JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

Regio- and Stereoselective Synthesis of 2-Amino-dienes via Decarboxylative Amination of 4-(Ethoxycarbonyl)-2,3-allenols by TsNCO

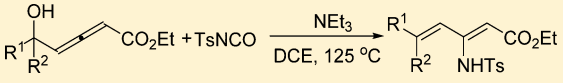
Lijun Wu,[†] Hui Huang,[†] Yun Liang,*[,†] and Pi Cheng*[,‡]

[†]National & Local Joint Engineering Laboratory for New Petro-chemical Materials and Fine Utilization of Resources, Key Laboratory of Chemical Biology and Traditional Chinese Medicine Research, Ministry of Education, Hunan Normal University, Changsha, Hunan 410081, China

[‡]National Research Center of Engineering Technology for Utilization of Functional Ingredients from Botanicals, Hunan Agricultural University, Changsha, Hunan 410128, China

Supporting Information

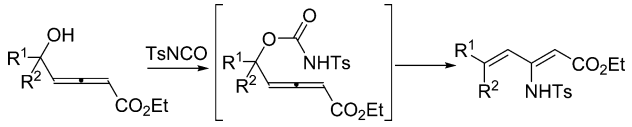
ABSTRACT: A metal-free decarboxylative amination of 4-(ethoxycarbonyl)-2,3-allenols by TsNCO via base-induced aza-Michael addition/elimination has been developed. A variety of substituted *N*-tosyl 1,3-dien-2-yl amines were obtained in good yields and excellent regio- and stereoselectivity. Moreover, this transformation could be applied in preparation of 2-amino-trienes.



1,3-Dienes not only are important and versatile synthetic intermediates in organic synthesis but also are significant moieties in many natural products and bioactive compounds.[1] For these reasons, the development of efficient and selective methods for the synthesis of 1,3-dienes remains an area of current interest. Recently, a particularly effective method for the synthesis of functionalized dienes is through translation of allene derivatives.[2−8] Among these approaches, 2,3-allenols or their derivatives are important synthons for the preparation of 2-substituted conjugated 1,3-dienes, such as 2-alkenyl 1,3-dienes,[3] 2-alkynyl 1,3-dienes,[4] 2-halo 1,3-dienes,[5] 2-OTf 1,3-dienes,[6] 1,3-butadien-2-ol esters,[7] and 2-furan or 2-furanone substituted 1,3-diene derivatives.[8] Considering the potential importance of 2-amino 1,3-dienes in the synthesis of complex nitrogen-containing natural products, we decide to further expand the reaction scope to synthesize 2-amino 1,3-dienes.[9] Recently, transition-metal-catalyzed decarboxylative amination of allylic carbamates represents a highly efficient and attractive method for the formation of C−N bond.[10] However, given the well-known fact that there is similar construction of allylic carbamates with allenyl methyl carbamates(buta-2,3-dien-1-yl carbamates), it is rather surprising that the analogous decarboxylative amination never has been realized. In our continued interest in decarboxylative coupling of allylic esters,[11] we envisioned that the rearrangement of allenic *N*-tosylcarbamates should offer a unique opportunity not only for the exploration of their rearrangement under metal-catalyzed or metal-free conditions but also for developing a new approach for regio- and stereoselective synthesis of 2-amino 1,3-dienes. Herein, we will detail our results (Scheme 1).

Considering the instability of allenic *N*-tosylcarbamates, it can be prepared in situ from the corresponding 2,3-allenols (which can be readily synthesized from terminal propargylic alcohols and ethyl diazoacetate in high yield in a one-pot process[6]) with TsNCO.[12] Therefore, we used the reaction of

Scheme 1. Synthesis of 2-Amino-dienes

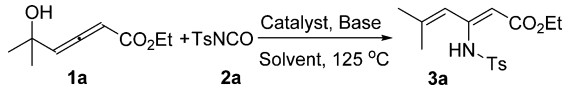


ethyl 5-hydroxy-5-methylhexa-2,3-dienoate (**1a**) with TsNCO as a model to screen the optimized conditions, and the results are summarized in Table 1. Initially, we used **1a** and TsNCO as the starting materials, CuI as catalyst, and NEt_3 as base in DCE at 125 °C (entry 1). Surprisingly, the reaction substrates were consumed completely in half an hour, and 79% yield of product 1,3-diene (**3a**) was obtained with excellent regio- and stereoselectivity. Then, the metal catalysts such as $PdCl_2$, $AuCl_3$, and AgOTf were also screened, and the results demonstrated that these metal catalysts showed a poor performance (entries 2−4). Control experiments revealed that the metal catalysts are unnecessary and bases are necessary for this transformation (entries 5−6). Therefore, different bases, such as DIPA, DABCO, DBU, K_2CO_3, NaOAc, K_3PO_4, and NaO*t*-Bu, were examined (entries 7−13). The results indicated that the base NEt_3 is the best for this decarboxylative amination reaction. Next, the solvents were also evaluated in the reaction. DCE was superior to toluene, THF, and CH_3CN. Finally, the reaction temperature and the amount of NEt_3 were evaluated. Relatively low yields were found when 1 or 3 equiv of NEt_3 was used in this reaction (entries 17 and 18), and when the reaction was carried out at 110 or 140 °C (entries 19 and 20). Thus, the optimized reaction conditions were as follows: **1a** (0.3 mmol), **2a** (0.45 mmol), NEt_3 (0.45 mmol), in DCE (2 mL) at 125 °C.

