

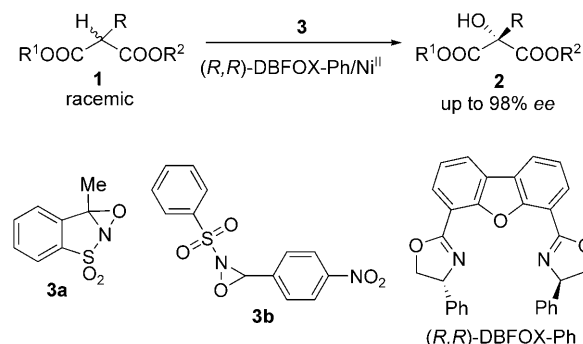
# Hydroxylation

## A Dynamic Kinetic Asymmetric Transformation in the $\alpha$ -Hydroxylation of Racemic Malonates and Its Application to Biologically Active Molecules\*\*

Dhande Sudhakar Reddy, Norio Shibata,\* Jun Nagai, Shuichi Nakamura, and Takeshi Toru

Chiral  $\alpha$ -hydroxy malonates and their equivalents are a valuable class of compounds utilized in the synthesis of drug candidates such as chlozolate and bicalutamide.<sup>[1]</sup> The synthesis of these compounds has been achieved by the enzymatic desymmetrization of prochiral malonate derivatives,<sup>[1a,d,2]</sup> or by the enzymatic and chemical desymmetrization of prochiral glycerols.<sup>[1b,c,3]</sup> Although in recent years significant progress has been made in the development of the catalytic asymmetric  $\alpha$ -hydroxylation reaction of carbonyls,<sup>[4–6]</sup> there have been no reports of catalytic enantioselective hydroxylation of malonate derivatives in the literature, and the reaction remains a challenge. Recently we reported the desymmetrization-like enantioselective fluorination of malonate derivatives in the presence of an (*R,R*)-DBFOX-Ph/ $\text{Zn}^{\text{II}}$  complex,<sup>[7,8]</sup> where chiral  $\alpha$ -fluorinated malonate derivatives<sup>[9]</sup> were obtained in high yields with high enantioselectivities. Herein, we present the first dynamic kinetic asymmetric transformation in the  $\alpha$ -hydroxylation of racemic malonate **1** using the (*R,R*)-DBFOX-Ph/ $\text{Ni}^{\text{II}}$  complex with oxaziridine **3a** to provide the chiral  $\alpha$ -hydroxy malonate **2**, which has a quaternary stereocenter, in high yield with a high enantioselectivity of up to 98 % *ee* (Scheme 1). Application of this reaction to the synthesis of biologically attractive molecules illustrates the efficiency of this strategy.

First, we attempted the direct  $\alpha$ -hydroxylation of racemic 2-benzyl-*tert*-butyl methyl malonate (**1a**) with oxaziridine **3a** under the best reaction conditions previously reported for the enantioselective fluorination of malonate derivatives:<sup>[7]</sup> the reaction was carried out in the presence of  $\text{Zn}(\text{OAc})_2$  and molecular sieves (M.S. 4 Å) in  $\text{CH}_2\text{Cl}_2$  at room temperature. However, even after 24 hours, the reaction did not proceed (Table 1, entry 1). Under reflux the corresponding 2-hydroxy-2-benzyl-*tert*-butyl methyl malonate (**2a**) was obtained in 15 % yield with 92 % *ee* (Table 1, entry 2). When the reaction was performed in the presence of  $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$  in  $\text{CH}_2\text{Cl}_2$



**Scheme 1.** A dynamic kinetic asymmetric transformation in the  $\alpha$ -hydroxylation of racemic malonate using (*R,R*)-DBFOX-Ph/ $\text{Ni}^{\text{II}}$  complex with oxaziridine.

**Table 1:** Catalytic enantioselective hydroxylation of racemic **1a**: optimization of the reaction conditions.<sup>[a]</sup>

