 mmol) and **3** (808 mg, 4 mmol) in benzene (40 mL) was photolyzed for 24 h to reach 48% conversion of IS. Workup as described above gave **11** and **12** as a mixture. Stepwise crystallization from petroleum ether−acetone gave pure **11** (166 mg, 44%) and **12** (180 mg, 48%).

11 [(*E*)-1-acetyl-1,3-dihydro-3-[3-benzoyl-1-phenyl-1-propylidene]-3*H*-indol-2-one]: yellow crystals from petroleum ether−acetone, mp 188−190 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.85 (s, 3H), 6.98 (t, 1H, J = 7.6 Hz), 7.12 (d, 1H, J = 7.5 Hz), 7.30−7.44 (m, 4H), 7.56 (t, 4H, J = 7.5 Hz), 7.70 (t, 1H, J = 7.2 Hz), 8.19 (dd, 2H, J = 7.5 and 1.2 Hz), 8.31 (d, 1H, J = 8.1 Hz); IR 2169, 1727, 1713, 1673, 1598, 1579, 1456, 1372, 1349, 1256, 1170, 1121, 970, 808, 785, 751, 685, 528 cm^{-1}; MS *m/z* (% base) 391 (M^+, 26), 349 (37), 320 (28), 304 (6), 214 (5), 105 (100), 77 (48). Anal. Calcd for $C_{26}H_{17}NO_3$: C, 79.79; H, 4.35; N, 3.58; Found: C, 79.82; H, 4.47; N, 3.34.

12 [(*Z*)-1-acetyl-1,3-dihydro-3-[3-benzoyl-1-phenyl-1-propylidene]-3*H*-indol-2-one]: yellow powders from petroleum ether−acetone, mp 204−206 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.59 (s, 3H), 7.34 (td, 1H, J = 7.8 and 1.0 Hz), 7.39−7.68 (m, 9H), 8.12 (dd, 2H, J = 7.2 and 1.5 Hz), 8.34 (d, 1H, J = 8.1 Hz), 8.45 (dd, 1H, J = 7.5 and 1.0 Hz); IR 2177, 1739, 1702, 1675, 1598, 1464, 1379, 1347, 1293, 1173, 1104, 1052, 748, 686, 596 cm^{-1}; MS *m/z* (% base) 391 (M^+, 26), 349 (37), 320 (28), 304 (6), 214 (5), 105 (100), 77 (48). Anal. Calcd for $C_{26}H_{17}NO_3$: C, 79.79; H, 4.35; N, 3.58. Found: C, 79.86; H, 4.59; N, 3.57.

Photolysis of IS with 4a. A solution of IS (378 mg, 2 mmol) and **4a** (1.02 g, 10 mmol) in benzene (40 mL) was photolyzed for 20 h to reach a complete conversion of IS. Workup as described above gave **13a** (250 mg, 52%) and **14a** (130 mg, 27%).

13a [(2′*R*,3′*S*,4′*S*)-1,1″-diacetyl-4′,5′-dihydro-4′-phenyldispiro-[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 179 °C; ^{1}HNMR (500 MHz, $CDCl_3$) δ 2.51 (s, 3H), 2.82 (s, 3H,), 5.80 (s, 1H), 6.79 (d, 1H, J = 7.5 Hz), 6.85 (t, 1H, J = 7.5 Hz), 7.10−7.33 (m, 8H), 7.63 (d, 1H, J = 6.7 Hz), 7.84 (d, 1H, J = 7.7 Hz), 8.18 (d, 1H, J = 8.3 Hz); IR 1800, 1770, 1720, 1600, 1460, 1370, 1340, 1310, 1280, 1180, 1018, 932, 770, 700 cm^{-1}; MS *m/z* (% base) 352 (0.9), 291 (26), 263 (41), 221 (100). Anal. Calcd for $C_{28}H_{20}N_2O_6$: C, 70.00; H, 4.17; N, 5.83. Found: C, 70.12; H, 4.09; N, 5.63.

