Organic LETTERS

Letter

Cite This: Org. Lett. XXXX, XXX, XXX−XXX

pubs.acs.org/OrgLett

Enantioselective Synthesis of 5-Alkylated Thiazolidinones via Palladium-Catalyzed Asymmetric Allylic C−H Alkylations of 1,4-Pentadienes with 5*H*-Thiazol-4-ones

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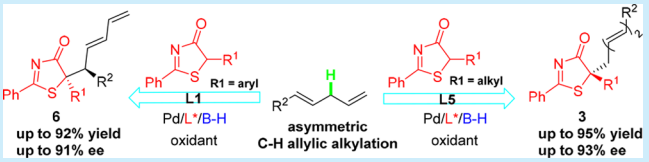
Supporting Information

ABSTRACT: A palladium-catalyzed, enantioselective allylic C−H alkylation of 1,4-pentadienes with 5*H*-thiazol-4-ones has been developed. Under the cooperative catalysis of a palladium complex of chiral phosphoramidite ligand and an achiral Brønsted acid, a broad range of substituted 5*H*-thiazol-4-ones bearing sulfur-containing tertiary chiral centers were accessed from the allylic C−H alkylation in high levels of yields and enantioselectivities. Alkyl and aryl 1,4-pentadienes led to linear and branched allylation products, respectively.



Optically active sulfides are frequently found in natural products and pharmaceuticals, playing key roles in many biological structures and functions.[1] They are also versatile intermediates that are widely applicable in asymmetric synthesis.[2] The consequent desire for their preparation has driven the development of abundant asymmetric synthetic approaches to access optically active thiol derivatives.[3] Although these reactions are well suited for the preparation of secondary thiol derivatives, by contrast, few methods are applicable to the enantioselective synthesis of tertiary thiol and thioether derivatives.[4] Significantly, 5-alkylated thiazolidinones have been found in follicle-stimulating hormone (FSH) receptor agonists as a core structural element (Figure 1).[4f] As such, it is a remarkably valuable task to create asymmetric, catalytic transformations yielding chiral tertiary thiol derivatives.

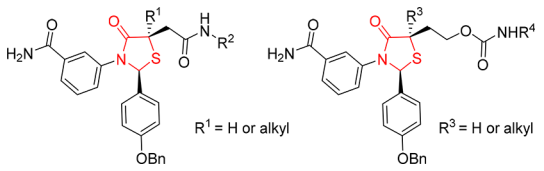
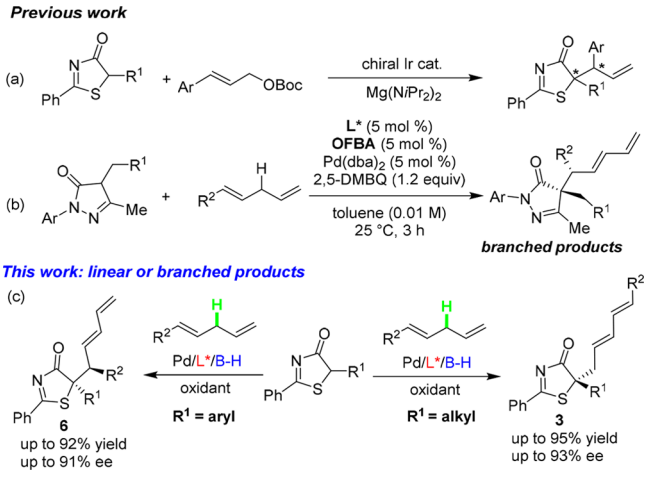


Figure 1. Follicle-stimulating hormone receptor agonists.

Asymmetric functionalization of easily accessible prochiral organosulfur compounds provides an ideal approach to access chiral, tertiary thiol derivatives.[3−5] 5*H*-Thiazol-4-ones, first introduced by Palomo in an organocatalytic, asymmetric Michael addition to nitroalkenes,[5a] have been recognized as excellent sulfur-containing pronucleophiles to prepare chiral tertiary thiol derivatives. Subsequently, Lu reported a chiral phosphine-catalyzed γ-addition reaction with allenoates.[5d] Jiang developed an organocatalytic, asymmetric [4 + 2] reaction of 5*H*-thiazol-4-ones.[5h] Hartwig has established an Ir-catalyzed allylation of 5*H*-thiazol-4-ones with cinnamyl esters to produce highly enantioenriched tertiary thioether derivatives (Scheme 1a).[5b] In comparison with traditional