| $\text{MeOOC}-\text{CH}(\text{CH}_2\text{Ph})-\text{COO}t\text{Bu}$ ( <b>1a</b> , racemic) $\xrightarrow[\text{solvent, temp}]{\text{Lewis acid (10 mol\%), (R,R)-DBFOX-Ph (11 mol\%), time, M.S. (4 \text{ \AA})}}$ $\text{MeOOC}-\text{CH}(\text{CH}_2\text{Ph})-\text{COO}t\text{Bu}$ ( <b>2a</b> , chiral) |                                                       |                                     |               |              |                          |                              |  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|-------------------------------------|---------------|--------------|--------------------------|------------------------------|--|
| Entry                                                                                                                                                                                                                                                                                                          | Lewis acid                                            | Solvent                             | <i>T</i> [°C] | <i>t</i> [h] | Yield [%] <sup>[b]</sup> | <i>ee</i> [%] <sup>[c]</sup> |  |
| 1                                                                                                                                                                                                                                                                                                              | $\text{Zn}(\text{OAc})_2$                             | $\text{CH}_2\text{Cl}_2$            | RT            | 24           | trace                    | –                            |  |
| 2                                                                                                                                                                                                                                                                                                              | $\text{Zn}(\text{OAc})_2$                             | $\text{CH}_2\text{Cl}_2$            | reflux        | 36           | 15                       | 92                           |  |
| 3                                                                                                                                                                                                                                                                                                              | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | $\text{CH}_2\text{Cl}_2$            | reflux        | 42           | 60                       | 91                           |  |
| 4 <sup>[d]</sup>                                                                                                                                                                                                                                                                                               | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | $\text{CH}_2\text{Cl}_2$            | RT            | 24           | 91                       | 82                           |  |
| 5 <sup>[d]</sup>                                                                                                                                                                                                                                                                                               | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | $\text{CH}_2\text{Cl}_2$            | –20           | 48           | 83                       | 84                           |  |
| 6                                                                                                                                                                                                                                                                                                              | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 48           | 82                       | 91                           |  |
| 7                                                                                                                                                                                                                                                                                                              | $\text{Zn}(\text{OAc})_2$                             | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 80           | trace                    | –                            |  |
| 8                                                                                                                                                                                                                                                                                                              | $\text{Zn}(\text{OTf})_2$                             | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 48           | 77                       | 89                           |  |
| 9                                                                                                                                                                                                                                                                                                              | $\text{Ni}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$   | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 48           | 0                        | –                            |  |
| 10                                                                                                                                                                                                                                                                                                             | $\text{Sc}(\text{OTf})_3$                             | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 60           | trace                    | 53                           |  |
| 11                                                                                                                                                                                                                                                                                                             | $\text{Mg}(\text{ClO}_4)_2$                           | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 60           | trace                    | 7                            |  |
| 12                                                                                                                                                                                                                                                                                                             | $\text{Mg}(\text{OTf})_2$                             | $\text{ClCH}_2\text{CH}_2\text{Cl}$ | reflux        | 60           | 19                       | 0                            |  |
| 13                                                                                                                                                                                                                                                                                                             | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | EtOH                                | reflux        | 60           | 0                        | –                            |  |
| 14                                                                                                                                                                                                                                                                                                             | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | toluene                             | 85            | 60           | 20                       | 85                           |  |
| 15 <sup>[e]</sup>                                                                                                                                                                                                                                                                                              | $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ | $\text{CH}_2\text{Cl}_2$            | reflux        | 62           | 28                       | 87                           |  |
| 16 <sup>[e]</sup>                                                                                                                                                                                                                                                                                              | $\text{Zn}(\text{OAc})_2$                             | $\text{CH}_2\text{Cl}_2$            | reflux        | 48           | 41                       | 49                           |  |

[a] Reaction conditions: Lewis acid (10 mol%), (*R,R*)-DBFOX-Ph (11 mol%), and molecular sieves (4 Å) in solvent. [b] Yield of isolated product. [c] Determined by HPLC on a chiral stationary phase. [d] 2,6-Lutidine (1 equiv) was added. [e] **3b** was used instead of **3a**.

at reflux, the yield was improved to 60 % with 91 % *ee* (Table 1, entry 3). The addition of 1 equivalent of 2,6-lutidine as base dramatically improved the yield of **2a** (83–91 % yield),

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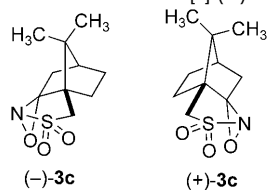
even at a lower temperature, but the enantioselectivity was not excellent (82–84 % *ee*; Table 1, entries 4–5). Optimization experiments for both the Lewis acid and the solvent were carried out to improve both the yield and enantioselectivity of the transformations (Table 1, entries 6–14), and the combination of Ni(ClO<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O in 1,2-dichloroethane at reflux was very effective for the dynamic kinetic asymmetric transformation in the  $\alpha$ -hydroxylation of malonate derivatives (Table 1, entry 6). The structure of the oxidant slightly affected the yield and enantioselectivity of **2a**. Changing the oxidant from cyclic oxaziridine **3a** to acyclic 3-(4-nitrophenyl)-2-(phenylsulfonyl)-1,2-oxaziridine (**3b**) resulted in lower yields with lower *ee* values (Table 1, entries 15–16).