14a [(2′*S*,3′*S*,4′*R*)-1,1″-diacetyl-4′,5′-dihydro-4′-phenyldispiro-[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′(1*H*,1′*H*)-trione]: colorless crystals from ethyl acetate, mp 270−272 °C; ^{1}HNMR (500 MHz, $CDCl_3$) δ 2.41 (s, 3H), 2.71 (s, 3H), 5.41 (s, 1H), 7.10 (d, 2H, J = 7.2 Hz), 7.18−7.39 (m, 7H), 7.59 (m, 2H), 7.92 (d, 1H, J = 8.0 Hz), 8.03 (d, 1H, J = 8.0 Hz); IR 1805, 1750, 1718, 1600, 1460, 1365, 1335, 1310, 1270, 1170, 1015, 940, 760, 700 cm^{-1}; MS *m/z* (% base) 367 (0.2), 352 (0.9), 291 (26), 263 (45), 221 (100). Anal. Calcd for $C_{28}H_{20}N_2O_6$: C, 70.00; H, 4.17; N, 5.83. Found: C, 70.09; H, 4.32; N, 6.02.

Photolysis of IS with 4b. A solution of IS (189 mg, 1 mmol) and **4b** (362 mg, 2 mmol) in benzene (20 mL) was photolyzed for 48 h to reach a complete conversion of IS. Workup as described above gave **13b** (130 mg, 46%), **14b** (65 mg, 23%), and **15** (47 mg, 25%).

13b [(2′*R*,3′*S*,4′*S*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4-bromophenyl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 239−241 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.47 (s, 3H), 2.73 (s, 3H), 5.41 (s, 1H), 7.01 (d, 2H, J = 8.4 Hz), 7.23 (td, 1H, J = 7.8 and 1.0 Hz), 7.28−7.46 (m, 5H), 7.58 (td, 2H, J = 7.2 and 1.0 Hz), 7.96 (dd, 1H, J = 7.2 and 1.2 Hz), 8.06 (d, 1H, J = 8.1 Hz); IR 1803, 1726, 1600, 1465, 1370, 1336, 1318, 1265, 1175, 1118, 1015, 935, 764, 596 cm^{-1}; MS *m/z* (% base) 559 (M^+, 1), 431 (3), 371 (53), 344 (65), 301 (100), 272 (12), 263 (12), 219 (23), 190 (14), 165 (18), 146 (27), 119 (2), 90 (18), 43 (69). Anal. Calcd for $C_{28}H_{19}N_2O_6Br$: C, 60.11; H, 3.40; N, 5.01. Found: C, 60.10; H, 3.38; N, 5.07.

14b [(2′*S*,3′*S*,4′*R*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4-bromophenyl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 247−249 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.52 (s, 3H), 2.83 (s, 3H), 5.80 (s, 1H), 6.78 (dd, 1H, J = 7.8 and 1.0 Hz), 6.87 (td, 1H, J = 7.8 and 1.0 Hz), 7.01 (d, 2H, J = 8.4 Hz), 7.29−7.37 (m, 5H), 7.58−7.64 (m, 1H), 7.87−7.93 (m, 1H), 8.20 (d, 1H, J = 8.1 Hz); IR 1803, 1726, 1600, 1465, 1370, 1336, 1318, 1265, 1175, 1118, 1015, 935, 764, 596 cm^{-1}; MS *m/z* (% base) 432 (2), 371 (50), 343 (45), 299 (100), 271 (9), 262 (8), 219 (20), 190 (11), 165 (9), 146 (55), 119 (7), 90 (16), 43 (89). Anal. Calcd for $C_{28}H_{19}N_2O_6Br$: C, 60.11; H, 3.40; N, 5.01. Found: C, 60.09; H, 3.64; N, 5.04.

Photolysis of IS with 4c. A solution of IS (756 mg, 4 mmol) and **4c** (1.056 g, 8 mmol) in benzene (80 mL) was photolyzed for 72 h to reach 75% conversion of IS. Workup as described above gave **13c** (407 mg, 53%), **14c** (215 mg, 28%), and **15** (78 mg, 14%).

