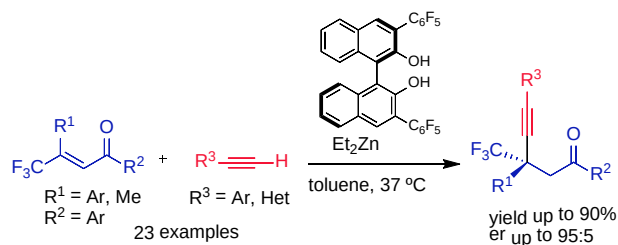


Catalytic enantioselective conjugate alkynylation of β -aryl- β -trifluoromethyl enones constructing propargylic all-carbon quaternary stereogenic centers

Amparo Sanz-Marco, Gonzalo Blay,* Carlos Vila and José R. Pedro*

Department de Química Orgànica, Facultat de Química, Universitat de València, C/ Dr. Moliner 50, E-46100 Burjassot (València), Spain

Supporting Information Placeholder



ABSTRACT: The enantioselective conjugate alkynylation of β -aryl- β -trifluoromethyl enones has been carried out using terminal alkynes and diethylzinc in the presence of 3,3'-bis(perfluorophenyl)BINOL as the chiral ligand, to give the corresponding ketones bearing a trifluoromethylated propargylic quaternary stereocenter with fair to good enantioselectivities. Enones bearing a bulky 2-naphthyl attached to the carbonyl group provided the best enantioselectivities. The synthetic applicability of the resulting products has been demonstrated with their iodo-cyclization to 4*H*-pyrans.

Chiral fluorinated compounds have found wide application in different fields including medicinal,¹ agricultural² and material sciences.³ In particular, molecules bearing a chiral center attached to a trifluoromethyl substituent⁴ have raised special interest due to the occurrence of this motif in biologically active compounds,⁵ chiral reagents⁶ or in materials with optoelectronic properties.⁷ The trifluoromethyl group has a larger size than the methyl group, and its high electron-withdrawing nature and high lipophilicity often alter the physical, chemical and biological properties of the parent molecules.¹⁻³ Accordingly, considerable efforts have been addressed to the catalytic asymmetric synthesis of molecules with a CF₃-containing stereocenter using either trifluoromethylation of prochiral carbons⁸ or the functionalization of trifluoromethylated prochiral carbons, i.e. trifluoromethyl ketones,⁹ trifluoromethyl imines¹⁰ or β -trifluoromethyl enones.¹¹ In this context, the synthesis of all-carbon quaternary stereocenters¹² containing a CF₃ group constitutes an extraordinary challenge for organic synthetic chemists.¹³ One way to achieve this goal is the use of electrophilic alkenes as Michael acceptors. After the pioneering work by Shibata on the conjugate addition of cyanide to β -aryl- β -trifluoromethyl enones,¹⁴ several carbon nucleophiles have been reacted with β -aryl- β -trifluoromethyl enones¹⁵ and nitroalkenes¹⁶ in a catalytic enantioselective fashion.

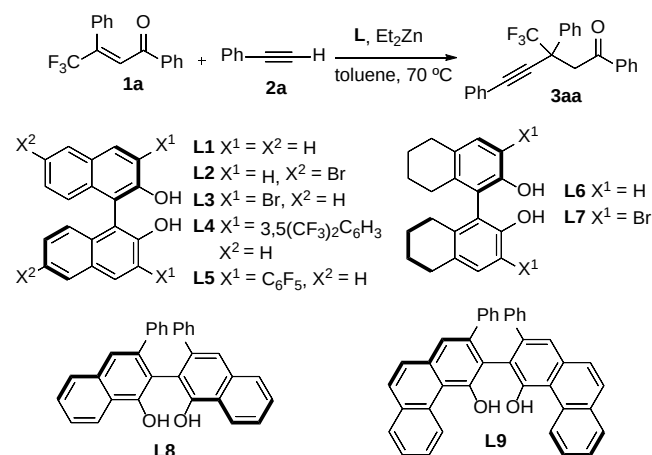
During the last years, the enantioselective conjugate addition of alkynes to unsaturated carbonyl compounds has been developed as a way to construct propargylic stereogenic centers.¹⁷ The resulting compounds are interesting building blocks due to the presence of two functional moieties, i.e. a carbonyl