Received: September 10, 2014
Published: October 24, 2014

   dx.doi.org/10.1021/jo502098b | *J. Org. Chem.* 2014, 79, 11264−11269

Table 1. Optimization of Reaction Conditions[a]



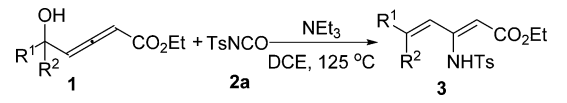
entry	catalyst	base	solvent	yield (%)[b]
1	CuI	NEt_3	DCE	79
2	AgOTf	NEt_3	DCE	53
3	$PdCl_2$	NEt_3	DCE	56
4	$AuCl_3$	NEt_3	DCE	59
5	CuI		DCE	5
6		NEt_3	DCE	85
7		DIPA	DCE	49
8		DABCO	DCE	78
9		DBU	DCE	15
10		K_2CO_3	DCE	71
11		NaOAc	DCE	70
12		K_3PO_4	DCE	63
13		NaO*t*-Bu	DCE	8
14		NEt_3	toluene	73
15		NEt_3	THF	63
16		NEt_3	CH_3CN	73
17[c]		NEt_3	DCE	72
18[d]		NEt_3	DCE	65
19[e]		NEt_3	DCE	68
20[f]		NEt_3	DCE	76

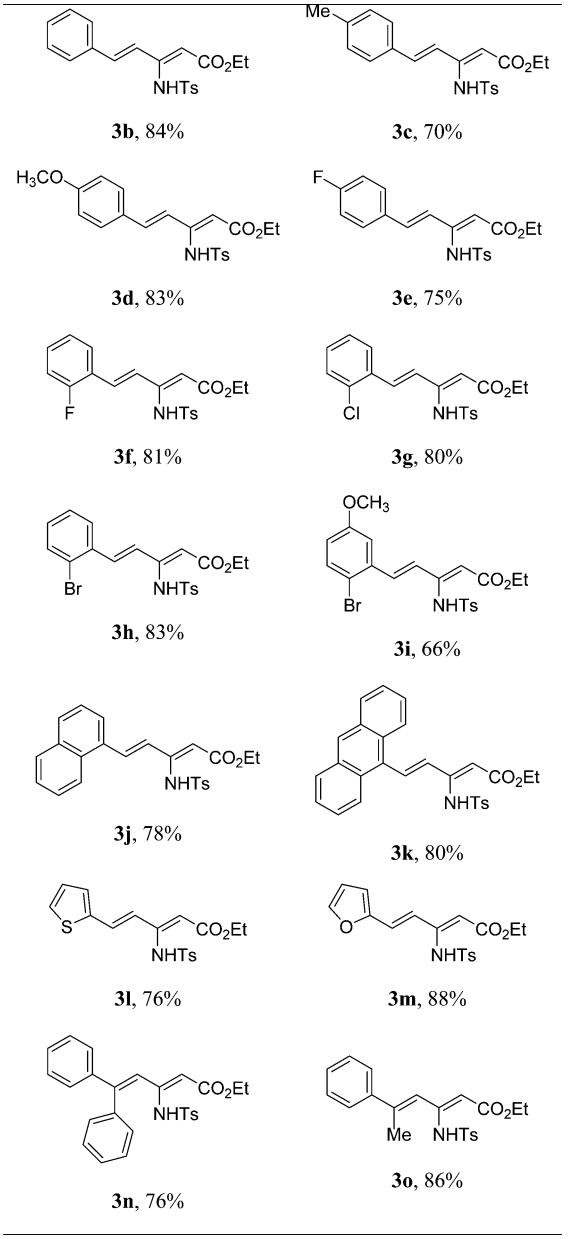
[a]Reaction conditions: **1a** (0.3 mmol), **2a** (0.45 mmol), catalyst (10 mol %), base (1.5 equiv), DCE (2 mL) in sealed Schlenk tube, at 125 °C for 0.5 h. [b]Isolated yields. [c]NEt_3 (1 equiv). [d]NEt_3 (3 equiv). [e]At 110 °C. [f]At 140 °C.

With the optimized reaction conditions in hand, the decarboxylative amination of various allenic alcohols by TsNCO were investigated, and the results are summarized in Table 2. Initially, the substituted phenyl was screened. The results demonstrated that both electron-rich and electron-deficient phenyl substituted allenic alcohols could be smoothly transformed into the desired products. For examples, ethyl-(2*Z*,4*E*)-5-(4-methoxyphenyl)-3-((4-methylphenyl)sulfonamido)penta-2,4-dienoate (**3d**) and ethyl(2*Z*,4*E*)-5-(4-fluorophenyl)-3-((4-methylphenyl)sulfonamido)penta-2,4-dienoate (**3e**) were obtained in 83% and 75%, respectively. These results indicated that an electronic effect on the substituted group did not play a significant role in regulating the reaction. It is noteworthy that the benzene ring bearing a methoxyl group and bromine atom substituted allenic alcohols could react with TsNCO under standard conditions. The desired product **3i** was afforded in 66% yield, and its structure was further established by X-ray diffraction study (Figure 1). In addition, 2-naphthyl and 9-phenanthryl substituted allenic alcohols could react with TsNCO and afford the expected products in 78% and 80% yields, respectively. Importantly, 2-thiophenyl and 2-furanyl substituted allenic alcohols were also tolerated in this transformation, generating **3l** and **3m** in 76% and 88% yield, respectively. Finally, double substituted allenic alcohols were evaluated, and ethyl (*Z*)-3-((4-methylphenyl)sulfonamido)-5,5-diphenylpenta-2,4-dienoate (**3n**) and ethyl (2*Z*,4*E*)-3-((4-methylphenyl)sulfonamido)-5-phenylhexa-2,4-dienoate (**3o**) were obtained in 76% or 86% yield, respectively. These results indicated that a steric effect on the substituted group did not play a significant role in regulating the reaction.

To extend the substrate scope of the methodology, we also examined the decarboxylative amination reaction of allenic

Table 2. Decarboxylative Amination of Allenic Alcohols by TsNCO[a,b]





[a]Reaction conditions: **1** (0.3 mmol), **2a** (0.45 mmol), NEt_3 (1.5 equiv), DCE (2 mL) in a sealed Schlenk tube, at 125 °C for 0.5 h. [b]Isolated yield.

alcohols by CbzNCO (Scheme 2). Compared with TsNCO, the relatively low yields of desired products were given. The reaction of PhNCO with allenic alcohol was also investigated under optimized conditions; however, no corresponding 2-amino 1,3-diene was produced. These results indicated that the reactivity of the substrate is highly dependent on the NH acidity of the carbamate.

