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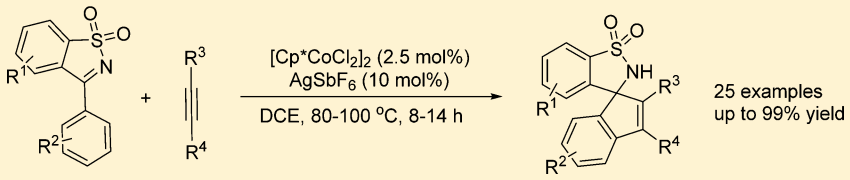
Cp*Co^{III}-Catalyzed C−H Alkenylation/Annulation to Afford Spiro Indenyl Benzosultam

Hui Liu, Jie Li, Miao Xiong, Jijun Jiang, and Jun Wang*

School of Chemistry and Chemical Engineering, Sun Yat-Sen University, Guangzhou 510275, P.R. China

Supporting Information

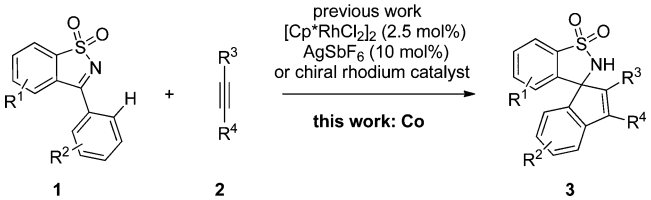


ABSTRACT: Cp*Co^{III}-catalyzed tandem inert C−H alkenylation/annulation of *N*-sulfonyl ketimines with alkynes is revealed. A series of spiro indenyl benzosultams were facilely prepared in good yields under mild reaction conditions.

Transition-metal-catalyzed directing-group-assisted inert C−H bond activation has drawn substantial attention for its great utility in the syntheses of drugs, materials, and natural products.[1] Noble metals such as rhodium,[2] ruthenium,[3] and palladium[4] have played dominant roles in realizing those transformations. However, due to their high costs, developing more abundant and less expensive metal-based catalysts becomes more and more desirable. In this context, first-row transition metals[5] such as iron,[6] cobalt,[7] nickel,[7c,8] and copper[9] have gained much attention and have been successfully developed as attractive alternatives to the noble metal catalysts. It is especially worth noting that the recent booming development of Cp*Co^{III}-catalyzed inert C−H bond functionalization was initiated by Matsunaga and Kanai's pioneering works on the Cp*Co^{III}-catalyzed addition of 2-arylpyridines to imines and α,β-unsaturated carbonyl compounds[10] as well as C2-selective addition of 2-pyrimidyl indoles to imines.[11]

Benzosultams[12] and indanes/indenes[13] possess diverse biological activities. Accordingly, spiro benzosultam derivatives **3** comprising both of these motifs hold great potential for biological and pharmaceutical studies (Scheme 1). Until now, only a few approaches were available to obtain access to this skeleton.[14,15] Of them, intermolecular annulation via transition-metal-catalyzed C−H activation constitutes one of the most convenient and efficient ways.[15] Specifically, they could be constructed in a single step by reacting cyclic sulfonyl ketimine **1** with alkene[15a] or alkyne[15b,c] in the presence of an iridium or rhodium catalyst, which was reported by Nishimura's and Dong's groups, respectively. Moreover, an asymmetric version of this reaction was also revealed recently by Cramer's group with a chiral rhodium catalyst.[15d] In view of the importance of spiro indenyl benzosultam derivatives, and encouraged by the effectiveness of Cp*Co^{III} catalysts in the alkenylation with alkynes as well as alkenylation/annulation reactions,[16] we investigated and report herein the Cp*Co^{III}-catalyzed syntheses of spiro benzosultams with cyclic sulfonyl ketimines and alkynes (Scheme 1).

Scheme 1. Synthesis of Spiro Benzosultam Derivatives



Preliminary studies showed that, in the presence of $[Cp^*CoCl_2]_2$ (2.5 mol %) and $AgSbF_6$ (10 mol %), the annulation of cyclic *N*-sulfonyl ketimine **1a** with diphenyl acetylene **2a** occurred in dichloroethane (DCE) at 100 °C to afford the spiro indenyl benzosultam **3aa** in 71% yield (Table 1, entry 1). Solvent screening indicated that solvents such as THF, toluene, and acetonitrile were not suitable for this reaction, probably due to either strong coordination abilities or solubility reasons (Table 1, entries 2−4). The employment of $Cu(OAc)_2\cdot H_2O$, Ag_2CO_3, or KOAc as additives did not improve yield (Table 1, entries 5−7). Investigation of different ratios of **1a** to **2a** for the reaction revealed that 2:1 was superior, giving 99% yield (Table 1, entries 8−11). Reducing the amount of catalyst loading from 2.5 to 1.0 mol % decreased the yield dramatically to 22% (Table 1, entry 12). We tried to perform the reaction at a lower temperature and found that the product was obtained in 99% yield at 80 °C and 70% yield at 60 °C (Table 1, entries 13−14). Though shortening the reaction time from 14 to 8 h did not affect the yield (99%), further shortening to 4 h decreased the yield to 70% (Table 1, entries 15−16).

