

Letter

Asymmetric Arylation of 2,2,2-Trifluoroacetophenones Catalyzed by Chiral Electrostatically-Enhanced Phosphoric Acids

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(5) Supporting Information

ABSTRACT: A series of highly reactive metal-free chiral phosphoric acids possessing positively charged phosphonium ion substituents are reported and have been applied to Friedel–Crafts alkylations of indoles and 2,2,2-trifluoromethyl aryl ketones. These catalysts are orders-of-magnitude more active and have similar or better enantioselectivities than their noncharged analogues. High tolerance to a range of substrates with electron-withdrawing and electron-donating substituents was also observed.



I ndoles are among the most important type of nitrogencontaining heterocyclic scaffolds, as they are widely found in natural products,¹ pharmaceuticals,² and synthetic chemicals.³ Most of these indole-based compounds possess special chemical properties as well as bioactivities, and thus, they have attracted widespread attention.⁴ Fluorinated species are another important class of organic materials since the small size and high electronegativity of a fluorine atom lead to compounds with remarkably different properties than their fluorine-free analogues.⁵ A combination of fluorine substituents on indole frameworks leading to novel bioactivities and pharmaceutical properties made the synthesis of such compounds inviting targets.^{6,7}

A number of strategies have been devised to incorporate fluorine atoms into indole derivatives.^{7c,8} Given the electron-rich nature and the enhanced reactivity in electrophilic alkylations (especially at the C-3 position) of this heterocycle,⁹ one of the most straightforward methods for synthesizing these derivatives is to carry out a Friedel-Crafts alkylation with an indole and a fluorine-containing electrophile.¹⁰ This type of transformation is also a powerful method for the formation of carbon-carbon bonds that can be applied to construct optically active compounds.¹¹ In general, these reactions proceed in good yields and high enantioselectivities with suitable catalysts. For the specific case of Friedel-Crafts alkylations of indole derivatives with 2,2,2-trifluoromethyl aryl ketones, inorganic bases,¹² cinchona alkaloids,¹³ guanidine,¹⁴ trifluoromethanesulfonic acid,¹⁵ and phosphoric acids¹⁶ were reported to be successful catalysts. Most of these studies, however, focused on either racemic products or bis-coupled adducts. There are only a few reports on asymmetric alkylations, and these required either long reaction times (i.e., up to 96 h)¹⁶ or harsh reaction conditions (i.e., up to 9 kbar pressure)¹⁷ presumably because it is a challenge to trigger the alkylation and terminate it at the monoarylated stage.^{15,16} More effective enantioselective catalysts, consequently, are still needed for this transformation.

In general, there is a good correlation between reactivity and the acidity of related organocatalysts.¹⁷ For this reason, electron-withdrawing substituents such as trifluoromethyl or nitro groups are sometimes incorporated into phenyl rings at the 3 and 3' positions of BINOL-derived phosphoric acids.^{18,19} In previous studies from our laboratory, positively charged ion centers were found to enhance the catalytic reactivities of phenols,²⁰ thioureas,²¹ and phosphoric acids²² by orders of magnitude. This approach was also used to obtain good to excellent enantioselectivities for the alkylation of indoles with *trans-* β -nitrostyrene derivatives using chiral thioureas.²³ As a result, we decided to develop a series of BINOL-based phosphoric acid catalysts possessing 3,3'-phosphonium ion substituents (Figure 1)



Figure 1. Catalysts used in this work.

that were prepared using reported synthetic methods.²⁴ These large groups provide needed steric bulk and two acidity-enhancing positively charged ion centers. Their performance in the

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Friedel–Crafts reactions of indole derivatives with 2,2,2-trifluoromethyl aryl ketones are reported herein.