Considering conjugated trienes with widespread application in biological chemistry, natural products synthesis and material science,[13] we decided to further expand the substrate scope to C4-alkenyl-substituted substrates. Fortunately, the high regio-

dx.doi.org/10.1021/jo502098b | J. Org. Chem. 2014, 79, 11264−11269

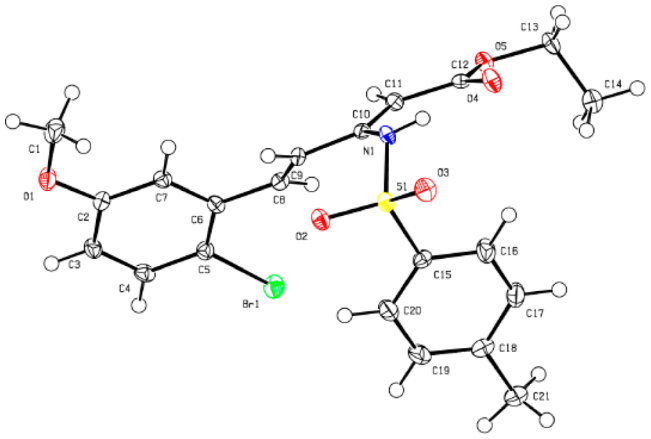
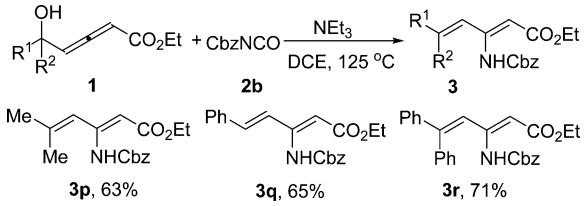


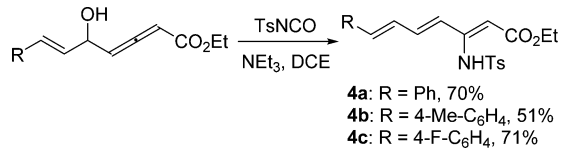
Figure 1. OPTEP structure of **3i**. Selected bond lengths [Å] for **3i**: C(6)−C(8) 1.467(3), C(8)−C(9) 1.338(3), C(9)−C(10) 1.469(3), C(10)−N(1) 1.407(3), C(10)−C(11) 1.348(3), C(11)−C(12) 1.464(3); Selected bond angles [deg] for **3i**: C(6)−C(8)−C(9) 125.1(2), C(8)−C(9)−C(10) 121.9(2), N(1)−C(10)−C(9) 117.4(2), C(11)−C(10)−N(1) 120.6(2), C(11)−C(10)−C(9) 121.9(2), C(10)−C(11)−C(12) 123.6(2).

Scheme 2. Decarboxylative Amination of Allenic Alcohols with CbzNCO



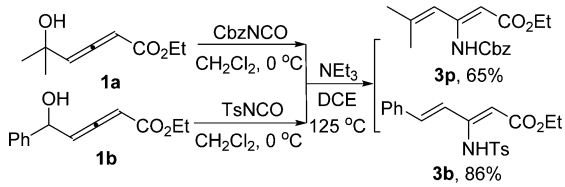
and steroselective conjugated trienes were obtained in moderate yields (Scheme 3).

Scheme 3. Synthesis of Conjugated Trienes



To further gain insight into the mechanism, a crossover experiment was conducted (Scheme 4). First, the reactions of

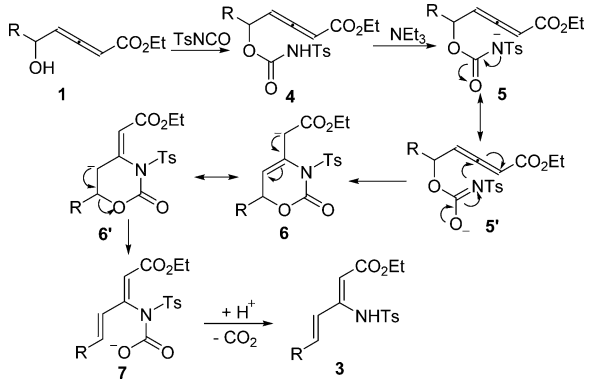
Scheme 4. Crossover Experiment



ethyl 5-hydroxy-5-methylhexa-2,3-dienoate with CbzNCO and ethyl 5-hydroxy-5-phenylpenta-2,3-dienoate with TsNCO were performed in half an hour at 0 °C, respectively. Then, the reactive products were mixed together, and continued to react under standard conditions. Only the desired products of ethyl (*Z*)-3-((benzyloxy)carbonyl)amino)-5-methylhexa-2,4-dienoate (**3p**) and ethyl (2*Z*,4*E*)-3-((4-methylphenyl)sulfonamido)-5-phenylpenta-2,4-dienoate (**3b**) were afforded in 65% and 86% yield, respectively. No crossover product was observed. This result supported that the reaction possibly underwent a cyclization-induced intramolecular aza-Michael addition.

On the basis of these results and previous reports,[10,14] we propose a cyclization-induced aza-Michael addition/elimination pathway to account for the product formation (Scheme 5).

Scheme 5. Plausible Mechanism



First, *N*-tosylcarbamate is produced in situ from the corresponding 2,3-allenol with TsNCO, and then it is deprotonated into intermediate **5** by NEt_3. The intermediate **5** undergoes an intramolecular aza-Michael addition on the ester function-activated double bond, giving rise to the six-membered-ring intermediate **6** that undergoes the rearrangement and elimination to give dienyl *N*-tosyl carbamate ion **7**. Finally, decarboxylative and protonation of intermediate **7** occurs, leading to the 2-amino diene product.