group and a triple C-C bond. Good results in terms of yield and enantioselectivities have been obtained with different catalytic systems for a number of β -monosubstituted carbonyl compounds, including the alkynylation of β -trifluoromethyl enones reported by our group.^{17d} Fillion has reported the conjugate alkynylation of alkylidene Meldrum's acids with alkynylalanes and alkynyl Grignards providing quaternary propargylic stereocenters in a non-enantioselective manner.¹⁸ However, to the best of our knowledge, an enantioselective conjugate alkynylation of β,β -disubstituted enones has not been reported to date. Herein we describe the first example of enantioselective conjugate alkynylation of β -aryl- β -trifluoromethyl enones with terminal alkynes.

To start our research, we studied the reaction between phenylacetylene (**2a**) and the (*E*)-enone **1a** under the conditions developed previously by our group for the alkynylation of β -trifluoromethyl enones, which involve the use of Cu(I) salts and biphosphine ligands,^{17d-g} not observing any advance of the reaction. Therefore, we moved to a Zn-based catalytic system constituted by binaphthol ligands and diethylzinc in toluene at 70 °C (Scheme 1, Table 1) used by us in the alkynylation of endiones.^{17k} From all commercially available BINOL-type ligands, ligand **L4**, bearing two 3,5-bis(trifluoromethyl)phenyl groups at positions 3 and 3' of the binaphthol system provided the best enantioselectivity (78:22 er Table 1, entry 4). Since the presence of electron-withdrawing groups at these positions seemed to improve the enantioselectivity, we prepared and tested ligand **L5**, bearing two perfluorophenyl groups, which provided **3aa** in 68% yield and 85:15 er (Table 1, entry 5).

Other binaphthol and related ligands such as VANOL (**L8**) and VAPOL (**L9**) gave lower results (Table 1, entries 6-9).

Table 1. Optimization of reaction conditions.^a



entry	L (mol %)	2a (equiv)	Et ₂ Zn (equiv)	temp (°C)	time (h)	yield (%)	er ^b
1	L1 (20)	7.5	2	70	20	80	70:30
2	L2 (20)	7.5	2	70	20	-	-
3	L3 (20)	7.5	2	70	20	29	55:45
4	L4 (20)	7.5	2	70	20	70	78:22
5	L5 (20)	7.5	2	70	20	68	85:15
6	L6 (20)	7.5	2	70	20	-	-
7	L7 (20)	7.5	2	70	20	50	50:50
8	L8 (20)	7.5	2	70	20	60	75:25
9	L9 (20)	7.5	2	70	20	46	50:50
10	-	7.5	2	70	20	50	50:50
11	L5 (20)	7.5	2	37	30	53	88.5:11.5
12	L5 (20)	7.5	2	rt	-	-	-
13 ^c	L5 (20)	7.5	2	37	-	-	-
14 ^d	L5 (20)	7.5	2	37	30	35	80:20
15	L5 (20)	5	2	37	30	40	88.5:11.5
16	L5 (20)	7.5	1.3	37	30	46	88.5:11.5
17	L5 (10)	7.5	2	37	30	39	83:17

^a **1a** (0.125 mmol), **2a**, 1.5 M Et₂Zn in toluene, **L**, toluene (1.5 mL). ^b Determined by HPLC with chiral stationary phases. ^c EtNO₂ as additive. ^d CH₂Cl₂ as additive.

To minimize an observed non-enantioselective background reaction (Table 1, entry 10), the temperature was decreased to 37 °C what improved the enantioselectivity to 88.5:11.5 er (Table 1, entry 11); however further decrease of temperature to rt brought about a complete lack of reactivity. The use of co-solvents such as nitroethane^{17k} or dichloromethane did not improve the results (Table 1, entries 13 and 14). Decreasing the number of equivalents of alkyne or diethylzinc did not affect the enantioselectivity although it was deleterious for the reaction yield (Table 1, entries 15 and 16). Finally, a decrease in the catalyst load to 10 mol % produced a decrease of enantioselectivity and yield (Table 1, entry 17).