Scheme 1. (a) Ir-Catalyzed Allylation of 5*H*-Thiazol-4-ones with Cinnamyl Esters. (b) Allylic C−H Alkylation of 1,4-Pentadienes with Pyrazol-5-ones. (c) Allylic C−H Functionalization of 1,4-Pentadienes with 5*H*-Thiazol-4-ones



Received: May 30, 2018

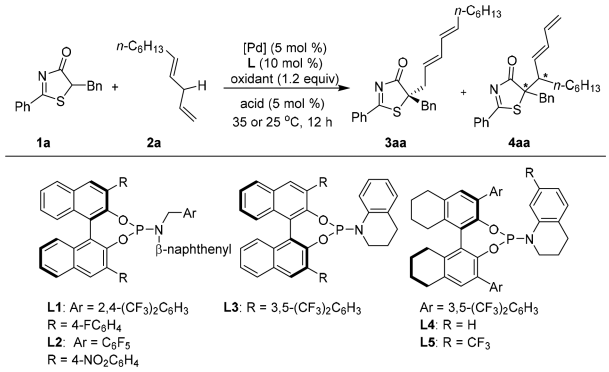
DOI: 10.1021/acs.orglett.8b01697
Org. Lett. XXXX, XXX, XXX−XXX

transition-metal-catalyzed allylic alkylation reactions, the allylic C−H activation-based alkylation reaction obviously holds unique advantages, including the ability to use simple alkenes, avoiding the installation of allylic leaving groups. In recent decades, growing interest has been devoted to the development and applications of allylic C−H functionalization reactions.[6] Although the first palladium-catalyzed allylic C−H alkylation reaction was reported several decades ago,[6g] the creation of highly enantioselective variants still represents and will continue to be a formidable challenge, given only a limited number of successful examples in C−O and C−N bond-forming reactions.[7] Even rarer examples regarding asymmetric construction of C−C bonds have been reported.[8] Unlike traditional asymmetric allylic alkylations (AAA) reactions,[9] to date, only a few successful examples describe highly enantioselective allylic C−H functionalization reactions with carbon nucleophiles, including 2-acetyl-1-tetralones,[8a,c] pyrazol-5-ones,[8d] and in situ generated enamines.[8b]

1,4-Pentadienes, upon undergoing the allylic C−H functionalization, will introduce a conjugated diene subunit to the products, which will definitely have more synthetic transformations of carbon−carbon double bonds. However, simultaneously addressing issues in the activation of the C−H bonds makes control of stereo- and regioselectivity in allylic C−H functionalization of 1,4-pentadienes more challenging. Indeed, the allylic C−H alkylation of 1,4-pentadienes had not appeared until Trost reported a racemic variant.[10] Very recently, we established a highly enantioselective allylic C−H alkylation of 1,4-pentadienes with pyrazol-5-ones cooperatively catalyzed by a palladium complex of chiral phosphoramidite ligand and an achiral Brønsted acid, favoring the branched products (Scheme 1b).[8d] Herein, we describe the first asymmetric allylic C−H functionalization of 1,4-pentadienes with 5*H*-thiazol-4-ones (Scheme 1c).

Inspired by the successful allylic C−H alkylation reactions reported previously,[8d,10] some phosphorus ligands were initially examined for the reaction of 1,4-pentadiene (**2a**) with 5*H*-thiazol-4-one (**1a**) using 2,6-DMBQ as the oxidant and $Pd(dba)_2$ as a precatalyst in the presence of 2-fluorobenzoic acid (OFBA) (Table 1, entries 1−3). However, the PPh_3 was unable to accelerate the palladium-catalyzed reaction (entry 1). The chiral palladium complexes of phosphoramidites **L1** and **L2** showed promising stereoselectivity but gave modest yields (entries 2 and 3). Thus, a variety of other chiral phosphoramide ligands were screened (entries 4−6 and Table S1) and indicated that H8-BINOL-derived ligand **L5** delivered the highest enantiomeric excess (entries 4 and 5 vs 6). The presence of 2,5-dimethylquinone as an oxidant also offered high enantioselectivity, but provided lower yield than 2,6-DMBQ (entry 7). A brief screening of the palladium source identified $Pd_2(dba)_3$ as a slightly superior precatalyst (entry 6 vs 8 and 9). Previous reports[7b,8d] indicate that the Brønsted acid cocatalyst might have an impact on the control of stereoselectivity. Thus, a number of Brønsted acids were investigated (entries 10−13 and entries 12−19 in Table S1). Interestingly, carboxylic acids exerted very little effect on the enantioselectivity but significantly affected the conversion (entries 10 and 11). The diphenylphosphinic acid was also a good cocatalyst, whereas a strong Brønsted acid, such as *p*-methylbenzenesulfonic acid, somehow completely inhibited the catalytic activity of the palladium complex (entries 12 and 13). Notably, dramatically diminished enantioselectivity and yield were observed in the absence of Brønsted acid, implying