In conclusion, we have demonstrated a novel decarboxylative amination of allenic alcohols by TsNCO or CbzNCO. This method provides an effective approach to synthesize highly regio- and stereoselective 1,3-dienes in good yields. This transformation could be performed under metal-free conditions and, therefore, represents an efficient and environmentally benign protocol for the synthesis of conjugated dienes and trienes.

EXPERIMENTAL SECTION

General Considerations. The ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ solvent on a NMR spectrometer using TMS as internal standard. HRMS was measured on an electrospray ionization (ESI) apparatus using time-of-flight (TOF) mass spectrometry. Melting points are uncorrected. Column chromatography was performed using EM Silica gel 60 (200−300 mesh).

Preparation of Allenic Alcohols (1). All allenic alcohols (**1**) were synthesized according to the known methods.[6]

Typical Experimental Procedure for the Synthesis of 2-Amino-dienes from TsNCO and 4-(Ethoxycarbonyl)-2,3-allenols. A sealed Schenk tube was charged with allenic alcohol **1** (0.3 mmol), **2** (0.45 mmol, 1.5 equiv), and NEt_3 (0.45 mmol, 1.5 equiv). Then, 2.0 mL of anhydrous DCE was added as solvent. The mixture was heated to 125 °C for 30 min, then cooled down to room temperature, quenched with H_2O, and extracted with ethyl acetate. The organic layer was dried over Na_2SO_4. After removal of the solvent in vacuo, the crude product was purified by flash column chromatography on silica gel with petroleum ether−ethyl acetate as eluent to give the desired products **3**.

*(Z)-Ethyl 5-Methyl-3-(4-methylphenylsulfonamido)hexa-2,4-dienoate (**3a**).* White solid, isolated yield 85% (82 mg); mp: 59.0−60.8 °C; ^1H NMR ($CDCl_3$, 500 MHz) δ = 10.87 (s, 1H), 7.68 (d, J = 8.5 Hz, 2H), 7.26 (d, J = 8.0 Hz, 2H), 5.95 (s, 1H), 4.82 (s, 1H), 4.17

dx.doi.org/10.1021/jo502098b | J. Org. Chem. 2014, 79, 11264−11269

(q, J = 7.0 Hz, 2H), 2.41 (s, 3H), 1.77 (s, 3H), 1.36 (s, 3H), 1.27 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.1, 151.1, 143.9, 143.8, 137.4, 129.4, 127.6, 118.7, 97.7, 60.2, 26.2, 21.5, 19.6, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{16}H_{21}NO_4SH$ 324.1264; Found 324.1265.

*(2Z,4E)-Ethyl 3-(4-Methylphenylsulfonamido)-5-phenylpenta-2,4-dienoate (**3b**).* Yellow viscous oil, isolated yield 84% (93 mg); ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.85 (s, 1H), 7.70 (d, J = 8.5 Hz, 2H), 7.43 (d, J = 7.0 Hz, 2H), 7.39−7.34 (m, 3H), 7.22 (d, J = 8.0 Hz, 2H), 7.13 (d, J = 16.0 Hz, 1H), 6.88 (d, J = 16.0 Hz, 1H), 5.35 (s, 1H), 4.17 (q, J = 7.0 Hz, 2H), 2.38 (s, 3H), 1.27 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 152.0, 144.1, 136.8, 136.5, 135.3, 129.6, 129.4, 128.9, 127.5, 127.3, 121.1, 95.5, 60.3, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{21}NO_4SH$ 372.1264; Found 372.1267.

*(2Z,4E)-Ethyl 3-(4-Methylphenylsulfonamido)-5-p-tolylpenta-2,4-dienoate (**3c**).* Yellow solid, isolated yield 70% (81 mg); mp: 79.5−81.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.87 (s, 1H), 7.69 (d, J = 8.0 Hz, 2H), 7.32 (d, J = 7. 5 Hz, 2H), 7.20 (d, J = 8.0 Hz, 2H), 7.17 (d, J = 8.0 Hz, 2H), 7.08 (d, J = 16.0 Hz, 1H), 6.85 (d, J = 16.0 Hz, 1H), 5.33 (s, 1H), 4.16 (q, J = 7.0 Hz, 2H), 2.36 (s, 6H), 1.26 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 152.0, 144.0, 139.7, 136.9, 136.5, 132.6, 129.5, 127.4, 127.3, 119.9, 95.1, 60.2, 21.4, 21.3, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{21}H_{23}NO_4SH$ 386.1421; Found 386.1423.

*(2Z,4E)-Ethyl 5-(4-Methoxyphenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3d**).* Yellow solid, isolated yield 83% (100 mg); mp: 82.7−84.3 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.87 (s, 1H), 7.69 (d, J = 8.0 Hz, 2H), 7.37 (d, J = 8.5 Hz, 2H), 7.21 (d, J = 8.0, 2H), 6.99 (d, J = 16.0 Hz, 1H), 6.89 (d, J = 9.0 Hz, 2H), 6.85 (d, J = 16.0 Hz, 1H), 5.31 (s, 1H), 4.16 (q, J = 7.0 Hz, 2H), 3.84 (s, 3H), 2.37 (s, 3H), 1.26 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.1, 160.7, 152.4, 144.0, 136.9, 136.2, 129.6, 129.0, 128.2, 127.3, 118.6, 114.3, 94.7, 60.2, 55.3, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{21}H_{23}NO_5SH$ 402.1370; Found 402.1368.