With the reaction conditions now optimized, we next explored the range of substrates that could be tolerated during the hydroxylation reaction (Table 2). First we examined the malonate derivatives and looked at the effect that substituents on the stereogenic center at the  $\alpha$  position had on the hydroxylation reaction. The results showed that the

**Table 2:** Catalytic enantioselective hydroxylation of racemic **1a–p**.  
**3a** (1.2 equiv)

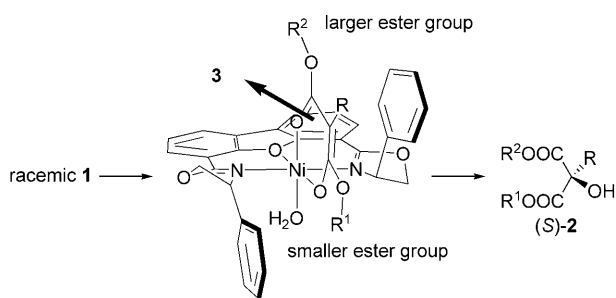
| racemic <b>1</b>    |           | $\begin{array}{c} \text{H}_3\text{C} \quad \text{R} \\ \diagup \quad \diagdown \\ \text{R}^1\text{OOC} \quad \text{C} \quad \text{COOR}^2 \\ \diagdown \quad \diagup \end{array}$                                                   |                |                |              | $\begin{array}{c} \text{HO} \quad \text{R} \\ \diagup \quad \diagdown \\ \text{R}^1\text{OOC} \quad \text{C} \quad \text{COOR}^2 \\ \diagdown \quad \diagup \end{array}$ |           |                              |
|---------------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|----------------|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------------------------------|
|                     |           | $\begin{array}{c} \text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O} (10 \text{ mol}\%) \\ (R,R)\text{-DBFOX-Ph} (11 \text{ mol}\%) \\ \text{ClCH}_2\text{CH}_2\text{Cl, reflux} \\ \text{time, M.S. (4 } \text{\AA}) \end{array}$ |                |                |              | chiral- <b>2</b>                                                                                                                                                         |           |                              |
| Entry               | <b>1</b>  | R                                                                                                                                                                                                                                   | R <sup>1</sup> | R <sup>2</sup> | <i>t</i> [h] | <b>2</b>                                                                                                                                                                 | Yield [%] | <i>ee</i> [%] <sup>[a]</sup> |
| 1                   | <b>1a</b> | CH <sub>2</sub> Ph                                                                                                                                                                                                                  | Me             | <i>t</i> Bu    | 48           | <b>2a</b>                                                                                                                                                                | 82        | 91                           |
| 2                   | <b>1b</b> | Ph                                                                                                                                                                                                                                  | Me             | <i>t</i> Bu    | 12           | <b>2b</b>                                                                                                                                                                | 83        | 93                           |
| 3                   | <b>1c</b> | Me                                                                                                                                                                                                                                  | Me             | <i>t</i> Bu    | 16           | <b>2c</b>                                                                                                                                                                | 84        | 98                           |
| 4                   | <b>1d</b> | Et                                                                                                                                                                                                                                  | Me             | <i>t</i> Bu    | 36           | <b>2d</b>                                                                                                                                                                | 74        | 95                           |
| 5                   | <b>1e</b> | Bu                                                                                                                                                                                                                                  | Me             | <i>t</i> Bu    | 36           | <b>2e</b>                                                                                                                                                                | 80        | 94                           |
| 6                   | <b>1f</b> | <i>i</i> Bu                                                                                                                                                                                                                         | Me             | <i>t</i> Bu    | 48           | <b>2f</b>                                                                                                                                                                | 65        | 88                           |
| 7                   | <b>1g</b> | CH <sub>2</sub> Ph                                                                                                                                                                                                                  | Et             | <i>t</i> Bu    | 48           | <b>2g</b>                                                                                                                                                                | 71        | 91                           |
| 8                   | <b>1h</b> | Ph                                                                                                                                                                                                                                  | Et             | <i>t</i> Bu    | 16           | <b>2h</b>                                                                                                                                                                | 74        | 90                           |
| 9                   | <b>1i</b> | Me                                                                                                                                                                                                                                  | Et             | <i>t</i> Bu    | 14           | <b>2i</b>                                                                                                                                                                | 72        | 94                           |
| 10                  | <b>1j</b> | Et                                                                                                                                                                                                                                  | Et             | <i>t</i> Bu    | 62           | <b>2j</b>                                                                                                                                                                | 52        | 90                           |
| 11                  | <b>1k</b> | CH <sub>2</sub> Ph                                                                                                                                                                                                                  | Pr             | <i>t</i> Bu    | 48           | <b>2k</b>                                                                                                                                                                | 63        | 90                           |
| 12                  | <b>1l</b> | CH <sub>2</sub> Ph                                                                                                                                                                                                                  | <i>i</i> Pr    | <i>t</i> Bu    | 62           | <b>2l</b>                                                                                                                                                                | 48        | 82                           |
| 13                  | <b>1m</b> | CH <sub>2</sub> Ph                                                                                                                                                                                                                  | Me             | Et             | 14           | <b>2m</b>                                                                                                                                                                | 98        | 12                           |
| 14                  | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 3            | <b>2n</b>                                                                                                                                                                | 80        | 66                           |
| 15 <sup>[b]</sup>   | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 2            | <b>2n</b>                                                                                                                                                                | 55        | 60                           |
| 16 <sup>[c]</sup>   | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 3            | <b>2n</b>                                                                                                                                                                | 79        | 54                           |
| 17 <sup>[b,c]</sup> | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 1            | <b>2n</b>                                                                                                                                                                | 59        | 47                           |
| 18 <sup>[d]</sup>   | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 16           | <b>2n</b>                                                                                                                                                                | 24        | 81                           |
| 19 <sup>[e]</sup>   | <b>1n</b> | Me                                                                                                                                                                                                                                  | Et             | Ph             | 24           | <b>2n</b>                                                                                                                                                                | trace     | –                            |
| 20                  | <b>1o</b> | Me                                                                                                                                                                                                                                  | Et             | <i>o</i> -FPh  | 2            | <b>2o</b>                                                                                                                                                                | 91        | 88                           |
| 21                  | <b>1p</b> | Me                                                                                                                                                                                                                                  | Et             | 1-naphthyl     | 2            | <b>2p</b>                                                                                                                                                                | 93        | 90                           |