Under the optimized reaction conditions, we investigated various substituted cyclic *N*-sulfonyl ketimines **1** (Scheme 2). *N*-sulfonyl ketimines (**1a−e**) with either electron-withdrawing or electron−donating R^2 substituents at the *para* position of the

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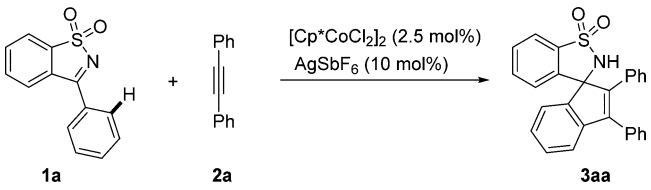
Table 1. Optimizations of Reaction Conditions[a]



1a 2a 3aa

	1a:2a[b]	solvent	t (h)	T (°C)	yield (%)[c]
1	1:2	DCE	14	100	71
2	1:2	THF	24	100	trace
3	1:2	toluene	24	100	trace
4	1:2	CH_3CN	24	100	trace
5[d]	1:2	DCE	14	100	34
6[e]	1:2	DCE	14	100	5
7[f]	1:2	DCE	14	100	trace
8	2:3	DCE	14	100	40
9	1:1	DCE	14	100	32
10	3:2	DCE	14	100	35
11	2:1	DCE	14	100	99
12[g]	2:1	DCE	14	100	22
13	2:1	DCE	14	80	99
14	2:1	DCE	14	60	70
15	***2:1***	***DCE***	***8***	***80***	***99***
16	2:1	DCE	4	80	70

[a]Reaction conditions: $[Cp^*CoCl_2]_2$ (2.5 mol %), $AgSbF_6$ (10 mol %), and solvent (0.4 mL). [b]**1a** (0.1 mmol) was used for entries 1−8, and **2a** (0.1 mmol) was used for entries 9−16. [c]Determined by ^1H NMR analysis of the crude reaction mixture using methyl 4-iodobenzoate as the internal standard. [d]$Cu(OAc)_2·H_2O$ (0.05 mmol) was used as an additive. [e]Ag_2CO_3 (0.05 mmol) was used as an additive. [f]KOAc (0.05 mmol) was used as an additive. [g]$[Cp^*CoCl_2]_2$ (1.0 mol %) and $AgSbF_6$ (4 mol %).

phenyl ring Ar^2 were studied. It was observed that the electronic effects influenced the reaction significantly, and electron−donating groups such as methyl and methoxyl groups benefited the reaction (**3aa**−**ea**). The substituted fashion also affected the reactivity. For example, in contrast to the ketimine **1e** with a 4-methoxyl phenyl group, the ketimine **1f** with a 2-methoxyl phenyl group afforded the corresponding products in only 22% yield (**3fa**). The low yield may be attributed to the coordination of the *ortho* methoxyl group to the Co^{III} species, which would deactivate the catalyst, or possibly by the steric repulsion of the methoxyl group with the Ar^1 group, which may destabilize the metallacycle intermediate. To determine which one is dominant, ketimine **1h** bearing an *ortho* methyl phenyl group was tried, and 17% yield was obtained, which indicated that steric hindrance might be the major reason. The corresponding *meta* methoxyl ketimine **1g** reacted smoothly to give the product in 80% yield with excellent regioselectivity (10:1). The structure of the major isomer was determined unambiguously by single-crystal X-ray diffraction. The C−H activation preferentially occurs at the *para* position of the methoxyl group. To our delight, ketimine **1i** showed complete regioselectivity, and the corresponding product **3ia** was obtained in 99% yield. Ketimines **1j**−**l** with either an electron-withdrawing or electron−donating R^1 group on Ar^1 ring were also evaluated, affording corresponding products in 33−87% yield. When the ketimine with Ar^2 as 2-pyridyl was taken as the substrate, no product was obtained. It may be attributed to the strong coordination of the *N*-atom to the Co^{III} species, causing deactivation of the catalyst.

Then, a series of internal alkynes **2** were studied (Scheme 3). The diaryl acetylenes **2b**−**e** with substituents on the *para* positions of both aryl rings provided products in high yields, regardless of the substituent electronic properties. Interestingly, while the diaryl acetylene bearing two 4-nitrophenyl groups (**2e**) was transformed in good yield of 87%, the isomeric alkyne with two 3-nitrophenyl groups (**2f**) gave a moderate yield (59%), and the one with two 2-nitrophenyl groups (**2g**) merely gave trace amounts of product. When decyne **2h** was treated in this reaction, the desired product was isolated in 99% yield. Additionally, the unsymmetrical alkyne **2i** reacted well with ketimine **1a** to give a mixture of isomers in good yield (99%) with good regioselectivity (3:1). The structure of the minor isomer **3ai** was determined unambiguously by single-crystal X-ray diffraction. Terminal alkynes were also investigated. When trimethylsiylacetylene was used, the product was obtained as the single regioisomer in 35% yield, the structure of which was determined to be **3aj** by the NOE spectrum. Unexpectedly, phenylacetylene failed to give any desired product. We also attempted to synthesize multisubstituted spiro indenyl benzosultams by reacting several substituted *N*-sulfonyl ketimines with substituted internal alkynes. The corresponding products **3dc**, **3eb**, **3kc**, and **3hd** were all obtained in excellent yields. It is noteworthy that the product **3hd** was obtained as the sole regioisomer with the structure determined unambiguously by single-crystal X-ray diffraction. The single-crystal structures of compounds **3ga**, **3ai**, and **3hd** are shown in the Supporting Information.