*(2E,4E)-Ethyl 5-(4-Fluorophenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3e**).* Yellow solid, isolated yield 75% (88 mg); mp: 74.3−76.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.83 (s, 1H), 7.68 (d, J = 8.0 Hz, 2H), 7.41 (dd, J = 8.5 Hz, 5.0 Hz, 2H), 7.22 (d, J = 8.5 Hz, 2H), 7.08−7.02 (m, 3H), 6.84 (d, J = 16.0 Hz, 1H), 5.33 (s, 1H), 4.17 (q, J = 7.0 Hz, 2H), 2.38 (s, 3H), 1.27 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 163.3 (d, J = 249.0 Hz), 151.8, 144.1, 136.9, 135.2, 131.6, 129.6, 129.2 (d, J = 8.3 Hz), 127.3, 121.0, 116.0 (d, J = 21.8 Hz), 95.7, 60.4, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{20}FNO_4SH$ 390.1170; Found 390.1172.

*(2Z,4E)-Ethyl 5-(2-Fluorophenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3f**).* Yellow solid, isolated yield 81% (95 mg); mp: 81.0−82.5 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.85 (s, 1H), 7.70 (d, J = 8.5 Hz, 2H), 7.53 (t, J = 7.5 Hz, 1H), 7.34−7.29 (m, 1H), 7.24−7.15 (m, 4H), 7.08−7.02 (m, 2H), 5.37 (s, 1H), 4.17 (q, J = 7.0 Hz, 2H), 2.38 (s, 3H), 1.27 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 161.6 (d, J = 250.4 Hz), 151.8, 144.2, 136.8, 130.8 (d, J = 8.6 Hz), 129.6, 128.5 (d, J = 3.6 Hz), 127.9 (d, J = 2.9 Hz), 127.3, 124.5 (d, J = 3.4 Hz), 123.3 (d, J = 2.1 Hz), 123.3 (d, J = 9.1 Hz), 115.9 (d, J = 21.8 Hz), 96.0, 60.4, 21.5, 14.1. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{20}FNO_4SH$ 390.1170; Found 390.1174.

*(2Z,4E)-Ethyl 5-(2-Chlorophenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3g**).* Yellow solid, isolated yield 80% (97 mg); mp: 81.3−82.5 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.83 (s, 1H), 7.69 (d, J = 8.5 Hz, 2H), 7.62 (d, J = 7.0 Hz, 1H), 7.39 (d, J = 7.0 Hz, 1H), 7.32−7.28 (m, 2H), 7.25−7.21 (m, 3H), 7.12 (d, J = 16.0, 1H), 5.38 (s, 1H), 4.18 (q, J = 7.0 Hz, 2H), 2.39 (s, 3H), 1.28 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 151.7, 144.2, 136.9, 134.0, 133.6, 132.2, 130.2, 129.9, 129.7, 127.6, 127.3, 127.3, 124.1, 96.5, 60.5, 21.6, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{20}ClNO_4SH$ 406.0874; Found 406.0877.

*(2Z,4E)-Ethyl 5-(2-Bromophenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3h**).* Yellow solid, isolated yield 83% (112 mg); mp: 91.5−93.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.83 (s, 1H), 7.69 (d, J = 8.0 Hz, 2H), 7.62−7.57 (m, 2H), 7.35 (t, J = 7.5 Hz, 1H), 7.24 (d, J = 8.5 Hz, 2H), 7.22−7.16 (m, 2H), 7.08 (d, J = 16.0 Hz, 1H), 5.38 (s, 1H), 4.18 (q, J = 7.0 Hz, 2H), 2.39 (s, 3H), 1.28 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 151.6, 144.2, 136.8, 135.4, 134.7, 133.1, 130.4, 129.7, 127.9, 127.8, 127.3, 124.4, 124.3, 96.5, 60.5, 21.6, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{20}{}^{79}BrNO_4SH$ 450.0369; Found 450.0372.

*(2Z,4E)-Ethyl 5-(2-Bromo-5-methoxyphenyl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3i**).* Yellow solid, isolated yield 66% (95 mg); mp: 126.3−128.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.82 (s, 1H), 7.69 (d, J = 8.5 Hz, 2H), 7.45 (d, J = 8.5 Hz, 1H), 7.25 (d, J = 8.0 Hz, 2H), 7.13 (d, J = 16.0 Hz, 1H), 7.10 (d, J = 3.0 Hz, 1H), 7.05 (d, J = 16.0 Hz, 1H), 6.79 (dd, J = 9.0 Hz, 3.0 Hz, 1H), 5.37 (s, 1H), 4.18 (q, J = 7.0 Hz, 2H), 3.85 (s, 3H), 2.40 (s, 3H), 1.28 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 159.1, 151.5, 144.2, 136.8, 136.0, 134.8, 133.7, 129.8, 127.3, 124.4, 116.9, 115.0, 112.5, 96.6, 60.5, 55.6, 21.6, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{21}H_{22}{}^{79}BrNO_5SH$ 480.0475; Found 480.0475.

*(2Z,4E)-Ethyl 3-(4-Methylphenylsulfonamido)-5-(naphthalen-1-yl)penta-2,4-dienate (**3j**).* Yellow oil, isolated yield 78% (99 mg); ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.88 (s, 1H), 7.94 (dd, J = 6.5 Hz, 3.5 Hz, 1H), 7.88−7.85 (m, 2H), 7.71−7.69 (m, 3H), 7.65 (d, J = 15.5 Hz, 1H), 7.53−7.48 (m, 3H), 7.18−7.14 (m, 3H), 5.43 (s, 1H), 4.20 (q, J = 7.0 Hz, 2H), 2.35 (s, 3H), 1.29 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 152.3, 144.1, 136.8, 133.8, 133.6, 132.7, 131.1, 129.7, 129.6, 128.8, 127.4, 126.5, 126.0, 125.6, 124.9, 124.1, 123.2, 96.3, 60.4, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{24}H_{23}NO_4SH$ 422.1421; Found 422.1422.