With the best conditions affordable with this catalytic system, we studied the applicability of the reaction (Table 2). A number of 1-phenylenones **1** ($\text{R}^2 = \text{Ph}$) having different aryl substituents on the β carbon reacted with phenylacetylene to give the expected products **3** with fair to good yields and enantiomeric ratios between 83.5:16.5 to 88.5:11.5 (Table 2, entries 1-5). The use of an *E/Z* mixture (45:55) of enone **1b** yielded compound **3ba** with 62:38 er, indicating the im-

portance of the double bond geometry (Table 2, entry 2).¹⁹ The 1- and 3-aryl groups were also amenable to variation. In particular, a bulky 2-naphthyl group attached to the carbonyl moiety provided the highest enantioselectivities (90:10 to 93:7 er) in the addition of phenylacetylene (Table 2, entries 9-12). A methyl group at the β position (**1l**) was tolerated, although the reaction product was obtained with low er (Table 1, entry 12). On the other hand, no conjugate addition was observed with methyl enone **1m**, which provided the racemic 1,2-addition product (Table 2, entry 13). Although ligand **L5** normally gave the highest enantioselectivity, ligand **L4** provided better results with compounds **3ea** and **3ga** (Table 2, entries 5 and 7) which were obtained in 47% yield (74:26 er) and 45% yield (70:30 er), respectively, with **L5**. The reaction was also tested with substituted phenylacetylenes **2** having electron-donating or electron-withdrawing groups on the phenyl ring (Table 2, entries 14-25), and with 3-ethynylthiophene (Table 2, entries 22-23), which performed similarly or better than phenylacetylene, providing the expected alkynylated products with er from 87:13 to 95:5. Unfortunately, neither 4-nitrophenylacetylene (**2f**) nor 4-phenyl-1-butyne (**2g**) reacted under the optimized conditions (Table 2, entries 24-25). Finally, it is interesting to note that compounds **3** are prone to crystallize as racemics from hexane-CH₂Cl₂ mixtures, allowing to obtain almost enantiomerically pure compounds from the crystallization mother liquors (Table 2, entries 7, 17 and 18).

Although racemic compounds **3** could be obtained in crystalline form, highly enantiomerically enriched compounds **3** were obtained as oils, thus hampering the determination of their absolute stereochemistry by X-ray techniques. To determine the absolute stereochemistry of compound (+)-**3aa**, it was transformed into aldehyde **5** in a sequence involving hydrogenation of the triple bond with Lindlar's catalyst, followed by ozonolysis of the double bond in compound **4** (Scheme 1). The optical rotation sign and chiral HPLC traces of compound **5** thus obtained coincided with those of the same compound prepared by a Nef-type reaction from the known-stereochemistry compound *R*-(+)-**6** which was synthesized by a modification of Shibata's procedure.^{15a} Accordingly, the *R* configuration was assigned to the quaternary stereocenter in compound **3aa** and for the rest of alkynylation products **3** upon the assumption of a uniform stereochemical pathway.

To show the potential applicability of compounds **3** we have developed a cyclization reaction promoted by iodine in basic medium (Scheme 2).²⁰ Under these conditions, a number of β -alkynyl enones **3** were converted into the corresponding 3-iodo-4*H*-pyrans **7** bearing a trifluoromethylated quaternary stereocenter with good yields. On the other hand, compound **3ab** having a 4-methoxyphenyl group attached to the triple bond provided the deiodinated pyran **8ab** in 90% yield under similar conditions (see Scheme S-1).