A probable catalytic cycle is proposed as shown in Scheme 4. First, $[Cp^*CoCl_2]_2$ reacts with $AgSbF_6$ in situ to generate the catalytically active species **A**. Then, the *N*-sulfonyl ketimine **1a** coordinates to species **A** to afford the five-membered intermediate **B** with the loss of a proton. Subsequently, the alkyne coordinates to Co^{III} and undergoes a migratory insertion to give the intermediate **D**, which further undergoes a Grignard-type addition to the C=N bond to form the intermediate **E**. Lastly, protonation of intermediate **E** delivers the desired product **3aa** and regenerates the catalyst species **A**.

In summary, we have disclosed efficient Cp^*Co^{III}-catalyzed syntheses of spiro indenyl benzosultams via directed C−H alkenylation/annulations of *N*-sulfonyl ketimines with internal alkynes. Various *N*-sulfonyl ketimines and alkynes could be applied in this reaction, and the corresponding products were obtained in good yields.

EXPERIMENTAL SECTION

General Experimental Methods. Unless otherwise noted, all commercially available reagents were used as received without purification. Dichloroethane was dried over anhydrous Na_2SO_4 before use. $[Cp^*CoCl_2]_2$,[17] *N*-sulfonyl ketimines **1a**−**i**,[18] *N*-sulfonyl ketimines **1j**−**l**,[19] and alkynes **2b**−**g**[20] were synthesized according to the literature procedures. Alkynes **2a** and **2h**−**j** are commercially available. Flash column chromatography was performed with silica gel (100−200 mesh). Chemical shifts are given in dimensionless δ values, and frequency is referenced relative to TMS in ^1H and ^{13}C NMR spectra. HRMS data were recorded on an ESI-Q-TQF mass spectrometer.

General Procedure for the Synthesis of Spiro Indenyl Benzosultam. All reactions were carried out in dry reaction vessels with Teflon screw caps in a nitrogen atmosphere. Sulfonyl ketimine **1** (0.2 mmol, 2.0 equiv), alkyne **2** (0.1 mmol, 1.0 equiv), $[Cp^*CoCl_2]_2$ (1.3 mg, 2.5 mol %), and $AgSbF_6$ (3.4 mg, 10 mol %) were stirred in DCE (0.4 mL) at 80 or 100 °C for 8−14 h. The reaction mixture was directly subjected to silica gel column chromatography and eluted by

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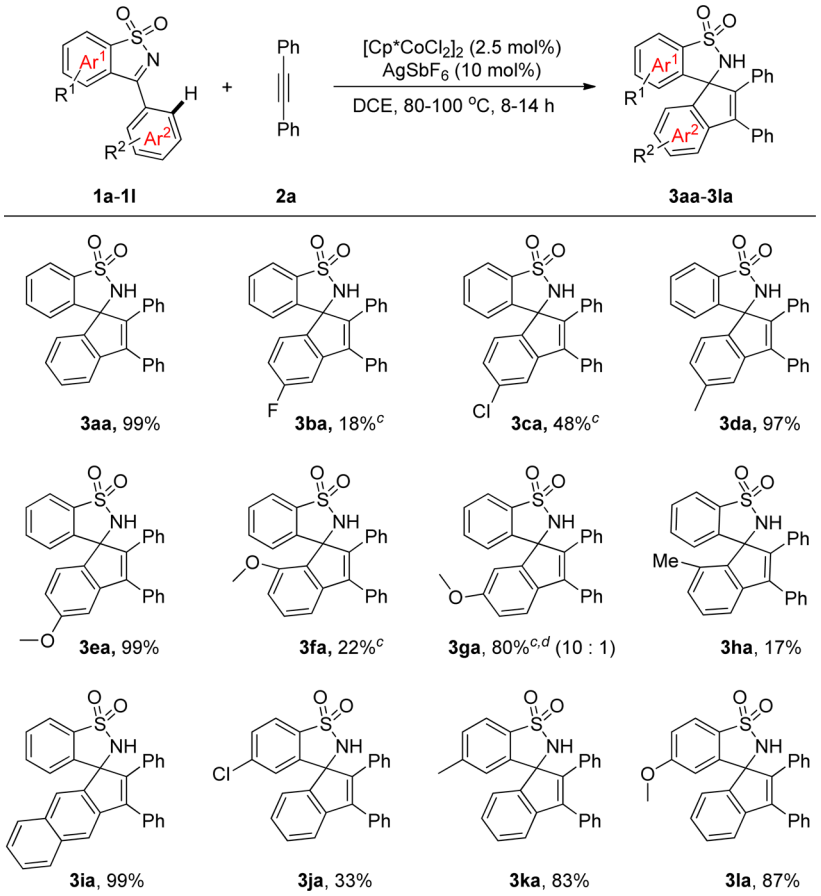
Scheme 2. Substrate Scope of *N*-Sulfonyl Ketimines[a,b]



[a]Reaction conditions unless otherwise specified: **1** (0.2 mmol), **2** (0.1 mmol), $[Cp^*CoCl_2]_2$ (2.5 mol %), $AgSbF_6$ (10 mol %), and DCE (0.4 mL) at 80 °C for 8 h. [b]Isolated yield. [c]Reacted at 100 °C for 14 h. [d]The major isomer is shown.

petroleum ether/dichloromethane (1:2) to pure DCM to afford the product **3**.