*(2Z,4E)-Ethyl 5-(Anthracen-9-yl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3k**).* Yellow solid, isolated yield 80% (113 mg); mp: 146.0−147.2 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.99 (s, 1H), 8.42 (s, 1H), 8.09 (d, J = 9.0 Hz, 2H), 8.00 (d, J = 9.0 Hz, 2H), 7.80 (d, J = 16.0 Hz, 1H), 7.72 (d, J = 8.0 Hz, 2H), 7.50−7.46 (m, 4H), 7.21 (d, J = 8.0 Hz, 2H), 7.01 (d, J = 16.0 Hz, 1H), 5.62 (s, 1H), 4.24 (q, J = 7.0 Hz, 2H), 2.40 (s, 3H), 1.32 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 151.9, 144.1, 137.0, 133.6, 131.3, 129.9, 129.8, 129.5, 128.8, 128.0, 127.4, 126.1, 125.3, 125.3, 96.3, 60.5, 21.6, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{28}H_{25}NO_4SH$ 472.1577; Found 472.1577.

*(2Z,4E)-Ethyl 3-(4-Methylphenylsulfonamido)-5-(thiophen-2-yl)penta-2,4-dienoate (**3l**).* Yellow solid, isolated yield 76% (86 mg); mp: 97.5−98.8 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.84 (s, 1H), 7.70 (d, J = 8.0 Hz, 2H), 7.35−7.31 (m, 2H), 7.27 (d, J = 8.0 Hz, 1H), 7.23 (d, J = 8.0 Hz, 2H), 6.95 (d, J = 16.0 Hz, 1H), 6.91 (d, J = 16.0 Hz, 1H), 5.31 (s, 1H), 4.16 (q, J = 7.0 Hz, 2H), 2.39 (s, 3H), 1.26 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 152.0, 144.0, 138.4, 136.9, 130.4, 129.6, 127.3, 126.9, 126.0, 125.1, 120.8, 95.2, 60.3, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{18}H_{19}NO_4S_2H$ 378.0828; Found 378.0830.

*(2Z,4E)-Ethyl 5-(Furan-2-yl)-3-(4-methylphenylsulfonamido)penta-2,4-dienoate (**3m**).* Yellow oil, isolated yield 88% (95 mg); ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.77 (s, 1H), 7.72 (d, J = 8.0 Hz, 2H), 7.46 (s, 1H), 7.24 (d, J = 8.0 Hz, 2H), 6.97 (d, J = 16.0 Hz, 1H), 6.75 (d, J = 16.0 Hz, 1H), 6.45 (s, 2H), 5.29 (s, 1H), 4.15 (q, J = 7.0 Hz, 2H), 2.39 (s, 3H), 1.25 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 151.6, 144.2, 144.1, 136.8, 129.6, 127.5, 123.8, 118.9, 112.6, 112.1, 95.7, 60.3, 21.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{18}H_{19}NO_5SH$ 362.1057; Found 362.1060.

*(Z)-Ethyl 3-(4-Methylphenylsulfonamido)-5,5-diphenylpenta-2,4-dienoate (**3n**).* Yellow solid, isolated yield 76% (102 mg); mp: 114.5−116.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 11.04 (s, 1H), 7.76 (d, J = 8.5 Hz, 2H), 7.34−7.27 (m, 5H), 7.23−7.17 (m, 3H), 7.12 (t, J = 7.5, 2H), 6.74 (s, 1H), 6.52 (d, J = 7.0 Hz, 2H), 4.55 (s, 1H), 4.03 (q, J = 7.0 Hz, 2H), 2.43 (s, 3H), 1.14 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.2, 150.5, 149.6, 144.3, 141.4, 138.5, 137.5, 129.7, 129.4, 128.8, 128.3, 128.1, 128.0, 128.0, 127.9, 119.6, 98.6, 60.1, 21.6, 14.1. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{26}H_{25}NO_4SH$ 448.1577; Found 448.1581.

dx.doi.org/10.1021/jo502098b | J. Org. Chem. 2014, 79, 11264−11269

*(2Z,4E)-Ethyl 3-(4-Methylphenylsulfonamido)-5-phenylhexa-2,4-dienoate (**3o**).* Yellow solid, isolated yield 86% (99 mg); mp: 94.8−95.9 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.94 (s, 1H), 7.66 (d, J = 8.5 Hz, 2H), 7.44 (dd, J = 8.5 Hz, 1.5 Hz, 2H), 7.40−7.33 (m, 3H), 7.21 (d, J = 8.0 Hz, 2H), 6.54 (s, 1H), 4.98 (s, 1H), 4.20 (q, J = 7.0 Hz, 2H), 2.38 (s, 3H), 1.76 (s, 3H), 1.29 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 150.9, 143.9, 143.8, 141.7, 137.3, 129.5, 128.5, 128.4, 127.5, 126.0, 120.4, 98.6, 60.3, 21.5, 17.5, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{21}H_{23}NO_4SH$ 386.1421; Found 386.1423.

*(Z)-Ethyl 3-Benzamido-5-methylhexa-2,4-dienoate (**3p**).* White solid, isolated yield 63% (52 mg); mp: 51.5−53.2 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 12.05 (s, 1H), 7.99 (d, J = 7.5 Hz, 2H), 7.56−7.47 (m, 3H), 6.56 (s, 1H), 5.05 (s, 1H), 4.22 (q, J = 7.0 Hz, 2H), 1.94 (s, 3H), 1.92 (s, 3H), 1.32 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.6, 164.9, 152.3, 140.1, 133.9, 132.2, 128.7, 127.6, 121.2, 98.3, 60.0, 26.6, 20.2, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{16}H_{19}NO_3H$ 274.1438; Found 274.1440.