This investigation was initiated by examining the reaction of indole (3a) with 2,2,2-trifluoroacetophenone (4a) using the tri(*p*-tolyl)phosphonium ion containing phosphoric acid at the 3,3'-positions of the (*R*)-BINOL backbone (i.e., 2b) along with the noncoordinating tetrakis(3,5-bis(trifluoromethyl)phenyl)-borate (BAr^F₄⁻) counterion; more common and interacting anions lead to less active catalysts.^{20–22} At room temperature in CH₂Cl₂ with a 5 mol % catalyst loading, both the desired and undesired mono- and bis-coupled products (5a and 6, respectively) were formed, respectively (eq 1). This led to a loss of yield



for the former species, as previously has been reported with other strong acid catalysts,^{12,15} and the enantioselectivity was also poor (Table 1, entry 1). To our delight, when the reaction temperature

 Table 1. Optimization Conditions for the Reaction of Indole

 with 2,2,2-Trifluoroacetophenone^a

entry	cat.	<i>t</i> (°C)	additive	time (h)	yield of $5a (\%)^b$	ee (%) ^c
1	2b	20		5	48	17
2	2b	0		22	90	85
3	2b	-30		96	87	86
4 ^{<i>d</i>}	2b	0	3 Å MS	22	92	87
5 ^d	2b	0	4 Å MS	22	87	66
6 ^{<i>d</i>}	2b	0	5 Å MS	21	79	80
7^d	2b	0	13X MS	21	58	85
8 ^e	2b	0	Na_2SO_4	20	81	83
9 ^e	2b	0	NaCl	20	86	80
10 ^e	2b	0	$MgSO_4$	20	83	80
11 ^e	2b	0	$CaCl_2$	20	81	80
12 ^{d,f}	2b	0	3 Å MS	20	87	87
13 ^d	2a	0	3 Å MS	22	30 ^g	77
14 ^d	2c	0	3 Å MS	22	91	86
15 ^d	2d	0	3 Å MS	22	86	86
16 ^d	2e	0	3 Å MS	22	68 ^g	84
17 ^d	2b	-30	3 Å MS	40	85	90

^{*a*}Experiments performed with 0.140 mmol of indole, 0.168 mmol of 2,2,2-trifluoroacetophenone, 0.007 mmol of catalyst in 0.25 mL of CH₂Cl₂. ^{*b*}Isolated yield. ^{*c*}Determined by chiral HPLC. ^{*d*}5 mg of MS were used. ^{*e*}1.0 equiv of salt was used. ^{*f*}0.014 mmol catalyst was employed. ^{*g*}Starting material was present.

was reduced to 0 °C, the formation of the bis-coupled byproduct was nearly eliminated and a dramatic increase in the ee from 17% to 85% was observed (entry 2). A further decrease to -30 °C only led to a 1% increase in the ee at the expense of a much longer reaction time (entry 3), and this result was surpassed by adding 3 Å molecular sieves (MS) at 0 °C (i.e., 87% ee, entry 4). Other MS (4 Å, 5 Å, and 13X) decreased both the yield and the enantioselectivity (entries 5–7). Attempts to improve this transformation with inorganic salts (Na₂SO₄, NaCl, MgSO₄, and CaCl₂) as drying agents also led to poorer results (entries 8–11). An increase in the catalyst loading to 10 mol % did not improve the enantioselectivity further (entry 12) so the other phosphonium ion containing species were screened with 5 mol % catalyst at 0 °C in the presence of 3 Å MS. The triphenylphosphonium containing derivative 2a gave a much lower yield (30%) and selectivity (77% ee) (entry 13), while the tri(*p*-ethylphenyl) and tri(*p*-propylphenyl)phosphonium derivatives 2c and 2d gave similar results to 2b (entries 14–15). Interestingly, the diphenyl(p-tolyl)phosphonium ion tagged catalyst 2e, which is sterically similar to 2a and electronically in between 2a and 2b, afforded the product with a reduced yield and ee relative to 2b of 68% and 84%, respectively. These results suggest that the large difference between 2a and 2b is due to electronic effects brought about by replacing a hydrogen atom with a methyl group on each of the phenyl rings attached to the phosphorus atom. A lower temperature experiment at -30 °C was also performed with 3 Å MS, and a 3% increase in ee to 90% was observed (entry 17). A further drop in the temperature to -50 °C was impractical due to reduced catalyst solubility.