*2′,3′-Diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3aa**).* Known compound.[15d] White solid, 42 mg, 99% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−7.86 (m, 1H), 7.60−7.50 (m, 2H), 7.45−7.30 (m, 8H), 7.24−7.20 (m, 1H), 7.15−7.06 (m, 4H), 6.91−6.89 (m, 2H), 4.84 (s, 1H).

*5′-Fluoro-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ba**).* Known compound.[15d] White solid, 8 mg, 18% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−7.86 (m, 1H), 7.65−7.51 (m, 2H), 7.40−7.39 (m, 6H), 7.15−7.13 (m, 2H), 7.10−7.03 (m, 3H), 6.89−6.87 (m, 3H), 4.85 (s, 1H).

*5′-Chloro-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene] 1,1-dioxide (**3ca**).* White solid, 22 mg, 48% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−7.86 (m, 1H), 7.60−7.55 (m, 2H), 7.41−7.36 (m, 6H), 7.31 (m, 1H), 7.19−7.06 (m, 5H), 6.88−6.87 (m, 2H), 4.87 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 145.6, 144.3, 144.0, 142.5, 138.9, 135.4, 135.3, 134.0, 133.1, 131.8, 130.0, 129.1, 129.0, 128.6, 128.5, 128.4, 127.5, 124.4, 123.3, 121.9, 121.8, 74.6. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{27}H_{18}ClNO_2SNa$ 478.0639, found 478.0638.

*5′-Methyl-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3da**).* White solid, 42 mg, 97% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86−7.84 (m, 1H), 7.56−7.49 (m, 2H), 7.40 (m, 5H), 7.32−7.30 (m, 1H), 7.14−7.01 (m, 6H), 6.90−6.89 (m, 2H), 4.84 (s, 1H), 2.34 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 144.6, 143.4, 143.2, 142.4, 139.8, 139.4, 135.3, 133.9, 133.8, 132.5, 129.7, 129.3, 129.2, 128.8, 128.3, 128.2, 128.1, 123.4, 123.0, 122.3, 121.8, 75.0, 21.6. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_2SNa$ 458.1185, found 458.1184.

*5′-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ea**).* Known compound.[15d] White solid, 45 mg, 99% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87−7.80 (m, 1H), 7.60−7.47 (m, 2H), 7.46−7.29 (m, 6H), 7.19−7.00 (m, 4H), 6.97−6.83 (m, 3H), 6.76−6.64 (m, 1H), 4.84 (s, 1H), 3.78 (s, 3H).

*7′-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3fa**).* White solid, 10 mg, 22% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77−7.75 (m, 1H), 7.51−7.49 (m, 2H), 7.38−7.29 (m, 6H), 7.12−7.04 (m, 4H), 7.01−6.99 (m, 1H), 6.88−6.87 m, 2H), 6.77−6.75 (m, 1H), 5.04 (s, 1H), 3.67 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.1, 146.5, 144.9, 141.4, 138.3, 136.4, 133.7, 133.2, 132.5, 131.5, 131.4, 129.7, 129.4, 129.3, 128.5, 128.0, 127.9, 123.1, 121.4, 114.2, 110.5, 75.3, 55.4. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_3SNa$ 474.1134, found 474.1139.

*6′-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ga**) and 4′-methoxy-2′,3′-diphenyl-2H-spiro-[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ga′**).* 10:1 **3ga**:**3ga′**. White solid, 36 mg, 80% yield.

*6′-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ga**).* ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−7.87 (m, 1H), 7.59−7.52 (m, 2H), 7.39−7.37 (m, 5H), 7.26−7.24 (m, 1H), 7.17−7.04 (m, 5H), 6.86−6.84(m, 3H), 4.88 (s, 1H), 3.75 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.9, 149.4, 143.2, 140.8, 139.9, 135.3, 134.7, 133.9, 133.8, 132.5, 129.8, 129.2, 129.1, 128.7, 128.3, 128.2, 127.9, 123.5, 122.2, 121.8, 114.6, 109.5, 74.9, 55.6. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_3SNa$ 474.1134, found 474.1139.

*4′-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ga′**).* ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86−7.84 (m, 1H), 7.56−7.54 (m, 2H), 7.35−7.34 (m, 2H), 7.29−7.27 (m, 3H), 7.20−7.17 (m, 2H), 7.09−7.00 (m, 4H), 6.86−6.84 (m, 1H), 6.80−6.78 (m, 2H), 4.85 (s, 1H), 3.62 (s, 3H). ^{13}C NMR (100 MHz,