13c [(2′*R*,3′*S*,4′*S*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4-methoxyphenyl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 236−238 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.46 (s, 3H), 2.72 (s, 3H), 3.79 (s, 3H), 5.40 (s, 1H), 6.73 (d, 2H, J = 8.8 Hz), 7.04 (d, 2H, J = 8.7 Hz), 7.19−7.41 (m, 4H), 7.58−7.62 (m, 2H), 7.93−7.96 (m, 1H), 8.04 (d, 1H, J = 8.2 Hz); IR 1811, 1766, 1732, 1721, 1603, 1515, 1464, 1370, 1336, 1263, 1172, 1017, 764 cm^{-1}; MS *m/z* (% base) 510 (M^+, 2), 382 (2), 321 (37), 320 (22), 293 (82), 278 (15), 251 (100), 208 (29), 180 (14), 146 (27), 90 (17), 43 (79). Anal. Calcd for $C_{29}H_{22}N_2O_7$: C, 68.24; H, 4.31; N, 5.49. Found: C, 68.31; H, 4.59; N, 5.55.

14c [(2′*S*,3′*S*,4′*R*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4-methoxyphenyl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 234−236 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.52 (s, 3H), 2.84 (s, 3H), 3.70 (s, 3H), 5.79 (s, 1H), 6.67 (d, 2H, J = 8.8 Hz), 6.84−6.87 (m, 2H), 7.01 (d, 2H, 8.7), 7.27−7.36 (m, 3H), 7.64−7.67 (m, 1H), 7.87−7.89 (m, 1H), 8.19 (d, 1H, J = 8.2 Hz); IR 1798, 1771, 1749, 1720, 1680, 1604, 1517, 1464, 1277, 1176, 1016, 759 cm^{-1}; MS *m/z* (% base) 510 (M^+, 1), 382 (2), 321 (76), 293 (55), 278 (34), 251 (100), 208 (19), 146 (28), 90 (12), 43 (64). Anal. Calcd for $C_{29}H_{22}N_2O_7$: C, 68.24; H, 4.31; N, 5.49. Found: C, 68.20; H, 4.34; N, 5.42.

Photolysis of IS with 4d. A solution of IS (189 mg, 1 mmol) and **4d** (404 mg, 2 mmol) in benzene (20 mL) was photolyzed for 48 h to reach 70% conversion of IS. Workup as described above gave **13d** (113 mg, 56%), **14d** (47 mg, 23%), and **15** (19 mg, 14%).

13d [(2′*R*,3′*S*,4′*S*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4′-ethynylbiphenyl-4-yl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 279−281 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.47 (s, 3H), 2.74 (s, 3H), 3.14 (s, 1H), 5.50 (s, 1H), 7.21−7.27 (m, 3H), 7.33−7.66 (m, 12H), 7.96 (dd, 1H, J = 7.2 and 1.8 Hz), 8.06 (d, 1H, J = 8.1 Hz); IR 1802, 1771, 1720, 1604, 1465, 1371, 1336, 1275, 1178, 1114, 1017, 936, 821, 766, 590 cm^{-1}; MS *m/z* (% base) 580 (M^+, 2), 391 (8), 363 (17), 321 (26), 293 (4), 262 (5), 189 (8), 145 (43), 119 (36), 104 (9), 92 (26), 77 (6), 43 (100). Anal. Calcd for $C_{36}H_{24}N_2O_6$: C, 74.48; H, 4.14; N, 4.83. Found: C, 74.24; H, 4.22; N, 4.96.

14d [(2′*S*,3′*S*,4′*R*)-1,1″-diacetyl-4′,5′-dihydro-4′-(4′-ethynylbiphenyl-4-yl)dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 263−265 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.54 (s, 3H), 2.85 (s, 3H), 3.13 (s, 1H), 5.82 (s, 1H), 6.80−6.90 (m, 2H), 7.21 (d, 2H, J = 8.4 Hz), 7.25−7.32 (m, 2H), 7.37 (t, 4H, J = 8.4 Hz), 7.43 (d, 2H, J = 8.4 Hz), 7.51 (d, 2H, J = 8.4 Hz), 7.69 (dd, 1H, J = 7.2 and 2.0 Hz), 7.88 (dd, 1H, J = 7.2 and 2.0 Hz), 8.20 (d, 1H, J = 8.1 Hz); IR 1802, 1771, 1720, 1604, 1465, 1371, 1336, 1275, 1178, 1114, 1017, 936, 821, 766, 590 cm^{-1}; MS *m/z* (% base) 391 (76), 363 (43), 321 (100), 293 (14), 262 (22), 146 (38), 105 (10), 90 (8), 77 (7), 44 (52). Anal. Calcd for $C_{36}H_{24}N_2O_6$: C, 74.48; H, 4.14; N, 4.83. Found: C, 74.37; H, 4.34; N, 4.79.