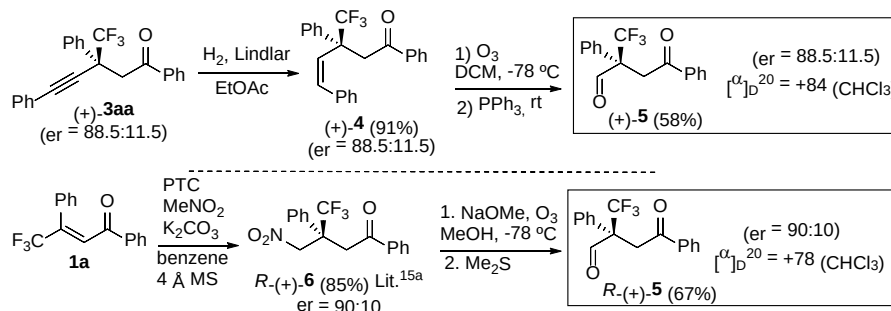
In summary, we have described the catalytic enantioselective conjugate alkynylation of β -aryl- β -trifluoromethyl enones²¹ by using terminal alkynes, diethylzinc and a BINOL-type ligand. The corresponding ketones bearing a trifluoromethylated propargylic quaternary stereocenter were obtained with fair to good yields and enantioselectivities. Bulky groups attached to the carbonyl moiety improved the enantioselectivity. This is the first catalytic enantioselective conjugate alkynylation of β,β -disubstituted enones reported in the literature. The synthetic applicability of the resulting products has been demonstrated with their cyclization to 4*H*-pyrans.

Table 2. Enantioselective conjugate alkylation of β -aryl- β -trifluoromethyl enones.^a

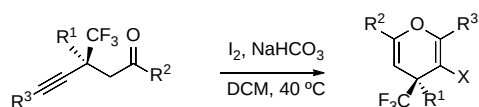
entry	1	R ¹	R ²	2	R ³	3	yield (%)	er ^b
1	a	C ₆ H ₅	C ₆ H ₅	a	C ₆ H ₅	3aa	53	88.5:11.5
2	b	4-MeC ₆ H ₄	C ₆ H ₅	a	C ₆ H ₅	3ba	50 (47) ^c	88:12 (62:38) ^c
3	c	4-MeOC ₆ H ₄	C ₆ H ₅	a	C ₆ H ₅	3ca	50	87.5:12.5
4	d	4-FC ₆ H ₄	C ₆ H ₅	a	C ₆ H ₅	3da	61	85.5:15.5
5 ^d	e	4-BrC ₆ H ₄	C ₆ H ₅	a	C ₆ H ₅	3ea	88	83.5:16.5
6	f	C ₆ H ₅	4-MeOC ₆ H ₄	a	C ₆ H ₅	3fa	70	89:11
7 ^d	g	C ₆ H ₅	4-ClC ₆ H ₄	a	C ₆ H ₅	3ga	60 (63) ^e	79.5:20.5 (97.5:2.5) ^f
8	h	C ₆ H ₅	4-NO ₂ C ₆ H ₄	a	C ₆ H ₅	3ha	44	83:17
9	i	C ₆ H ₅	2-naphthyl	a	C ₆ H ₅	3ia	50	91.5:8.5
10	j	3-MeC ₆ H ₄	2-naphthyl	a	C ₆ H ₅	3ja	76	93:7
11	k	3-MeOC ₆ H ₄	2-naphthyl	a	C ₆ H ₅	3ka	50	90:10
12	l	Me	2-naphthyl	a	C ₆ H ₅	3la	90	71.5:28.5
13	m	C ₆ H ₅	Me	a	C ₆ H ₅	3'ma	55 ^g	50:50 ^g
14	a	C ₆ H ₅	C ₆ H ₅	b	4-MeOC ₆ H ₄	3ab	65	90:10
15	i	C ₆ H ₅	2-naphthyl	b	4-MeOC ₆ H ₄	3ib	86	92:8
16	j	3-MeC ₆ H ₄	2-naphthyl	b	4-MeOC ₆ H ₄	3jb	72	90:10
17	a	C ₆ H ₅	C ₆ H ₅	c	3-FC ₆ H ₄	3ac	51 (77) ^e	87:13 (98.5:1.5) ^f
18	a	C ₆ H ₅	C ₆ H ₅	d	4-FC ₆ H ₄	3ad	81 (77) ^e	90:10 (99.5:0.5) ^f
19	i	C ₆ H ₅	2-naphthyl	d	4-FC ₆ H ₄	3id	90	95:5
20	n	4-MeC ₆ H ₄	2-naphthyl	d	4-FC ₆ H ₄	3nd	82	94:6
21	o	4-MeOC ₆ H ₄	2-naphthyl	d	4-FC ₆ H ₄	3od	66	91.5:8.5
22	a	C ₆ H ₅	C ₆ H ₅	e	3-thienyl	3ae	44	91:9
23	i	C ₆ H ₅	2-naphthyl	e	3-thienyl	3ie	64	93:7
24	i	C ₆ H ₅	2-naphthyl	f	4-NO ₂ C ₆ H ₄	-	-	-
25	a	C ₆ H ₅	C ₆ H ₅	g	PhCH ₂ CH ₂	-	-	-