*(2Z,4E)-Ethyl 3-Benzamido-5-phenylpenta-2,4-dienoate (**3q**).* Yellow solid, isolated yield 65% (63 mg); mp: 94.6−95.7 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 12.05 (s, 1H), 8.02 (d, J = 7.0 Hz, 2H), 7.79 (d, J = 16.0 Hz, 1H), 7.58−7.48 (m, 5H), 7.35 (t, J = 7.5 Hz, 2H), 7.32−7.28 (m, 1H), 7.08 (d, J = 16.0 Hz, 1H), 5.53 (s, 1H), 4.24 (q, J = 7.0 Hz, 2H), 1.33 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ =169.6, 165.6, 153.6, 136.0, 134.1, 133.8, 132.4, 128.8, 128.8, 128.7, 127.7, 127.5, 123.9, 95.0, 60.2, 14.3. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{20}H_{19}NO_3H$ 322.1438; Found 322.1441.

*(Z)-Ethyl 3-Benzamido-5,5-diphenylpenta-2,4-dienoate (**3r**).* Yellow solid, isolated yield 71% (85 mg); mp: 139.8−140.7 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 11.95 (s, 1H), 7.96 (d, J = 7.0 Hz, 2H), 7.56 (t, J = 7.5 Hz, 1H), 7.49 (t, J = 7.5 Hz, 2H), 7.31−7.26 (m, 10H), 7.13 (s, 1H), 4.84 (s, 1H), 4.09 (q, J = 7.0 Hz, 2H), 1.20 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.6, 165.1, 152.2, 145.9, 141.9, 139.5, 133.6, 132.4, 128.8, 128.3, 128.2, 127.7, 123.5, 100.1, 60.0, 14.2. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{26}H_{23}NO_3H$ 398.1751; Found 398.1754.

*(2Z,4E,6E)-Ethyl 3-(4-Methylphenylsulfonamido)-7-phenylhepta-2,4,6-trienoate (**4a**).* Yellow solid, isolated yield 70% (83 mg); mp: 104.5−106 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.82 (s, 1H), 7.71 (d, J = 8.0 Hz, 2H), 7.43 (d, J = 7.5 Hz, 2H), 7.35 (t, J = 7.5 Hz, 2H), 7.29 (d, J = 7.0 Hz, 1H), 7.25 (d, J = 8.0 Hz, 2H), 6.90−6.84 (m, 1H), 6.79−6.74 (m, 1H), 6.68 (d, J = 15.0 Hz, 2H), 5.30 (s, 1H), 4.15 (q, J = 7.0 Hz, 2H), 2.39 (s, 3H), 1.26 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 151.6, 144.0, 137.7, 137.1, 136.8, 136.2, 129.6, 128.7, 128.7, 127.4, 127.3, 126.9, 124.1, 95.5, 60.3, 21.5, 14.1. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{22}H_{23}NO_4SH$ 398.1421; Found 398.1423.

*(2Z,4E,6E)-Ethyl 3-(4-Methylphenylsulfonamido)-7-p-tolylhepta-2,4,6-trienoate (**4b**).* Yellow solid, isolated yield 51% (63 mg); mp: 122.5−124.0 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.82 (s, 1H), 7.71 (d, J = 8.5 Hz, 2H), 7.33 (d, J = 8.0 Hz, 2H), 7.25 (d, J = 8.0 Hz, 2H), 7.15 (d, J = 8.0 Hz, 2H), 6.85−6.64 (m, 2H), 6.65 (d, J = 15.0 Hz, 2H), 5.29 (s, 1H), 4.14 (q, J = 7.0 Hz, 2H), 2.38 (s, 3H), 2.35 (s, 3H), 1.25 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 169.0, 151.8, 144.0, 138.9, 137.8, 137.4, 136.8, 133.5, 129.6, 129.5, 127.3, 126.9, 126.5, 123.5, 95.2, 60.2, 21.5, 21.3, 14.1. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{23}H_{25}NO_4SH$ 412.1577; found 412.1575.

*(2Z,4E,6E)-Ethyl 7-(4-Fluorophenyl)-3-(4-methylphenylsulfonamido)hepta-2,4,6-trienoate (**4c**).* Yellow solid, isolated yield 71% (88 mg); mp: 126.6−128.1 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ = 10.80 (s, 1H), 7.71 (d, J = 8.5 Hz, 2H), 7.41 (dd, J = 8.5 Hz, 3.0 Hz, 2H), 7.26 (d, J = 8.5 Hz, 2H), 7.04 (t, J = 8.5 Hz, 2H), 6.82−6.73 (m, 2H), 6.70−6.63 (m, 2H), 5.30 (s, 1H), 4.15 (q, J = 7.0 Hz, 2H), 2.40 (s, 3H), 1.26 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 168.9, 162.9 (d, J = 247.9 Hz), 151.6, 144.1, 136.9, 136.8, 136.4, 132.5 (d, J = 3.5 Hz), 129.6, 128.5 (d, J = 8.1 Hz), 127.3, 127.2 (d, J = 2.1 Hz), 124.3, 115.8 (d, J = 21.6 Hz), 95.6, 60.3, 21.5, 14.1. HRMS (ESI-TOF) m/z: $[M + H]^+$ calcd for $C_{22}H_{22}FNO_4SH$ 416.1326; Found 416.1324.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Supporting Information for this article is available (experimental details, X-ray data of **3i** (CCDC-1014994), and scanned NMR spectra of all new products). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: yliang@hunnu.edu.cn (Y.L.).
*E-mail: picheng55@126.com (P.C.).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the Natural Science Foundation of China (21072054), the Ministry of Education of China (20094306120003, 213027A), the Training Program Foundation for the Young Talents by Hunan Normal University (ET21003), the Hunan Provincial Natural Science Foundation (12JJ2009), the Scientific Research Fund of Hunan Provincial Education Department (12A095), and the Aid Program for Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province.