Table 1. Optimization of Reaction Conditions[a]



entry	[Pd]	L	acid	yield[b] (%)	3/4[b]	ee[c] (%)
1	$Pd_2(dba)_3$	PPh_3	OFBA	trace		
2	$Pd_2(dba)_3$	**L1**	OFBA	67	13:1	−6
3	$Pd_2(dba)_3$	**L2**	OFBA	44	15:1	57
4	$Pd_2(dba)_3$	**L3**	OFBA	47	10:1	−58
5	$Pd_2(dba)_3$	**L4**	OFBA	62	17:1	78
6	$Pd_2(dba)_3$	**L5**	OFBA	91	18:1	88
7[d]	$Pd_2(dba)_3$	**L5**	OFBA	71	17:1	88
8	$Pd(dba)_2$	**L5**	OFBA	63	18:1	87
9	$Pd(OAc)_2$	**L5**	OFBA	16		87
10	$Pd_2(dba)_3$	**L5**	PhCOOH	50	17:1	87
11	$Pd_2(dba)_3$	**L5**	CH_3COOH	90	18:1	86
12	$Pd_2(dba)_3$	**L5**	Ph_2POOH	89	18:1	87
13	$Pd_2(dba)_3$	**L5**	$TsOH·H_2O$	trace		
14	$Pd_2(dba)_3$	**L5**	none	77	6:1	54
15[e]	$Pd_2(dba)_3$	**L5**	OFBA	95	20:1	90

[a]Reaction conditions: Unless indicated otherwise, reactions of **1a** (0.10 mmol), **2a** (0.20 mmol), Pd (0.005 mmol), ligand (0.01 mmol), OFBA (0.005 mmol), and 2,6-DMBQ (0.12 mmol) were carried out in toluene (2 mL) for 12 h. [b]The yields and ratios of **3aa**/**4aa** were determined by ^1H NMR analysis of the crude reaction mixture. [c]The ee value was determined by chiral HPLC analysis. [d]2,5-DMBQ (0.12 mmol) was used instead of 2,6-DMBQ. [e]The reaction was carried out at 25 °C. 2,5(6)-DMBQ = 2,5(6)-dimethylquinone, OFBA = 2-fluorobenzoic acid, dba = dibenzylidene acetone.

that the acid cocatalyst is crucial to catalytic activity and stereochemical control of the chiral palladium complex (entry 14 vs 6 and 10−11). Product **3a** could be isolated in 95% yield and 90% ee by conducting the reaction at room temperature (entry 15).

Under the optimized reaction conditions, we first explored the generality for different 5*H*-thiazol-4-ones **1** (Table 2). A broad range of 5*H*-thiazol-4-ones bearing various substituted benzyl groups underwent the allylic C−H alkylation reactions smoothly, providing the corresponding linear products in good to excellent yields (up to 95%) and with high enantioselectivities of up to 93% ee (entries 1−15). The substrate scope with regard to 1,4-pentadienes was then examined for the allylic C−H alkylation reaction with 5*H*-thiazol-4-one **1d** as the nucleophile (entries 16−29). 1,4-Pentadienes bearing a linear alkyl substituent were able to participate in clean reactions, allowing the desired products to be isolated in excellent yields (81−95%) and with high levels of enantioselectivity (89−93% ee, entries 16−20). 1-Cyclohexyl-1,4-pentadiene also underwent the reaction very smoothly, giving the linear product in 99% yield and 83% ee (entry 21). Moreover, 1-aryl-1,4-pentadienes also tuned out to be good substrates to give high