Reaction media were examined next with catalyst **2b**, and the results are summarized in Table 2. Solvents were found to have a

Table 2. Screening of Reaction Solvents^a

entry	solvent	time (h)	yield of $5a(\%)^b$	ee (%) ^c
1	CH ₂ Cl ₂	22	92	87
2	CHCl ₃	22	37	67
3	C ₆ H ₅ Cl	22	91	62
4	DCE	22	89	63
5	1:1 CH ₂ Cl ₂ /C ₆ H ₆	20	86	84
6	1:1 CH ₂ Cl ₂ /C ₆ H ₅ CH ₃	20	81	83
7	$1:1 \text{ CH}_2\text{Cl}_2/1, 3-(\text{CH}_3)_2\text{C}_6\text{H}_4$	20	88	83
8	1:1 CH_2Cl_2/CCl_4	20	89	85

^{*a*}Experiments performed with 0.140 mmol of indole, 0.168 mmol of 2,2,2-trifluoroacetophenone, 0.007 mmol of catalyst **2b**, and 5 mg of 3 Å MS in 0.25 mL of solvent at 0 $^{\circ}$ C. ^{*b*}Isolated yield. ^{*c*}Determined by chiral HPLC.

large influence on the reactivity and enantioselectivity. For example, $CHCl_3$ (entry 2) led to both a lower yield and enantioselectivity than CH_2Cl_2 (entry 1). Chlorobenzene (entry 3) and 1,2-dichloroethane (DCE, entry 4) gave similar results (91% and 89% yields along with 62% and 63% ee), neither of which is as good as CH_2Cl_2 . Several mixtures using CH_2Cl_2 and aromatic solvents (i.e., benzene, toluene, *m*-xylene) or CCl_4 were also tested (entries 5–8). None of these screenings led to better results than when CH_2Cl_2 was used.

The scope of this transformation was examined at 0 °C using 5 mol % 2b, CH₂Cl₂ as the solvent, and 3 Å MS as a drying agent (eq 2). As summarized in Table 3, a wide variety of substituents including electron-withdrawing and electron-donating groups on either reactant were tolerated. With a few exceptions, excellent yields (82-94%) and good enantioselectivities (79-91% ee) were obtained at 0 °C (entry 1-19). Halide substituents at the 5-positon of indole did not affect the selectivity (85-87% ee) (entries 1-2) relative to the parent compound (i.e., \mathbb{R}^3 , $\mathbb{R}^4 = H$), whereas electron-donating groups at the 5- and 6-positions led to reduced enantioselectivities of 79% and 48% ee (entries 3-4). Interestingly, while 6-methylindole (3e) gave the worst product enantiomeric purity (48% ee), its isomer 7-methylindole (3h) provided the highest enantioselectivity (91% ee, entry 7). This difference should be quite helpful in developing computational models for the mechanism of this reaction. Other substituents at the 7-position of indole (Cl, Br, Et) had no impact on the enantiomeric excess (entries 5-6 and 8), but 7-bromoindole (3g) slowed the reaction leading to approximately half the yield over the same time period. Introduction of electron-withdrawing



Table 3. Reaction Scope^{*a*}

entry	substrate	adduct	time (h)	yield (%) ^b	ee (%) ^c
1	3b + 4a	5b	26	85	85
2	3c + 4a	5c	26	82	87
3	3d + 4a	5d	20	84	79
4	3e + 4a	5e	20	83	48
5	3f + 4a	5f	28	87	87
6	3g + 4a	5g	28	41	88
7	3h + 4a	5h	14	92	91
8	3i + 4a	5i	20	85	88
9	3a + 4b	5j	20	92	90
10	3a + 4c	5k	20	88	89
11	3a + 4d	51	20	94	89
12	3a + 4e	5m	28	86	85
13	3a + 4f	5n	20	90	88
14	3a + 4g	50	20	89	85
15	3a + 4h	5p	20	91	86
16	3a + 4i	5q	20	85	86
17	3a + 4j	5r	20	88	88
18	3a + 4k	5s	24	28	64
19	3a + 4l	5t	28	36	84
20 ^d	3h + 4a	5h	18	96	95
21 ^d	3a + 4b	5j	42	91	93
22 ^{<i>d</i>,<i>e</i>}	3h + 4a	5h	65	93	96
23 ^f	3h + 4a	5h	70	96	96