^a **1** (0.125 mmol), **2** (0.94 mmol), 1.5 M Et₂Zn in toluene (0.13 mL, 0.25 mmol), **L5** (0.025 mmol), toluene (1.5 mL), 37 °C, 30 h. ^b Determined by HPLC with chiral stationary phases. ^c Reaction carried out with an *E/Z* mixture (45:55) of enone **1b**. ^d Reaction at rt with **L4**. ^e Recovered **3** from the crystallization mother liquors (hexane-CH₂Cl₂) in brackets. ^f er of **3** recovered from the mother liquors in brackets. ^g Yield and er of the 1,2-addition product (see SI).

Scheme 1. Determination of the absolute stereochemistry of compound 3aa



Scheme 2. Iodine-promoted cyclization of compounds 3 to 4H-pyrans 7



3aa, R¹ = R² = Ph, R³ = Ph
3ad, R¹ = R² = Ph, R³ = 4-FC₆H₄
3ae, R¹ = R² = Ph, R³ = 3-thienyl
3ba, R¹ = 4-MeC₆H₄, R² = Ph, R³ = Ph
3ca, R¹ = 4-MeOC₆H₄, R² = Ph, R³ = Ph
3fa, R¹ = Ph, R² = 4-MeOC₆H₄, R³ = Ph
3ha, R¹ = Ph, R² = 2-naphthyl, R³ = Ph
3ab, R¹ = R² = Ph, R³ = 4-MeOC₆H₄

7aa, X = I (70%)
7ad, X = I (63%)
7ae, X = I (68%)
7ba, X = I (87%)
7ca, X = I (78%)
7fa, X = I (77%)
7ha, X = I (62%)
8ab, X = H (90%)

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental procedures and characterization data for all new compounds (PDF)