DOI: 10.1021/acs.orglett.8b01697
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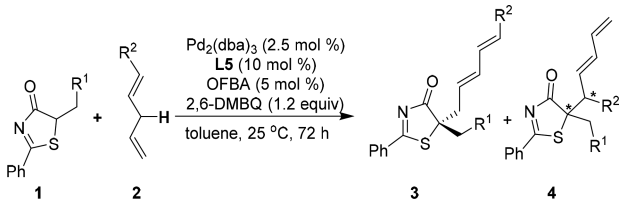
Table 2. Scope of 5*H*-Thiazol-4-ones and 1,4-Dienes[a]



entry	R^1	R^2	3	yield[b] (%)	3/4[c]	ee[d] (%)
1	C_6H_5	*n*-C_6H_{13}	**3aa**	95	20:1	90
2	4-FC_6H_4	*n*-C_6H_{13}	**3ba**	56	38:1	86
3	3-MeOC_6H_4	*n*-C_6H_{13}	**3ca**	91	17:1	84
4	4-CNC_6H_4	*n*-C_6H_{13}	**3da**	93	23:1	93
5	2-$C_{10}H_7$	*n*-C_6H_{13}	**3ea**	37	14:1	90
6	2-ClC_6H_4	*n*-C_6H_{13}	**3fa**	89	13:1	89
7	3-ClC_6H_4	*n*-C_6H_{13}	**3ga**	90	12:1	91
8	4-ClC_6H_4	*n*-C_6H_{13}	**3ha**	87	12:1	87
9	3-MeC_6H_4	*n*-C_6H_{13}	**3ia**	43	10:1	85
10	2-MeC_6H_4	*n*-C_6H_{13}	**3ja**	52	19:1	86
11	4-MeC_6H_4	*n*-C_6H_{13}	**3ka**	66	11:1	87
12	2-BrC_6H_4	*n*-C_6H_{13}	**3la**	66	13:1	88
13	3-BrC_6H_4	*n*-C_6H_{13}	**3ma**	89	15:1	89
14	4-BrC_6H_4	*n*-C_6H_{13}	**3na**	92	20:1	91
15	H	*n*-C_6H_{13}	**3oa**	94	30:1	83
16	4-CNC_6H_4	Me	**3db**	95	20:1	92
17	4-CNC_6H_4	*n*-Pr	**3dc**	91	23:1	91
18	4-CNC_6H_4	*n*-C_9H_{17}	**3dd**	90	38:1	93
19	4-CNC_6H_4	Ph$(CH_2)_2$	**3de**	91	20:1	93
20	4-CNC_6H_4	Cl$(CH_2)_3$	**3df**	81	21:1	89
21	4-CNC_6H_4	cyclohexyl	**3dg**	94	34:1	83
22	4-CNC_6H_4	Ph	**3dh**	81	24:1	90
23	4-CNC_6H_4	4-MeC_6H_4	**3di**	54	22:1	91
24	4-CNC_6H_4	4-MeOC_6H_4	**3dj**	50	17:1	92
25	4-CNC_6H_4	3-ClC_6H_4	**3dk**	86	40:1	93
26[e]	4-CNC_6H_4	H	**3dl**	73	5:1	84/70
27	4-CNC_6H_4	CO_2Et$(CH_2)_2$	**3dm**	99	11:1	84
28	4-CNC_6H_4	CONHBn$(CH_2)_2$	**3dn**	79	10:1	83
29	4-CNC_6H_4	TsO$(CH_2)_2$	**3do**	92	16:1	90

[a]Reaction conditions: Unless indicated otherwise, reactions of **1** (0.10 mmol), **2** (0.20 mmol), $Pd_2(dba)_3$ (0.0025 mmol), **L5** (0.01 mmol), OFBA (0.005 mmol), and 2,6-DMBQ (0.12 mmol) were carried out in toluene (2 mL) for 72 h. [b]Isolated yields with *E*/*Z* > 20:1. [c]The ratios of **3**/**4** and *E*/*Z* were determined by ^{1}H NMR spectroscopic analysis of the crude reaction mixture. [d]The ee value was determined by chiral HPLC analysis. [e]Ratios of *E*/*Z*.

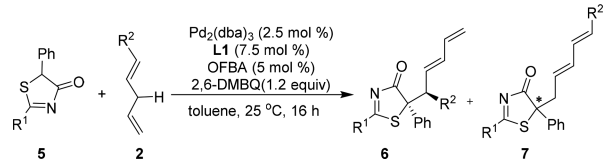
levels of enantioselectivity (entries 22−25) Basically, the presence of electron-rich aryl substituents led to considerably lower yields than the 1,4-dienes bearing a slightly electronically poor or electronically neutral aryl substituent, while similar, excellent enantioselectivities were observed (entries 23 and 24 vs 22 and 25). In the case of a simple 1,4-diene, the allylic alkylation product was obtained in moderate yield, good enantioselectivity, and a 5:1 regioisomeric ratio (entry 26). Ester, amide, and sulfonate functional groups could be tolerated to give excellent yields and high levels of enantioselectivity (entries 27−29). However, the allylbezene is too unreactive to undergo the desired allylic C−H alkylation reaction. The configuration of **3ha** was assigned to be (*R*) by X-ray analysis (see the Supporting Information).