^{*a*}Experiments performed with 0.140 mmol of indole, 0.168 mmol of 2,2,2-trifluoroacetophenone, 5 mol % of **2b** and 5 mg of 3 Å MS in 0.25 mL of CH₂Cl₂ at 0 °C. ^{*b*}Isolated yield. ^{*c*}Determined by chiral HPLC. ^{*d*}Reaction run at -30 °C with 10 mg of 3 Å MS. ^{*e*}1.5 mol % catalyst. ^{*f*}Larger scale reaction with 0.840 mmol of 7-methylindole, 1.008 mmol of 2,2,2-trifluoroacetophenone, 1.5 mol % of **2b** and 30 mg of 3 Å MS in 1.50 mL of CH₂Cl₂ at -30 °C; 247.5 mg of product was produced.

groups (F, Cl, Br, and CF₃) to the para position of 2,2,2trifluoroacetophenone gave slight improvements of 1-3% in the ee (entries 9–11 and 13), whereas an electron-donating methyl group at the same location lowered the enantioselectivity by an equivalent amount (entry 12). Halogen substituents at one or both of the meta positions in 2,2,2-trifluoroacetophenone had little, if any, impact on the reaction outcome (entries 14–17). Perfluoroacetophenone (**4k**) was found to give both a low yield (28%) and ee (64%, entry 18), while 2-chloro-2,2-difluoroacetophenone (41) also gave a low yield (36%) but without much difference in the enantioselectivity (i.e., an 84% ee was observed, entry 19). For the two reactions that gave \geq 90% ee at 0 °C (entries 7 and 9), a decrease in temperature to -30 °C resulted in improved selectivities of 95% and 93% ee (entries 20–21). The former transformation was further examined with a decreased catalyst loading of 1.5 mol %, and the enantioselectivity was preserved with a measured ee of 96% (entry 22). A larger scale reaction was also performed with six times more material and reactant weights in excess of 100 mg along with a catalyst loading of 1.5 mol %. This led to similar results to the small-scale transformation and afforded a 96% yield and a 96% ee (entry 23).

To compare the reactivity and enantioselectivity of our charged BINOL phosphoric acid derivative **2b** with noncharged analogues, three different structures (**1a**–**1c**) were used. These species included the unsubstituted BINOL phosphoric acid (**1a**), a sterically similar structure with triphenylsilyl substituents at the 3- and 3'-positions (**1b**), and 3,3'-bis(2,4,6-triisopropylphenyl)-BINOL phosphoric acid (**1c**). The last of these derivatives is known as TRIP and is one of the most successful phosphoric acid catalysts that has been reported.²⁵ 7-Methylindole (**3h**) and 2,2,2-trifluoroacetophenone (**4a**) in CH₂Cl₂ at -30 °C with a 1.5 mol % catalyst loading were used as the test reaction, and the results after 65 h are given in Table 4. The least sterically

Table 4. Catalyst Comparisons⁴

entry	catalyst	yield (%) ^b	ee (%) ^c
1	1a	1	1
2	1b	9	93
3	1c	43	97
4	2b	93	96
2 3 4	1b 1c 2b	9 43 93	93 97 96

^aExperiments performed with 0.140 mmol of 7-methylindole, 0.168 mmol of 2,2,2-trifluoroacetophenone, 1.5 mol % of the desired catalyst, and 10 mg of 3 Å MS in 0.25 mL of CH_2Cl_2 at -30 °C. ^bIsolated yield after 65 h. ^cDetermined by chiral HPLC.

hindered parent structure with hydrogen atoms at the 3 and 3'-positions (1a) was ineffective. Only a 1% yield was obtained, and this material was essentially racemic (i.e., 1% ee, entry 1). The catalyst 1b with two triphenylsilyl substituents only gave a yield of 9%, but this product was formed in 93% ee (entry 2). TRIP is more reactive, but only resulted in a 43% yield. The observed ee of 97%, however, is quite impressive (entry 3). Our charged phosphonium ion tagged phosphoric acid catalyst 2b proved to be superior in that an excellent yield of 93% was obtained along with a 96% ee (entry 4). Assuming second-order kinetics for these processes,²⁶ one can estimate that 2b is more reactive than 1a–1c by factors of 690, 70, and 10, respectively, but still is as selective as the best of these noncharged species.