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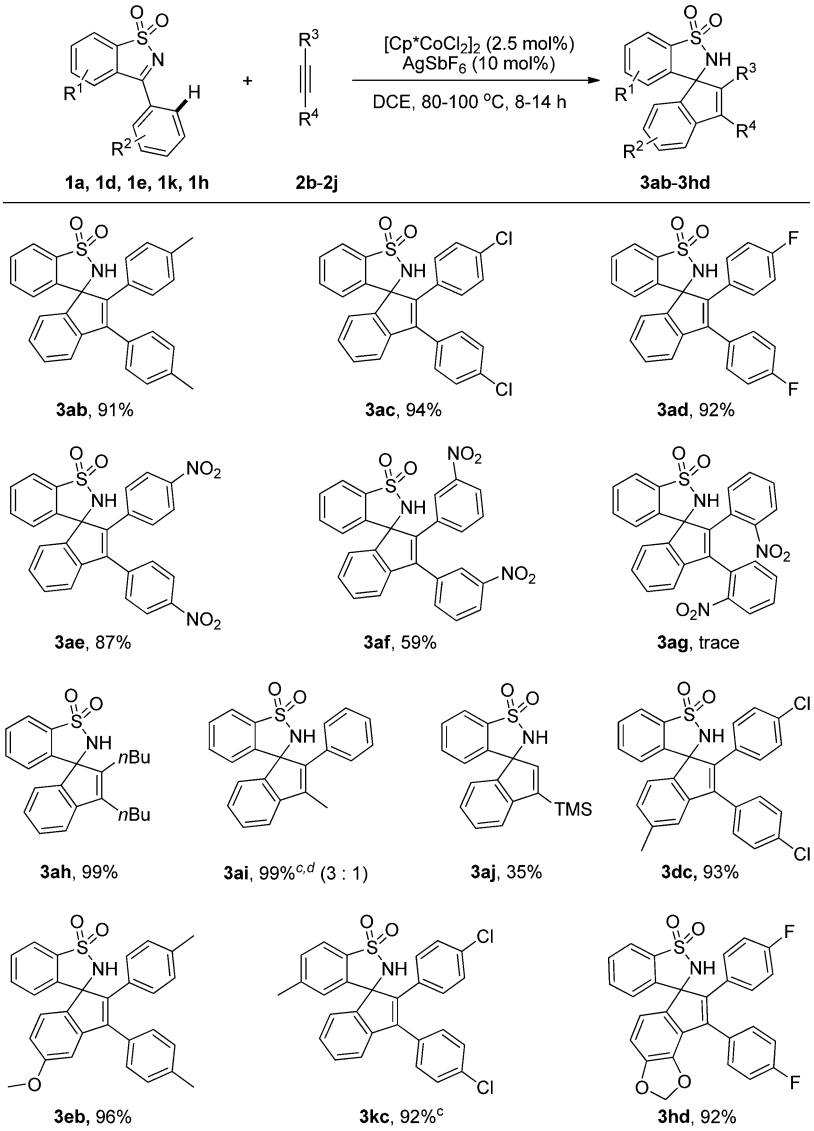
Scheme 3. Substrate Scope of Alkynes[a,b]



[a]Reaction conditions unless otherwise specified: **1** (0.2 mmol), **2** (0.1 mmol), $[Cp^*CoCl_2]_2$ (2.5 mol %), $AgSbF_6$ (10 mol %), and DCE (0.4 mL) at 80 °C for 8 h. [b]Isolated yield. [c]Reacted at 100 °C for 14 h. [d]The minor regioisomer is shown.

DMSO-d_6): δ 154.7, 150.0, 143.4, 142.7, 138.4, 136.2, 135.8, 134.1, 133.8, 130.3, 130.0, 129.8, 129.3, 128.8, 127.9, 127.8, 127.7, 127.6, 123.7, 121.6, 115.9, 113.5, 75.0, 55.9. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_3SNa$ 474.1134, found 474.1139.

*7′-Methyl-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene] 1,1-dioxide (**3ha**).* White solid, 7 mg, 17% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.80−7.78 (m, 1H), 7.59−7.57 (m, 2H), 7.31−7.28 (m, 6H), 7.23−7.21 (m, 1H), 7.15−7.13 (m, 2H), 7.09−7.05 (m, 2H), 7.02−7.00 (m, 1H), 6.72−6.70 (m, 2H), 4.75 (s, 1H), 2.05 (s, 3H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 146.5, 143.6, 143.5, 141.3, 136.8, 136.6, 134.8, 134.0, 133.9, 133.4, 130.5, 130.4, 129.9, 129.7, 129.5, 128.9, 128.3, 127.9, 123.7, 121.5, 118.9, 75.9, 17.3. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_2SNa$ 458.1185, found 458.1192.

*2′,3′-Diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-cyclopenta[b]-naphthalene]1,1-dioxide (**3ia**).* Known compound.[15d] White solid, 47 mg, 99% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.90 (d, J = 7.7 Hz, 1H), 7.85 (s, 1H), 7.78 (m, 2H), 7.71 (s, 1H), 7.61−7.36 (m, 9H), 7.20−7.05 (m, 4H), 6.96−6.94 (m, 2H), 4.92 (s, 1H).

*5-Chloro-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ja**).* White solid, 15 mg, 33% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.80−7.78 (m, 1H), 7.52−7.50 (m, 1H), 7.46−7.44 (m, 1H), 7.43−7.34 (m, 7H), 7.2−7.21 (m, 1H), 7.19−7.05 (m, 4H), 6.94−6.92 (m, 2H), 4.90 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.8, 143.8, 142.3, 142.1, 141.8, 140.3, 133.9, 133.4, 132.0, 130.5, 129.5, 129.2, 129.1, 128.8, 128.5, 128.4, 127.9, 123.5, 123.3, 123.1, 121.8, 74.7. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{27}H_{18}ClNO_2SNa$ 478.0639, found 478.0643.