AUTHOR INFORMATION

Corresponding Author

* Fax: +34963544328, e-mail: jose.r.pedro@uv.es, gonza-lo.blay@uv.es

ASSOCIATED CONTENT

Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) (a) Zhou, Y.; Wang, J.; Gu, Z.; Wang, S.; Zhu, W.; Aceña, J. L.; Soloshonok, V. A.; Izawa, K.; Liu, H. *Chem. Rev.* **2016**, *116*, 422-518. (b) Wang, J.; Sanchez-Rosello, M.; Aceña, J. L.; del Pozo, C.; Sorochinsky, A. E.; Fustero, S.; Soloshonok, F. A.; Liu, H. *Chem. Rev.* **2014**, *114*, 2432-2506. (c) Purser, S.; Moore, P. R.; Swallow, S.; Gouverneur, V. *Chem. Soc. Rev.* **2008**, *37*, 320-330. (d) Müller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881-1886. (e) Ojima, I. *Fluorine in Medicinal Chemistry and Chemical Biology*; Wiley-Blackwell: Chichester, 2009.
- (2) (a) Hiayama, T. in *Organofluorine Compounds: Chemistry and Applications*; Yamamoto, H. Ed.; Springer: New York, 2000. (b) Theodoridis, G. in *Agrochemical, Archaeological, Green Chemistry and Water*; Tressaud, A. Ed.; Elsevier: Amsterdam, 2006; Vol. 2, pp 121-175. (c) Uneyama, K. *Organofluorine Chemistry*; Blackwell: Oxford, 2006.
- (3) Berger, R.; Resnati, G.; Metrangola, P.; Weber, E.; Hulliger, J. *Chem. Soc. Rev.* **2010**, *40*, 3496-3508.
- (4) (a) Nie, J.; Guo, H.-C.; Cahard, D.; Ma, J.-A. *Chem. Rev.* **2011**, *111*, 455-529. (b) Cahard, D.; Xu, X.; Couve-Bonnaire, S.; Pannecoucke, X. *Chem. Soc. Rev.* **2010**, *39*, 558-568. (c) Ma, J.-A.; Cahard, D. *Chem. Rev.* **2008**, *108*, PR1-PR4. (d) Ma, J.-A.; Cahard, D. *Chem. Rev.* **2004**, *104*, 6119-6146.
- (5) (a) Brown, S. P.; Dransfield, P. J.; Vimolratana, M.; Jiao, X. Y.; Zhu, L.; Pattaropong, V.; Sun, Y.; Liu, J.; Luo, J.; Zhang, J.; Wong, S.; Zhuang, R.; Guo, Q.; Li, F.; Medina, J. C.; Swaminath, G.; Lin, D. C.-H.; Houze, J. B. *ACS Med. Chem. Lett.* **2012**, *3*, 726-730. (b) Kuo, G.-H.; Rano, T.; Pelton, P.; Demarest, K. T.; Gibbs, A. C.; Murray, W. V.; Damiano, B. P.; Connelly, M. A. *J. Med. Chem.* **2009**, *52*, 1768-1772. (c) Zhang, N.; Ayral-Kaloustian, S.; Nguyen, T.; Afragola, J.; Hernandez, R.; Lucas, J.; Gibbons, J.; Beyer, C. *J. Med. Chem.* **2007**, *50*, 319-327. (d) Caron, S.; Do, N. M.; Sieser, J. E.; Arpin, P.; Vazquez, E. *Org. Process Res. Dev.* **2007**, *11*, 1015-1024.
- (6) Dale, J. A.; Dull, D. L.; Mosher, H. S. *J. Org. Chem.* **1969**, *34*, 2543-2549.
- (7) Mikami, K.; Yajima, T.; Terada, M.; Suzuki, Y.; Kobayashi, I. *Chem. Commun.* **1997**, 57-58.
- (8) (a) Erdbrink, H.; Peuser, I.; Gerling, U. I. M.; Lentz, D.; Kokschi, B.; Czekelius, C. *Org. Biomol. Chem.* **2012**, *10*, 8583-8586. (b) Billard, T.; Langlois, B. R. *Eur. J. Org. Chem.* **2007**, 891-897. (c) Uneyama, K.; Katagiri, T.; Amii, H. *Acc. Chem. Res.* **2008**, *41*, 817-829. (d) Matsukawa, S.; Saijo, M. *Tetrahedron Lett.* **2008**, *49*, 4655-4657. (e) Mizuta, S.; Shibata, N.; Akita, S.; Fujimoto, H.; Nakamura, S.; Toru, T. *Org. Lett.* **2007**, *9*, 3707-3710.