Interestingly, when 2,5-diphenylthiazol-4(5*H*)-one **5a** was examined for the allylic C−H alkylation with a 1,4-pentadiene, the branched product was preferentially generated, but with poor yields and enantioselectivities. Thus, we reoptimized the reaction conditions and identified the phosphoramidite **L1** as the best ligand (see Table S2 for details and entry 1, Table 3). The reoptimized conditions were applied to different substrates, and the presence of an aryl group bearing either electron-donating or -withdrawing substituents at the *meta*- or *para*-position was found to proceed in good yields and stereocontrol (entries 2−4). 1,4-Pentadienes bearing different substituents were able to form the products in moderate yields and enantioselectivities (entries 5−7).

To demonstrate the practicability of the current reaction, a gram-scale reaction of **1d** with 1,4-diene was performed (Scheme 2a). A quantitative yield and a similar level of enantioselectivity were observed. The chiral 5*H*-thiazol-4-one **3la** obtained from this reaction can be transformed into α-thiol ester derivatives **P1** and **P2**, respectively (Scheme 2b). As shown in Scheme 2c, the treatment of **6da** with 91% ee with $NaBH_4$/MeOH and NsCl/NaH, readily generated 5-alkylated thiazolidinones **P3** in 69% yield and >99% ee after two steps and recrystallization. The configuration of **P3** was assigned to

DOI: 10.1021/acs.orglett.8b01697
Org. Lett. XXXX, XXX, XXX−XXX

Table 3. Scope of 2,5-Diarylthiazol-4(5*H*)-ones and 1,4-Dienes[a]

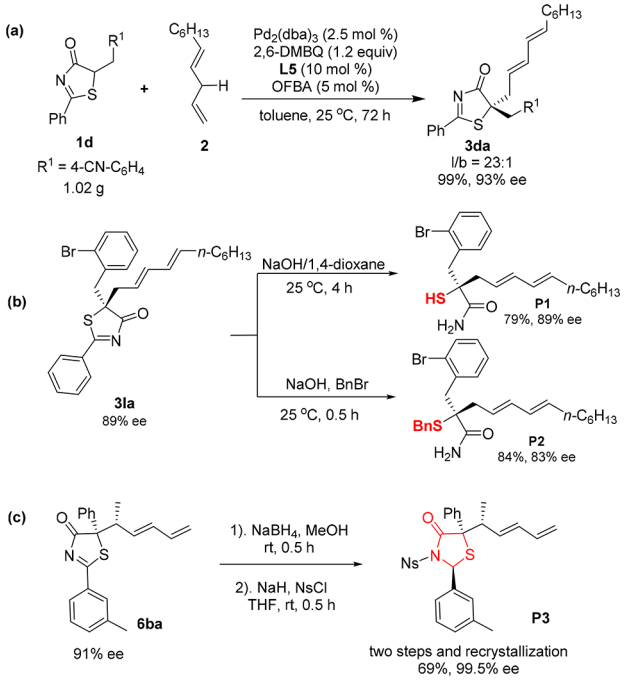


5 2 6 7

entry	R^1	R^2	6	yield[b] (%)	6/7[c]	dr[c]	ee[d] (%)
1	Ph	Me	**6aa**	90	11:1	5:1	87
2	3-MeC_6H_4	Me	**6ba**	70	10:1	6:1	91
3	4-BrC_6H_4	Me	**6ca**	87	13:1	4:1	88
4	4-FC_6H_4	Me	**6da**	80	10:1	5:1	88
5[e]	Ph	H	**6ab**	92		13:1	89
6	3-MeC_6H_4	^{n}Bu	**6bc**	57	10:1	3:1	91
7	3-MeC_6H_4	^{n}Pr	**6bd**	75	10:1	9:1	91

[a]Reaction conditions: Unless indicated otherwise, reactions of **5** (0.10 mmol), **2** (0.20 mmol), $Pd_2(dba)_3$ (0.0025 mmol), **L1** (0.0075 mmol), OFBA (0.005 mmol), and 2,6-DMBQ (0.12 mmol) were carried out in toluene (2 mL) for 16 h. [b]Isolated yields of **6** with *E*/*Z* > 20:1. [c]The ratios of *E*/*Z*, **6**/**7**, and diastereomeric ratio (dr) were determined by ^{1}H NMR analysis of the crude reaction mixture. [d]The ee value was determined by chiral HPLC analysis. [e]Ratios of *E*/*Z*.