*5-Methyl-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ka**).* White solid, 36 mg, 83% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.76−7.74 (m, 1H), 7.48−7.30 (m, 9H), 7.24−7.20 (m, 1H), 7.16−7.03 (m, 3H), 6.90−6.89 (m, 3H), 4.81 (s, 1H), 2.34 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.6, 145.0, 143.3, 142.9, 142.2, 139.9, 133.8, 132.7, 132.3, 131.0, 129.3, 129.2, 129.1, 128.8, 128.4, 128.3, 128.1, 127.7, 123.3, 123.2, 121.6, 121.5, 75.0, 21.8. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{21}NO_2SNa$ 458.1185, found 458.1191.

*5-Methoxy-2′,3′-diphenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3la**).* White solid, 39 mg, 87% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.78−7.76 (m, 1H), 7.49−7.47 (m, 1H), 7.44−7.27 (m, 7H), 7.23−7.20 (m, 1H), 7.11−7.03 (m, 4H), 6.94−6.93 (m, 2H), 6.51 (m, 1H), 4.85 (s, 1H), 3.73 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 164.1, 147.6, 143.3, 142.8, 142.3, 142.1, 133.8, 132.3, 129.3, 129.2, 128.8, 128.4, 128.3, 128.2, 127.7, 127.6, 123.4, 123.3, 121.5,

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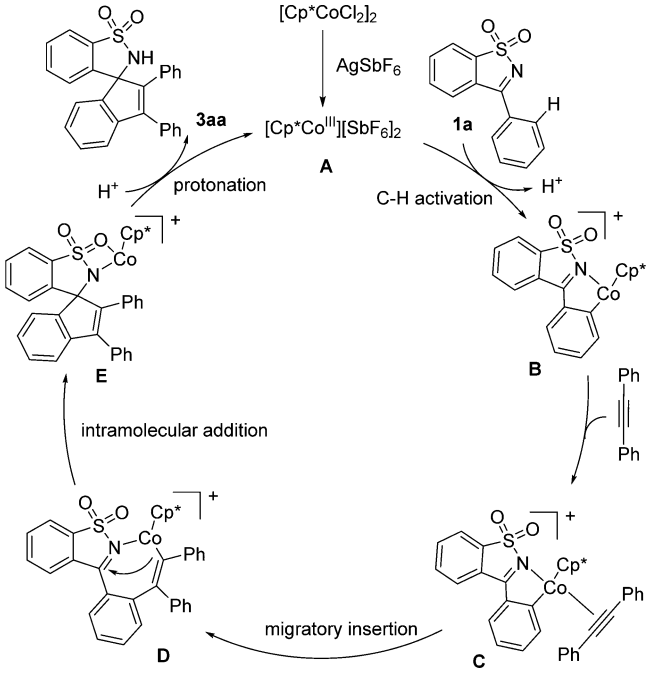
Scheme 4. Proposed Catalytic Cycle



116.5, 107.2, 74.8, 55.8. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{28}H_{21}NO_3SNa$ 474.1134, found 474.1137.

*2′,3′-Di-p-tolyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide(**3ab**).* White solid, 41 mg, 91% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87−7.85 (m, 1H), 7.56−7.49 (m, 2H), 7.44−7.42 (m, 1H), 7.35−7.29 (m, 4H), 7.21−7.17(m, 3H), 7.13−7.11 (m, 1H), 6.89−6.87 (m, 2H), 6.78−6.76 (m, 2H), 4.86 (s, 1H), 2.37 (s, 3H), 2.19 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.4, 142.8, 142.4, 142.3, 140.0, 138.1, 137.9, 135.4, 133.8, 130.8, 129.7, 129.5, 129.4, 129.14, 129.11, 129.0, 127.5, 123.5, 123.2, 121.8, 121.4, 75.1, 21.4, 21.2. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{29}H_{23}NO_2SNa$ 472.1342, found 472.1344.

*2′,3′-Bis(4-chlorophenyl)-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ac**).* White solid, 46 mg, 94% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87−7.85 (m, 1H), 7.58−7.50 (m, 2H), 7.44−7.29 (m, 7H), 7.25−7.21 (m, 1H), 7.08−7.06 (m, 3H), 6.90−6.88 (m, 2H), 4.87 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.1, 142.5, 142.5, 141.6, 138.4, 135.1, 134.5, 134.3, 134.0, 131.8, 130.7, 130.6, 130.5, 130.0, 129.5, 129.3, 128.7, 128.1, 123.4, 123.3, 121.9, 121.4, 75.1. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{27}H_{17}Cl_2NO_2SNa$ 512.0249, found 512.0258.