Photolysis of IS with 5. A solution of IS (756 mg, 4 mmol) and **5** (2.64 g, 40 mmol) in benzene (80 mL) was photolyzed for 48 h to reach 62% conversion of IS. Workup as described above gave **13e** (258 mg, 47%), **14e** (127 mg, 23%), and **15** (99 mg, 21%).

13e [(2′*R*,3′*S*,4′*S*)-1,1″-diacetyl-4′,5′-dihydro-4′-(cyclopropyl)-dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 190−192 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ −0.06 to 0.02 (m, 1H), 0.10−0.19 (m, 1H), 0.53−0.63 (m, 2H), 0.70−0.73 (m, 1H), 2.49 (s, 3H), 2.72 (s, 3H), 3.56 (d, 1H, J = 9.7 Hz), 6.73 (dd, 1H, J = 7.7 and 1.1 Hz), 6.83 (td, 1H, J = 7.7 and 0.8 Hz), 7.26−7.46 (m, 3H), 7.57−7.60 (m, 1H), 8.13 (t, 2H, J = 7.5 Hz); IR 1805, 1771, 1750, 1749, 1723, 1604, 1466, 1371, 1337, 1277, 1264, 1179, 1018, 767, 769 cm^{-1}; MS *m/z* (% base) 444 (M^+, 0.3), 388 (0.3), 287 (2), 255 (50), 227 (73), 185 (100), 170 (61), 146 (27), 130 (10), 90 (14), 43 (71). Anal. Calcd for $C_{25}H_{20}N_2O_6$: C, 67.57; H, 4.50; N, 6.31. Found: C, 67.56; H, 4.63; N, 6.29.

14e [(2′*S*,3′*S*,4′*R*)-1,1″-diacetyl-4′,5′-dihydro-4′-(cyclopropyl)-dispiro[3*H*-indole-3,2′(3′*H*)-furan-3′,3″-[3*H*]indole]-2,2″,5′-(1*H*,1′*H*)-trione]: colorless crystals from petroleum ether−acetone, mp 196−198 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ −0.36 to −0.27 (m, 1H), 0.09−0.18 (m, 1H), 0.44−0.52 (m, 1H), 0.69−0.89 (m, 1H), 1.01−1.11 (m, 1H), 2.61 (s, 3H), 2.65 (s, 3H), 3.27 (d, 1H, J = 7.4 Hz), 7.17−7.22 (m, 2H), 7.26−7.37 (m, 3H), 7.57 (dd, 1H, J = 7.7 and 1.0 Hz), 7.96 (d, 1H, J = 6.0 Hz), 8.05 (d, 1H, J = 8.2 Hz); IR 1805, 1750, 1730, 1720, 1604, 1464, 1372, 1337, 1264, 1178, 1016, 776, 761 cm^{-1}; MS *m/z* (% base) 444 (M^+, 0.4), 359 (0.2), 287 (2), 255 (60), 227 (83), 185 (100), 170 (69), 146 (28), 90 (17), 43 (84). Anal. Calcd for $C_{25}H_{20}N_2O_6$: C, 67.57; H, 4.50; N, 6.31. Found: C, 67.62; H, 4.67; N, 6.37.

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Supporting Information Available: X-ray crystallographic data for compounds **10**, **11**, **13c**, and **14b**; ^{1}HNMR (300 MHz, $CDCl_3$) of all new compounds (**10**, **11**, **12**, **13b**−**e**, **14b**−**e**); computational results on diradicals **VIa**, **VIIa**, **VIII**, and **IX**. This material is available free of charge via the Internet at http://pubs.acs.org.

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