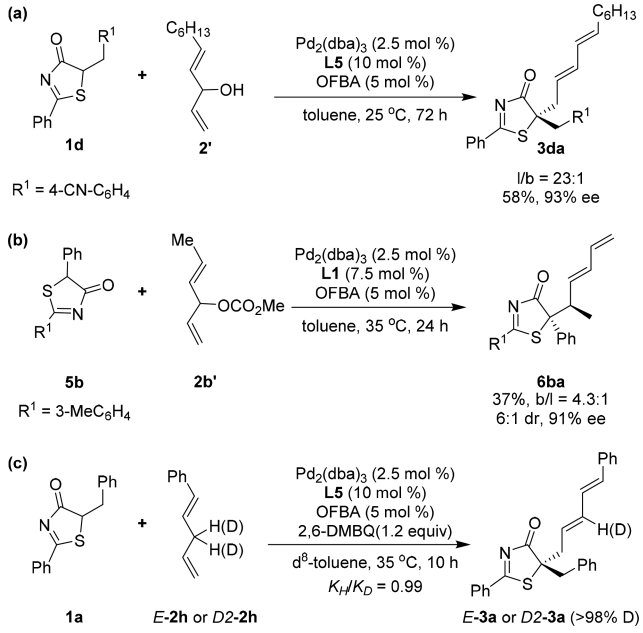
Scheme 2. Applications in Synthesis



be (*S*,*S*,*R*) by X-ray analysis, and thus, that of **6ba** was assigned to be (*S*,*R*).

To understand the reaction, a typical Pd-catalyzed allylic allylation of **1d** in the presence of ligand **L5** was conducted and resulted in 23:1 l/b selectivity (Scheme 3a), which is relatively close to the results observed in the small-scale reaction (entry 4, Table 2). Similarly, the Tsuji−Trost-type allylic substitution of an aryl-substituted nucleophile **5b** with **2b′** also favored the branched selection (Scheme 3b). These results imply that both the allylic C−H alkylation and Tsuji−Trost reactions share a similar intermediate. In addition, ESI-MS identified the allyl Pd intermediate, again suggesting that the protocol undergoes the

Scheme 3. Experiments for Mechanistic Study



elementary reaction of allylic substitution. A kinetic isotope effect of 0.99 (k_H/k_D) was observed for the reaction of D2-**2h** (Scheme 3c), which revealed that the allylic C−H cleavage was not the rate-determining step. Instead, the allylic substitution might determine the reaction rate (see the SI).

In conclusion, we have developed a palladium-catalyzed asymmetric allylic C−H alkylation reaction with 5*H*-thiazol-4-ones. The reaction features mild conditions, high yields, and high enantioselectivities with broad substrate scope. The regioselectivity of the product could be controlled by the structure of the 1,4-pentadienes. The method provides a simple and efficient route to access highly enantioenriched 2-mercapto acid surrogates and 5-alkylated thiazolidinone derivatives bearing a quaternary stereogenic center.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b01697.

Complete experimental procedures and characterization data for the prepared compounds (PDF)

Accession Codes

CCDC 1836280−1836281 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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DOI: 10.1021/acs.orglett.8b01697
Org. Lett. XXXX, XXX, XXX−XXX

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful for financial support from the MOST (973 project 2015CB856600), the NSFC (21472180) and the Chinese Academy of Sciences (Grant No. XDB20020000).

■ REFERENCES

(1) (a) Chatgliliaoglu, C.; Asmus, K.-D. *Sulfur-Centered Rractive Intermediates in Chemistry and Biology*, 1st ed.; Plenum Press: New York, 1990. (b) Moran, L. K. J.; Gutteridge, M. C.; Quinlan, G. J. *Curr. Med. Chem.* **2001**, *8*, 763. (c) Pachamuthu, K.; Schmidt, R. R. *Chem. Rev.* **2006**, *106*, 160.

(2) (a) Metzner, P.; Thuillier, A. In *Sulfur Reagents in Organic Synthesis*;Katritzky, A. R., Meth-Cohn, O., Rees, C. S., Eds.; Academic Press: San Diego, 1994. (b) *Organosulfur Chemistry in Asymmetric Synthesis*; Toru, T., Bolm, C., Eds.; Wiley-VCH: Weinheim, 2008.