*2′,3′-Bis(4-fluorophenyl)-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ad**).* White solid, 42 mg, 92% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87−7.85 (m, 1H), 7.58−7.50 (m, 2H), 7.44−7.42 (m, 1H), 7.38−7.31 (m, 4H), 7.26−7.21 (m, 1H), 7.13−7.09 (m, 3H), 6.94−6.91 (m, 2H), 6.81−6.77 (m, 2H), 4.86 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ162.6 (d, $^1J_{C-F}$ = 247 Hz), 162.3 (d, $^1J_{C-F}$ = 247 Hz), 147.1, 142.5, 142.2, 141.9, 138.6, 135.2, 133.9, 131.1, 131.0, 129.9, 129.4, 128.44, 128.41, 127.9, 123.4, 123.3, 121.9, 121.3, 116.2, 115.9, 115.6, 115.4, 75.2. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{27}H_{17}F_2NO_2SNa$ 480.0840, found 480.0836.

*2′,3′-Bis(4-nitrophenyl)-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ae**).* Yellow solid, 44 mg, 87% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32−8.30 (m, 2H), 7.98−7.96 (m, 2H), 7.89−7.87 (m, 1H), 7.62−7.54 (m, 4H), 7.48−7.41 (m, 2H), 7.35−7.32 (m, 2H), 7.17−7.16 (m, 2H), 7.10−7.08 (m, 1H), 4.91 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.9, 147.4, 146.9, 143.8, 143.4, 140.5, 139.6, 138.9, 137.0, 135.1, 134.2, 130.5, 130.2, 130.1, 130.0, 129.1, 124.3, 123.7, 123.1, 122.2, 121.7, 75.3. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{27}H_{17}N_3O_6SNa$ 534.0730, found 534.0726.

*2′,3′-Bis(3-nitrophenyl)-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3af**).* Yellow solid, 30 mg, 59% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.31 (s, 1H), 8.27 (d, J = 8.1 Hz, 1H), 8.00 (d, J = 8.0 Hz, 1H), 7.85−7.83 (m, 1H), 7.73−7.68 (m, 2H), 7.63−7.59 (m, 3H), 7.47−7.40 (m, 3H), 7.36−7.30 (m, 3H), 7.16−7.14 (m, 1H), 5.13 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.6, 147.9, 146.6, 143.6, 142.5, 140.8, 136.9, 135.3, 135.2, 134.5, 134.3, 133.7, 130.5, 130.4, 130.0, 129.7, 128.9, 124.3, 124.0, 123.8, 123.7, 123.4, 123.2, 122.1, 121.5, 75.3. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{27}H_{17}N_3O_6SNa$ 534.0730, found 534.0730.

*2′,3′-Dibutyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3ah**).* White solid, 38 mg, 99% yield.^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86−7.84 (m, 1H), 7.54−7.50 (m, 1H), 7.46−7.42 (m, 1H), 7.34−7.20 (m, 3H), 7.10−7.07 (m, 1H), 6.82−6.80 (m, 1H), 4.63 (s, 1H), 2.57−2.53 (m, 2H), 2.33−2.27 (m, 1H), 2.07−2.00 (m, 1H), 1.65−1.60 (m, 2H), 1.52−1.43 (m, 2H), 1.28−1.20 (m, 3H), 1.10−1.6 (m, 1H), 1.02−0.98 (t, J = 7.2 Hz, 3H), 0.79−0.76 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.6, 144.6, 143.7, 141.1, 139.2, 135.3, 133.3, 129.5, 129.1, 126.2, 123.6, 122.5, 121.4, 119.4, 75.2, 31.7, 30.8, 25.5, 24.8, 23.1, 23.0, 14.0, 13.7. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{23}H_{27}NO_2SNa$ 404.1655, found 404.1655.

*2′-Methyl-3′-phenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]-1,1-dioxide (**3ai′**) and 3′-methyl-2′-phenyl-2H-spiro[benzo[d]-isothiazole-3,1′-indene]1,1-dioxide (**3ai**).* 3:1 **3ai′**:**3ai**. White solid, 35 mg, 99% yield.

*3′-Methyl-2′-phenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]-1,1-dioxide (**3ai**).* ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83−7.81 (m, 1H), 7.53−7.46 (m, 3H), 7.40−7.35 (m, 4H), 7.26−7.24 (m, 1H), 7.21−7.17 (m, 1H), 7.07−7.00 (m, 3H), 4.74 (s, 1H), 2.27 (s, 3H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 147.8, 143.5, 142.6, 139.0, 138.9, 136.0, 134.1, 133.9, 130.2, 129.4, 129.3, 128.5, 128.0, 127.4, 123.6, 122.6, 121.5, 120.6, 75.0, 12.3. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{22}H_{17}NO_2SNa$ 382.0872, found 382.0875.

*2′-Methyl-3′-phenyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]-1,1-dioxide (**3ai′**).* ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90−7.88(m, 1H), 7.58−7.41 (m, 7H), 7.34−7.23 (m, 3H), 7.16−7.13 (m, 1H), 6.94−6.92 (m, 1H), 4.82 (s, 1H), 1.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.2, 143.4, 142.7, 140.5, 138.7, 135.5, 133.8, 133.5, 129.8, 129.3, 128.8, 128.7, 128.2, 126.6, 123.3, 123.2, 121.6, 120.5, 75.1, 10.1. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{22}H_{17}NO_2SNa$ 382.0872, found 382.0875.