To investigate the role of hydrogen bonding between the phosphoryl oxygen and indole substrate, a reaction lacking this interaction was performed with 1-methylindole and 2,2,2-trifluoroacetophenone at 0 $^{\circ}$ C (eq 3). The yield after 18 h was



71%, and the product was formed with a 24% ee. These results show that the selectivity is significantly lower and that the yield is

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worse than when indole is used (92% yield and 87% ee in 22 h). These findings indicate that indole reacts 2.6 times faster than *N*-methylindole even though the latter compound is a better nucleophile. This suggests that the $P=O\cdots H-N$ hydrogen bond is important both in terms of the reaction rate and the enantioselectivity as previously reported.²⁷

In summary, we demonstrated a successful application of chiral electrostatically enhanced phosphoric acids to a Friedel–Crafts alkylation to generate fluorinated indole derivatives. A wide scope of substrates is tolerated, giving the corresponding products in good yields and enantioselectivities. A larger synthetic scale reaction affording 250 mg of product was carried out with little, if any, change in the performance of the reaction. Our charged catalyst **2b** was also found to outperform noncharged analogues in terms of reaction rates by orders of magnitude, yet still gave as good or better enantioselectivities.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b00900.

Experiment procedures, NMR spectra, and HPLC traces (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) (a) Dixon, R. A. Nature 2001, 411, 843–847. (b) Li, S. M. Nat. Prod. Rep. 2010, 27, 57–78.

(2) (a) Kochanowska-Karamyan, A. J.; Hamann, M. T. Chem. Rev. 2010, 110, 4489–4497. (b) Zhang, M. Z.; Chen, Q.; Yang, G. F. Eur. J. Med. Chem. 2015, 89, 421–441.

(3) (a) Taber, D. F.; Tirunahari, P. K. *Tetrahedron* **2011**, *67*, 7195–7210. (b) Barluenga, J.; Rodriguez, F.; Fananas, F. J. *Chem. - Asian J.* **2009**, *4*, 1036–1048.

(4) (a) Melander, R. J.; Minvielle, M. J.; Melander, C. Tetrahedron
2014, 70, 6363-6372. (b) Rani, P.; Srivastava, V. K.; Kumar, A. Eur. J. Med. Chem. 2004, 39, 449-452. (c) Zhang, H. C.; Ye, H.; Moretto, A. F.; Brumfield, K. K.; Maryanoff, B. E. Org. Lett. 2000, 2, 89-92. (d) Du, Y. F.; Liu, R. H.; Linn, G.; Zhao, K. Org. Lett. 2006, 8, 5919-5922. (e) Radwan, M. A. A.; Ragab, E. A.; Sabry, N. M.; El-Shenawy, S. M. Bioorg. Med. Chem. 2007, 15, 3832-3841. (f) Agarwal, A.; Srivastava, K.; Puri, S. K.; Chauhan, P. M. S. Bioorg. Med. Chem. Lett. 2005, 15, 3133-3136. (g) Chen, J.-B.; Jia, Y.-X. Org. Biomol. Chem. 2017, 15, 3550-3567.

(5) (a) Muller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881–1886. (b) Biffinger, J. C.; Kim, H. W.; DiMagno, S. G. *ChemBioChem* **2004**, *5*, 622–627. (c) Mikami, K.; Itoh, Y.; Yamanaka, M. *Chem. Rev.* **2004**, *104*, 1–16.

(6) (a) Chae, J.; Konno, T.; Ishihara, T.; Yamanaka, H. *Chem. Lett.* **2004**, 33, 314–315. (b) Lin, R. Y.; Ding, S. T.; Shi, Z. Z.; Jiao, N. *Org. Lett.* **2011**, *13*, 4498–4501.

(7) (a) Shimizu, R.; Egami, H.; Nagi, T.; Chae, J.; Hamashima, Y.; Sodeoka, M. *Tetrahedron Lett.* 2010, 51, 5947–5949. (b) Yin, B.; Wang, L. H.; Inagi, S.; Fuchigami, T. *Tetrahedron* 2010, 66, 6820–6825. (c) Dolensky, B.; Nam, G.; Deng, W. P.; Narayanan, J.; Fan, J. F.; Kirk, K. L. J. Fluorine Chem. 2004, 125, 501–508.

(8) (a) Ferry, A.; Billard, T.; Bacque, E.; Langlois, B. R. J. Fluorine Chem. 2012, 134, 160–163. (b) Baudoux, J.; Salit, A. F.; Cahard, D.; Plaquevent, J. C. Tetrahedron Lett. 2002, 43, 6573–6574.