(3) (a) Kondo, T.; Mitsudo, T.-a. *Chem. Rev.* **2000**, *100*, 3205. (b) Marigo, M.; Wabnitz, T. C.; Fielenbach, D.; Jorgensen, K. A. *Angew. Chem., Int. Ed.* **2005**, *44*, 794. (c) Enders, D.; Luettgen, K.; Narine, A. A. *Synthesis* **2007**, *2007*, 959. (d) Tiong, E. A.; Gleason, J. L. *Org. Lett.* **2009**, *11*, 1725. (e) Peschiulli, A.; Procuranti, B.; O'Connor, C. J.; Connon, S. J. *Nat. Chem.* **2010**, *2*, 380. (f) Denmark, S. E.; Kornfilt, D. J. P.; Vogler, T. *J. Am. Chem. Soc.* **2011**, *133*, 15308. (g) Cai, Y.; Li, J.; Chen, W.; Xie, M.; Liu, X.; Lin, L.; Feng, X. *Org. Lett.* **2012**, *14*, 2726. (h) Takechi, S.; Yasuda, S.; Kumagai, N.; Shibasaki, M. *Angew. Chem., Int. Ed.* **2012**, *51*, 4218. (i) Wang, C.; Yang, X.; Loh, C. C. J.; Raabe, G.; Enders, D. *Chem. - Eur. J.* **2012**, *18*, 11531.

(4) (a) Palomo, C.; Oiarbide, M.; Dias, F.; López, R.; Linden, A. *Angew. Chem., Int. Ed.* **2004**, *43*, 3307. (b) Palomo, C.; Oiarbide, M.; López, R.; González, P. B.; Gómez-Bengoa, E.; Saá, J. M.; Linden, A. *J. Am. Chem. Soc.* **2006**, *128*, 15236. (c) Clayden, J.; MacLellan, P. *Beilstein J. Org. Chem.* **2011**, *7*, 582. (d) Wang, Y.-F.; Wu, S.; Karmaker, P. G.; Sohail, M.; Wang, Q.; Chen, F.-X. *Synthesis* **2015**, *47*, 1147. (e) Yu, J.-S.; Huang, H.-M.; Ding, P.-G.; Hu, X.-S.; Zhou, F.; Zhou, J. *ACS Catal.* **2016**, *6*, 5319. (f) Wrobel, J.; Jetter, J.; Kao, W.-L.; Rogers, J.; Di, L.; Chi, J.; Perez, M. C.; Chen, G.-C.; Shen, E. S. *Bioorg. Med. Chem.* **2006**, *14*, 5729.

(5) (a) Diosdado, S.; Etxabe, J.; Izquierdo, J.; Landa, A.; Mielgo, A.; Olaizola, I.; Lopez, R.; Palomo, C. *Angew. Chem., Int. Ed.* **2013**, *52*, 11846. (b) Chen, W.; Hartwig, J. F. *J. Am. Chem. Soc.* **2014**, *136*, 377. (c) Diosdado, S.; Lopez, R.; Palomo, C. *Chem. - Eur. J.* **2014**, *20*, 6526. (d) Wang, T.; Yu, Z.; Hoon, D. L.; Huang, K.-W.; Lan, Y.; Lu, Y. *Chem. Sci.* **2015**, *6*, 4912. (e) Li, J.; Qiu, S.; Ye, X.; Zhu, B.; Liu, H.; Jiang, Z. *J. Org. Chem.* **2016**, *81*, 11916. (f) Mielgo, A.; Palomo, C. *Beilstein J. Org. Chem.* **2016**, *12*, 918. (g) Qiu, S.; Tan, C.-H.; Jiang, Z. *Beilstein J. Org. Chem.* **2016**, *12*, 2293. (h) Zhu, B.; Qiu, S.; Li, J.; Coote, M. L.; Lee, R.; Jiang, Z. *Chem. Sci.* **2016**, *7*, 6060. (i) Badiola, E.; Fiser, B.; Gómez-Bengoa, E.; Mielgo, A.; Olaizola, I.; Urruzuno, I.; García, J. M.; Odriozola, J. M.; Razkin, J.; Oiarbide, M.; Palomo, C. *J. Am. Chem. Soc.* **2014**, *136*, 17869.