*3′-(trimethylsilyl)-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3aj**).* White foaming solid, 12 mg, 35% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86−7.85 (m, 1H), 7.55−7.45 (m, 2H), 7.41−7.28 (m, 3H), 7.19−7.15 (m, 1H), 6.83−6.81 (m, 1H), 6.51 (s, 1H), 4.81 (s, 1H), 0.34 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.0, 148.5, 148.3, 146.8, 139.8, 136.7, 134.9, 130.9, 130.8, 128.3, 124.9, 124.6, 124.3, 122.8, 75.7, 0.00. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{18}H_{19}NO_2SSiNa$ 364.0803, found 364.0800.

*2′,3′-Bis(4-chlorophenyl)-5′-methyl-2H-spiro[benzo[d]-isothiazole-3,1′-indene]1,1-dioxide (**3dc**).* White solid, 47 mg, 93% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85−7.83 (m, 1H), 7.58−7.48 (m, 2H), 7.41−7.39 (m, 2H), 7.35−7.27 (m, 3H), 7.06 (m, 5H), 6.90−6.88 (m, 2H), 4.81 (s, 1H), 2.35 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 144.3, 142.8, 142.5, 141.8, 139.7, 138.7, 135.0, 134.4, 134.2, 133.9, 131.9, 130.8, 130.6, 130.5, 130.0, 129.3, 128.7, 128.6, 123.2, 123.1, 122.1, 121.9, 74.9, 21.6. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{28}H_{19}Cl_2NO_2SNa$ 526.0406, found 526.0406.

*5′-Methoxy-2′,3′-di-p-tolyl-2H-spiro[benzo[d]isothiazole-3,1′indene]1,1-dioxide (**3eb**).* Yellow solid, 46 mg, 96% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85−7.83 (m, 1H), 7.54−7.48 (m, 2H), 7.33−7.25 (m, 3H), 7.21−7.19 (m, 2H), 7.13−7.11 (m, 1H), 6.88−6.86 (m, 3H), 6.78−6.76 (m, 2H), 6.69−6.67 (m, 1H), 4.81 (s, 1H), 3.77 (s, 3H), 2.39 (s, 3H), 2.18 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.8, 144.1, 143.6, 142.5, 140.3, 139.3, 138.0, 137.9, 135.2, 133.8, 130.8, 129.6, 129.5, 129.4, 129.1, 129.0, 124.0, 123.4, 121.7, 111.9, 108.0, 74.7, 55.6, 21.5, 21.2. HRMS (ESI) [M + Na]$^+$ calcd. for $C_{30}H_{25}NO_3SNa$ 502.1447, found 502.1445.

*2′,3′-Bis(4-chlorophenyl)-5-methyl-2H-spiro[benzo[d]isothiazole-3,1′-indene]1,1-dioxide (**3kc**).* White solid, 46 mg, 92% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75−7.73 (m, 1H), 7.44−7.41 (m, 3H), 7.35−7.30 (m, 5H), 7.25−7.21 (m, 1H), 7.08−7.06 (m, 2H), 6.90−6.88 (m, 2H), 6.81 (s, 1H), 4.82 (s, 1H), 2.33 (s, 3H). ^{13}C NMR (100

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MHz, $CDCl_3$): δ 147.3, 145.2, 142.5, 142.4, 141.5, 138.8, 134.5, 134.2, 132.6, 131.9, 131.2, 130.8, 130.6, 130.4, 129.4, 129.3, 128.8, 128.1, 123.4, 123.1, 121.7, 121.3, 75.0, 21.9. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{19}Cl_2NO_2SNa$ 526.0406, found 526.0410.

*6′,7′-Bis(4-fluorophenyl)-2H-spiro[benzo[d]isothiazole-3,5′-indeno[5,6-d][1,3]dioxole] 1,1-dioxide (**3hd**).* White solid, 46 mg, 92% yield. ^1H NMR (400 MHz, $CDCl_3$): δ 7.82−7.81 (m, 1H), 7.55−7.53 (m, 2H), 7.39−7.35 (m, 2H), 7.14−7.13 (m, 1H), 7.04−7.00 (m, 2H), 6.93−6.87 (m, 3H), 6.80−6.76 (m, 2H), 6.67−6.65 (m, 1H), 5.96−5.94 (d, J = 8 Hz, 2H), 4.79 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 162.6 (d, $^1J_{C-F}$ = 247 Hz), 162.4 (d, $^1J_{C-F}$ = 250 Hz), 149.8, 143.3, 141.0, 140.9, 139.6, 139.1, 134.8, 134.0, 131.56 (d, $^3J_{C-F}$ = 8.0 Hz), 131.23 (d, $^3J_{C-F}$ = 8.0 Hz), 129.9, 129.22 (d, $^4J_{C-F}$ = 3.3 Hz), 128.41 (d, $^4J_{C-F}$ = 3.4 Hz), 123.4, 123.1, 121.8, 117.0, 115.56 (d, $^2J_{C-F}$ = 21.6 Hz), 115.3 (d, $^2J_{C-F}$ = 21.6 Hz), 107.0, 101.6, 75.2. HRMS (ESI) $[M + Na]^+$ calcd. for $C_{28}H_{17}F_2NO_4SNa$ 524.0739, found 524.0738.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00976.

^1H NMR and ^{13}C NMR spectra (PDF)

X-ray crystallographic data for compounds **3ga**, **3ai**, and **3hd** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: wangjun23@mail.sysu.edu.cn.

Notes

The authors declare no competing financial interest.

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