(9) Lakhdar, S.; Westermaier, M.; Terrier, F.; Goumont, R.; Boubaker, T.; Ofial, A. R.; Mayr, H. J. Org. Chem. **2006**, 71, 9088–9095.

(10) (a) Wen, L. L.; Shen, Q. L.; Wan, X. L.; Lu, L. J. Org. Chem. 2011, 76, 2282–2285. (b) Blay, G.; Fernandez, I.; Munoz, M. C.; Pedro, J. R.; Vila, C. Chem. - Eur. J. 2010, 16, 9117–9122. (c) Shevchenko, N. E.; Shmatova, O. I.; Balenkova, E. S.; Roschenthaler, G. V.; Nenajdenko, V. G. Eur. J. Org. Chem. 2013, 2013, 2237–2245.

(11) (a) Parmar, D.; Sugiono, E.; Raja, S.; Rueping, M. Chem. Rev.
2014, 114, 9047–9153. (b) You, S. L.; Cai, Q.; Zeng, M. Chem. Soc. Rev.
2009, 38, 2190–2201. (c) Poulsen, T. B.; Jorgensen, K. A. Chem. Rev.
2008, 108, 2903–2915. (d) Uraguchi, D.; Terada, M. J. Am. Chem. Soc.
2004, 126, 5356–5357.

(12) Liu, X. D.; Wang, Y.; Ma, H. Y.; Xing, C. H.; Yuan, Y.; Lu, L. Tetrahedron **2017**, 73, 2283–2289.

(13) (a) Kasztelan, A.; Biedrzycki, M.; Kwiatkowski, P. Adv. Synth. Catal. 2016, 358, 2962–2969. (b) Biedrzycki, M.; Kasztelan, A.; Kwiatkowski, P. ChemCatChem 2017, 9, 2453–2456.

(14) Bandini, M.; Sinisi, R. Org. Lett. 2009, 11, 2093-2096.

(15) Wang, Y.; Yuan, Y.; Xing, C. H.; Lu, L. Tetrahedron Lett. 2014, 55, 1045–1048.

(16) (a) Nie, J.; Zhang, G. W.; Wang, L.; Fu, A. P.; Zheng, Y.; Ma, J. A. *Chem. Commun.* **2009**, 2356–2358. (b) Wang, T.; Zhang, G.-W.; Teng, Y.; Nie, J.; Zheng, Y.; Ma, J.-A. *Adv. Synth. Catal.* **2010**, 352, 2773–2777.

(17) Kaupmees, K.; Tolstoluzhsky, N.; Raja, S.; Rueping, M.; Leito, I. Angew. Chem., Int. Ed. **2013**, *52*, 11569–11572.

(18) Akiyama, T.; Morita, H.; Itoh, J.; Fuchibe, K. Org. Lett. 2005, 7, 2583–2585.

(19) (a) Akiyama, T.; Itoh, J.; Yokota, K.; Fuchibe, K. Angew. Chem., Int. Ed. 2004, 43, 1566–1568. (b) Zhou, F. T.; Yamamoto, H. Angew. Chem., Int. Ed. 2016, 55, 8970–8974.

(20) Samet, M.; Buhle, J.; Zhou, Y. W.; Kass, S. R. J. Am. Chem. Soc. 2015, 137, 4678-4680.

- (21) Fan, Y.; Kass, S. R. Org. Lett. 2016, 18, 188-191.
- (22) Ma, J.; Kass, S. R. Org. Lett. 2016, 18, 5812-5815.
- (23) Fan, Y.; Kass, S. R. J. Org. Chem. 2017, 82, 13288-13296.
- (24) Hermeke, J.; Toy, P. H. Tetrahedron 2011, 67, 4103-4109.

(25) (a) Clot-Almenara, L.; Rodriguez-Escrich, C.; Osorio-Planes, L.;

Pericas, M. A. ACS Catal. 2016, 6, 7647–7651. (b) Reid, J. P.; Goodman, J. M. Chem. - Eur. J. 2017, 23, 14248–14260.

(26) Wang, Y. Z.; Liu, W.; Ren, W. L.; Shi, Y. Org. Lett. 2015, 17, 4976–4979.

(27) Fu, A.; Meng, W.; Li, H.; Nie, J.; Ma, J. A. Org. Biomol. Chem. 2014, 12, 1908–1918.