(6) (a) Jensen, T.; Fristrup, P. *Chem. - Eur. J.* **2009**, *15*, 9632. (b) Liu, G.; Wu, Y. In *C–H Activation*; Yu, J.-Q., Shi, Z., Eds.; Springer: Berlin, 2010; p 195. (c) Engelin, C. J.; Fristrup, P. *Molecules* **2011**, *16*, 951. (d) Li, B.-J.; Shi, Z.-J. *Chem. Soc. Rev.* **2012**, *41*, 5588. (e) Liron, F.; Oble, J.; Lorion, M. M.; Poli, G. *Eur. J. Org. Chem.* **2014**, *2014*, 5863. (f) Mann, S. E.; Benhamou, L.; Sheppard, T. D. *Synthesis* **2015**, *47*, 3079. (g) Hegedus, L. S.; Hayashi, T.; Darlington, W. H. *J. Am. Chem. Soc.* **1978**, *100*, 7747. (h) Li, Z.; Li, C.-J. *J. Am. Chem. Soc.* **2006**, *128*, 56. (i) Lin, S.; Song, C.-X.; Cai, G.-X.; Wang, W.-H.; Shi, Z.-J. *J. Am. Chem. Soc.* **2008**, *130*, 12901. (j) Young, A. J.; White, M. C. *J. Am. Chem. Soc.* **2008**, *130*, 14090. (k) Young, A. J.; White, M. C. *Angew. Chem., Int. Ed.* **2011**, *50*, 6824. (l) Trost, B. M.; Hansmann, M. M.; Thaisrivongs, D. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 4950. (m) Howell, J. M.; Liu, W.; Young, A. J.; White, M. C. *J. Am. Chem. Soc.* **2014**, *136*, 5750. (n) Kondo, H.; Yu, F.; Yamaguchi, J.; Liu, G. S.; Itami, K. *Org. Lett.* **2014**, *16*, 4212. (o) Wang, P. S.; Lin, H. C.; Zhou, X. L.; Gong, L. Z. *Org. Lett.* **2014**, *16*, 3332. (p) Tao, Z. L.; Li, X. H.; Han, Z. Y.; Gong, L. Z. *J. Am. Chem. Soc.* **2015**, *137*, 4054. (q) Sharpless, K. B.; Teranishi, A. Y.; Bäckvall, J. E. *J. Am. Chem. Soc.* **1977**, *99*, 3120. (r) Bäckvall, J. E. *Acc. Chem. Res.* **1983**, *16*, 335. (s) Bäckvall, A.; Heumann, J. E. *J. Am. Chem. Soc.* **1986**, *108*, 7107.

(7) (a) Ammann, S. E.; Liu, W.; White, M. C. *Angew. Chem., Int. Ed.* **2016**, *55*, 9571. (b) Wang, P. S.; Liu, P.; Zhai, Y. J.; Lin, H. C.; Han, Z. Y.; Gong, L. Z. *J. Am. Chem. Soc.* **2015**, *137*, 12732. (c) Takenaka, K.; Akita, M.; Tanigaki, Y.; Takizawa, S.; Sasai, H. *Org. Lett.* **2011**, *13*, 3506. (d) Du, H.; Zhao, B.; Shi, Y. *J. Am. Chem. Soc.* **2008**, *130*, 8590. (e) Covell, D. J.; White, M. C. *Angew. Chem., Int. Ed.* **2008**, *47*, 6448. (f) El-Qisiari, A. K.; Qaseer, H. A.; Henry, P. M. *Tetrahedron Lett.* **2002**, *43*, 4229.

(8) (a) Trost, B. M.; Thaisrivongs, D. A.; Donckele, E. J. *Angew. Chem., Int. Ed.* **2013**, *52*, 1523. (b) Wang, P. S.; Lin, H. C.; Zhai, Y. J.; Han, Z. Y.; Gong, L. Z. *Angew. Chem., Int. Ed.* **2014**, *53*, 12218. (c) Trost, B. M.; Donckele, E. J.; Thaisrivongs, D. A.; Osipov, M.; Masters, J. T. *J. Am. Chem. Soc.* **2015**, *137*, 2776. (d) Lin, H.-C.; Wang, P.-S.; Tao, Z.-L.; Chen, Y.-G.; Han, Z.-Y.; Gong, L.-Z. *J. Am. Chem. Soc.* **2016**, *138*, 14354.

(9) (a) Trost, B. M.; VanVranken, D. L. *Chem. Rev.* **1996**, *96*, 395. (b) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921. (c) Lu, Z.; Ma, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 258. (d) Dai, L.-X.; Tu, T.; You, S.-L.; Deng, W.-P.; Hou, X.-L. *Acc. Chem. Res.* **2003**, *36*, 659.

(10) Trost, B. M.; Hansmann, M. M.; Thaisrivongs, D. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 4950.

DOI: 10.1021/acs.orglett.8b01697
Org. Lett. XXXX, XXX, XXX–XXX