- (9) (a) Cook, A. M.; Wolf, C. *Angew. Chem. Int. Ed.* **2016**, *55*, 2929-2933. (b) Jing, Z.; Bai, X.; Chen, W.; Zhang, G.; Zhu, B.; Jiang, Z. *Org. Lett.* **2016**, *18*, 260-263. (c) Wang, C.; Qin, J.; Shen, X.; Riedel, R.; Harms, K.; Meggers, E. *Angew. Chem. Int. Ed.* **2016**, *55*, 685-688. (d) Lv, J.; Zhang, Q.; Zhong, X.; Luo, S. *J. Am. Chem. Soc.* **2015**, *137*, 15576-15583. (e) Aikawa, K.; Kondo, D.; Honda, K.; Mikami, K. *Chem. Eur. J.* **2015**, *21*, 17565-17569. (f) Montesinos-Magraner, M.; Vila, C.; Blay, G.; Fernandez, I.; Munoz, M. C.; Pedro, J. R. *Adv. Synth. Catal.* **2015**, *357*, 3047-3051. (g) Ren, H.; Wang, P.; Wang, L.; Tang, Y. *Org. Lett.* **2015**, *17*, 4886-4889. (h) Sanchez-Diez, E.; Fernandez, M.; Uria, U.; Reyes, E.; Carrillo, L.; Vicario, J. L. *Chem. Eur. J.* **2015**, *21*, 8384-8388. (i) G. Blay, I. Fernandez, A. Monleón, J. R. Pedro, C. Vila, *Org. Lett.* **2009**, *11*, 441-444.
- (10) (a) Lou, H.; Wang, Y.; Jin, E.; Lin, X. *J. Org. Chem.* **2016**, *81*, 2019-2026. (b) Zhou, D.; Huang, Z.; Yu, X.; Wang, Y.; Li, J.; Wang, W.; Xie, H. *Org. Lett.* **2015**, *17*, 5554-5557. (c) Zhang, S.; Li, Lijun; H. Yanbin; L. i. Yanan; Y. Yu; Zha, Z.; Wang, Z. *Org. Lett.* **2015**, *17*, 5036-5039. (d) Zhao, M.-X.; Bi, H.-L.; Jiang, R.-H.; Xu, X.-W.; Shi, M. *Org. Lett.* **2014**, *16*, 4566-4569. (e) Chen, Y.-J.; Chen, Y.-H.; Feng, C.-G.; Lin, G.-Q. *Org. Lett.* **2014**, *16*, 3400-3403. (f) Huang, G.; Yin, Z.; Zhang, X. *Chem. Eur. J.* **2013**, *19*, 11992-11998. (g) Zhang, F.-G.; Zhu, X.-Y.; Li, S.; Niea, J.; Ma, J.-A. *Chem. Commun.* **2012**, *48*, 11552-11554.
- (11) (a) Zhao, M.-X.; Zhu, H.-K.; Dai, T.-L.; Shi, M. *J. Org. Chem.* **2015**, *80*, 11330-11338. (b) Zhang, L.-Y.; Zhou, J.-H.; Xu, Y.-H.; Loh, T.-P. *Chem. Asian J.* **2015**, *10*, 844-848. (c) Li, L.; Guo, J.-Y.; Liu, X.-G.; Chen, S.; Wang, Y.; Tan, B.; Liu, X.-Y. *Org. Lett.* **2014**, *16*, 6032-6035. (d) Zhao, Y.; Wang, X.-J.; Lin, Y.; Cai, C.-X.; Liu, J.-T. *Tetrahedron* **2014**, *70*, 2523-2528. (e) Davies, A. T.; Taylor, J. E.; Douglas, J.; Collett, C. J.; Morrill, L. C.; Fallan, C.; Slawin, A. M. Z.; Churchill, G.; Smith, A. D. J. *Org. Chem.* **2013**, *78*, 9243-9257. (f) Wen, L.; Yin, L.; Shen, Q.; Lu, L. *ACS Catalysis* **2013**, *3*, 502-506. (g) Kawai, H.; Kitayama, T.; Tokunaga, E.; Matsumoto, T.; Sato, H.; Shiro, M.; Shibata, N. *Chem. Commun.* **2012**, *48*, 4067-4069. (h) Wang, W.-T.; Lian, X.-J.; Chen, D.-H.; Liu, X.-H.; Lin, L.-L.; Feng, X.-M. *Chem. Commun.* **2011**, *47*, 7821-7823. (i) Blay, G.; Fernandez, I.; Muñoz, M. C.; Pedro, J. R.; Vila, C. *Chem. Eur. J.* **2010**, *16*, 9117-9122.
- (12) Reviews: (a) Cozzi, P. G.; Hilgraf, R.; Zimmermann, N. *Eur. J. Org. Chem.* **2007**, 5969-5994. (b) Bella, M.; Gasperi, T. *Synthesis* **2009**, 1583-1614. (c) Riant, O.; Hannedouche, J. *Org. Biomol. Chem.* **2007**, *5*, 873-888. (d) *Quaternary Stereocenters: Challenges and Solutions for Organic Synthesis*; Christoffers, J.; Baro, A., Eds.; Wiley-VCH: Weinheim, Germany, 2006.