■ REFERENCES

(1) (a) Rappoport, Z. *The Chemistry of Dienes and Polyenes*; John Wiley & Sons: Chichester, 2001; Vol. 2. (b) Rappoport, Z. *The Chemistry of Dienes and Polyenes*; John Wiley & Sons: Chichester, U.K., 1997; Vol. 1. (c) Takeuchi, D.; Osakada, K. *Polymer* **2008**, *49*, 4911. (d) Negishi, E. I.; Huang, Z.; Wang, G.; Mohan, S.; Wang, C.; Hattori, H. *Acc. Chem. Res.* **2008**, *41*, 1474. (e) Deagostino, A.; Prandi, C.; Zavattaro, C.; Venturello, P. *Eur. J. Org. Chem.* **2006**, 2463. (f) Luh, T. Y.; Wrong, K. T. *Synthesis* **1993**, 349.

(2) (a) Hampton, C. S.; Harmata, M. *Org. Lett.* **2014**, *16*, 1256. (b) Xu, S.; Zhou, L.; Zeng, S.; Ma, R.; Wang, Z.; He, Z. *Org. Lett.* **2009**, *11*, 3498. (c) Yu, F.; Lian, X.; Ma, S. *Org. Lett.* **2007**, *9*, 1703. (d) Jiang, X.; Ma, S. *J. Am. Chem. Soc.* **2007**, *129*, 11600. (e) Pacheco, Ma. C.; Gouverneur, V. *Org. Lett.* **2005**, *7*, 1267. (f) Ma, S. *Chem. Rev.* **2005**, *105*, 2829. (g) Fu, C.; Ma, S. *Org. Lett.* **2005**, *7*, 1707.

(3) Wang, H.; Beiring, B.; Yu, D. G.; Collins, K. D.; Glorius, F. *Angew. Chem., Int. Ed.* **2013**, *52*, 12430.

(4) Wang, H.; Beiring, B.; Yu, D. G.; Collins, K. D.; Glorius, F. *Angew. Chem., Int. Ed.* **2013**, *52*, 12430.

(5) (a) Deng, Y.; Jin, X.; Fu, C.; Ma, S. *Org. Lett.* **2009**, *11*, 2169. (b) Deng, Y.; Jin, X.; Ma, S. *J. Org. Chem.* **2007**, *72*, 5901. (c) Horváth, A.; Bäckvall, J. E. *J. Org. Chem.* **2001**, *66*, 8120.

(6) Sabbasani, V. R.; Mamidipalli, P.; Lu, H.; Xia, Y.; Lee, D. *Org. Lett.* **2013**, *15*, 1552.

(7) Buzas, A. K.; Istrate, F. M.; Gagosz, F. *Org. Lett.* **2007**, *9*, 985.

(8) (a) Deng, Y.; Yu, Y.; Ma, S. *J. Org. Chem.* **2008**, *73*, 585. (b) Ma, S.; Gu, Z. *J. Am. Chem. Soc.* **2005**, *127*, 6182.

(9) (a) Hayashi, R.; Hsung, R. P.; Feltenberger, J. B.; Lohse, A. G. *Org. Lett.* **2009**, *11*, 2125. (b) Enders, D.; Meyer, O. *Liebigs Ann.* **1996**, 1023. (c) Krohn, K. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1582. (d) Campbell, A. L.; Lenz, G. R. *Synthesis* **1987**, 421. (e) Overman, L. E. *Acc. Chem. Res.* **1980**, *13*, 218. (f) Petrzilka, M. *Synthesis* **1981**, 753.

(10) (a) Xing, D.; Yang, D. *Org. Lett.* **2010**, *12*, 1068. (b) Singh, O. V.; Han, H. *J. Am. Chem. Soc.* **2007**, *129*, 774. (c) Singh, O. V.; Han, H. *Org. Lett.* **2007**, *9*, 4801. (d) Mellegaard-Waetzig, S. R.; Rayabarapu, D. K.; Tunge, J. A. *Synlett* **2005**, 2759.

(11) (a) Pi, S.-F.; Yang, X.-H.; Huang, X.-C.; Liang, Y.; Yang, G. -N; Zhang, X.-H.; Li, J.-H. *J. Org. Chem.* **2010**, *75*, 3484. (b) Pi, S.-F.; Tang, B.-X.; Li, J.-H.; Liu, Y.-L.; Liang, Y. *Org. Lett.* **2009**, *11*, 2309.

(12) Liu, G.; Lu, X. *Org. Lett.* **2001**, *3*, 3879.

(13) (a) Kawabe, Y.; Kato, S. *Dyes Pigm.* **2012**, *95*, 614. (b) Liu, G.; Wilkerson, P. D.; Toth, C. A.; Xu, H. *Org. Lett.* **2012**, *14*, 858. (c) Ishida, K.; Lincke, T.; Hertweck, C. *Angew. Chem., Int. Ed.* **2012**, *51*, 5470. (d) Shimizu, M.; Tatsumi, H.; Mochida, K.; Shimono, K.; Hiyama, T. *Chem.—Asian. J.* **2009**, *4*, 1289. (e) Zhuang, Z. P.; Kung, H. F. *J. Med. Chem.* **2006**, *49*, 2841. (f) Lu, C. K.; Chou, H. N.; Lee, C. K.; Lee, T. H. *Org. Lett.* **2005**, *7*, 3893. (g) Spiegel, R. J.; Magrath, I. T.; Shutta, J. A. *Cancer Res.* **1981**, *41*, 452.

(14) (a) Steunenberg, P.; Sijm, M.; Zuilhof, H.; Sanders, J. P. M.; Scott, E. L.; Franssen, M. C. R. *J. Org. Chem.* **2013**, *78*, 3802. (b) Miyaji, R.; Asano, K.; Matsubara, S. *Org. Lett.* **2013**, *15*, 3658. (c) Wang, X.-F.; An, J.; Zhang, X.-X.; Tan, F.; Chen, J.-R.; Xiao, W.-J. *Org. Lett.* **2011**, *13*, 808. (d) Colantoni, D.; Fioravanti, S.; Pellacani, L.; Tardella, P. A. *Org. Lett.* **2004**, *6*, 197. (e) Colantoni, D.; Fioravanti, S.; Pellacani, L.; Tardella, P. A. *Org. Lett.* **2004**, *6*, 197.