- (13) (a) Wozniak, L.; Murphy, J. J.; Melchiorre, P. *J. Am. Chem. Soc.* **2015**, *137*, 5678-5681. (b) Du, D.; Jiang, Y.; Xu, Q.; Tang, X.-Y.; Shi, M. *ChemCatChem* **2015**, *7*, 1366-1371. (c) Deng, Q.-H.; Wadepohl, H.; Gade, L. H. *J. Am. Chem. Soc.* **2012**, *134*, 10769-10772. (d) Denton, J. R.; Sukumaran, D.; Davies, H. M. L. *Org. Lett.* **2007**, *9*, 2625-2628. (e) Kimura, M.; Yamazaki, T.; Kitazume, T.; Kubota, T. *Org. Lett.* **2004**, *25*, 4651-4654.
- (14) Kawai, H.; Okusu, S.; Tokunaga, E.; Sato, H.; Shiro, M.; Shibata, N. *Angew. Chem. Int. Ed.* **2012**, *51*, 4959-4962.
- (15) (a) Kawai, H.; Yuan, Z.; Kitayama, T.; Tokunaga, E.; Shibata, N. *Angew. Chem. Int. Ed.* **2013**, *52*, 5575-5579. (b) Kwiatkowski, P.; Cholewiak, A.; Kasztelan, A. *Org. Lett.* **2014**, *16*, 5930-5933.
- (16) (a) Gao, J.-R.; Wu, H.; Xiang, B.; Yu, W.-B. Han, L.; Jia, Y.-X. *J. Am. Chem. Soc.* **2013**, *135*, 2983-2986. (b) Chen, Q.; Wang, G.; Jiang, X.; Xu, Z.; Lin, L.; Wang, R. *Org. Lett.* **2014**, *16*, 1394-1397. (c) Hou, X.; Ma, H.; Zhang, Z.; Xie, L.; Qin, Z.; Fu, B. *Chem. Commun.* **2016**, *52*, 1470-1473.
- (17) Selected examples. Cu catalysis: (a) Knopfel, T. F.; Zarotti, P.; Ichikawa, T.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, 9682-9683. (b) Yazaki, R.; Kumagai, N.; Shibasaki, M. *J. Am. Chem. Soc.* **2010**, *132*, 10275-10277. (c) Yazaki, R.; Kumagai, N.; Shibasaki, M. *Chem. Asian J.* **2011**, *6*, 1778-1790. (d) Sanz-Marco, A.; Garcia-Ortiz, A.; Blay, G.; Pedro, J. R. *Chem. Commun.* **2014**, *50*, 2275-2278. (e) Sanz-Marco, A.; Garcia-Ortiz, A.; Blay, G.; Fernandez, I.; Pedro, J. R. *Chem. Eur. J.* **2014**, *20*, 668-672. (f) Sanz-Marco, A.; Blay, G.; Muñoz, M. C.; Pedro, J. R. *Chem. Commun.* **2015**, *51*, 8958-8961. (g) Sanz-Marco, A.; Blay, G.; Muñoz, M. C.; Pedro, J. R. *Chem. Eur. J.* **2016**, DOI: 10.1002/chem.201601303. Rh catalysis: (h) Nishimura, T.; Sawano, T.; Hayashi, *Angew. Chem. Int. Ed.* **2009**, *48*, 8057-8059. (i) Fillion, E.; Zoritto, A. K. *J. Am. Chem. Soc.* **2009**, *131*, 14608-14609. (j) Dou, X.; Huang, Y.; Hayashi, T. *Angew. Chem. Int. Ed.* **2016**, *55*, 1133-1137. Zn catalysis: (k) Blay, G.; Cardona, L.; Pedro, J. R.; Sanz-Marco, A. *Chem. Eur. J.* **2012**, *18*, 12966-12969. (l) Blay, G.; Muñoz, M. C.; Pedro, J. R.; Sanz-Marco, A. *Adv. Synth. Catal.* **2013**, *355*, 1071-1076.
- (18) Ahmar, S.; Fillion, E. *Org. Lett.* **2014**, *16*, 5748-5751.
- (19) (E)-Enones **1** are obtained with very high selectivity and can be separated from the (Z)-isomer by column chromatography.
- (20) Monleón, A.; Blay, G.; Domingo, L. R.; Muñoz, M. C.; Pedro, J. R. *Chem. Eur. J.* **2013**, *19*, 14852-14860.
- (21) The β -CF₃ moiety is required to activate the double bond. Enones lacking this group did not react under these conditions.