[a] Determined by HPLC on a chiral stationary phase. The absolute configuration of **2n** was determined to be *S* by comparison with the optical rotation of the known (*S*)-1-ethyl 3-phenyl-2-hydroxy-2-methylmalonate,<sup>[1a]</sup> and the configuration of **2** was tentatively assumed to be the same by analogy. [b] **3b** was used instead of **3a**. The reaction was performed at RT. [c] 2 equivalents of **3a** or **3b** was used. [d] (+)-**3c** was used instead of **3a**. [e] (–)-**3c** was used instead of **3a**.



aryl and alkyl substituents at the  $\alpha$  position of **1** have less of an effect on the yields and enantioselectivities, and they were indeed good substrates to afford **2a–e** in high enantioselectivity (91–98 % *ee*; Table 2, entries 1–5). The hydroxylation of **1f** with a sterically demanding *i*Bu group also proceeded nicely to give **2f** with 88 % *ee* (Table 2, entry 6). We next investigated the scope, limitation, and ability of the present method to discriminate between ester moieties of different steric bulk. As shown in Table 2, the (*R,R*)-DBFOX/Ni<sup>II</sup> catalyst efficiently discriminated between the Me/*t*Bu ester system (Table 2, entries 1–6), the Et/*t*Bu ester system (Table 2, entries 7–10), as well as the Pr/*t*Bu ester system (Table 2, entry 11), and gave at least 90 % *ee*. Notably, the discrimination between both sterically hindered *i*Pr and *t*Bu esters was possible, and gave **2l** with 82 % *ee* (Table 2, entry 12). We then attempted the discrimination between Me and Et ester substituents using **1m**. However, the desired product **2m** was obtained in 98 % yield with only 12 % *ee* (Table 2, entry 13). These results indicate that the *t*Bu ester moiety in **1** is responsible for the enantioselective transformation. Discrimination between the Ph and Et esters of **1n** was also possible with the (*R,R*)-DBFOX/Ni<sup>II</sup> catalyst, and gave **2n** with 66 % *ee* (Table 2, entry 14), however, the *ee* value was not satisfactory. When oxaziridine **3b** was used, **2n** was obtained with 60 % *ee* (Table 2, entry 15). To improve the enantioselectivity, we attempted the same reaction of **1n** using 2 equivalents of **3a** or **3b**, but the results were slightly worse (Table 2, entries 16 and 17). This outcome could be explained in light of the “matched/mismatched” concept between two chiral molecules, namely, (*R,R*)-DBFOX-Ph and the oxaziridine derivatives. To identify the “matched/mismatched” effect of **3** more clearly, we investigated the reaction of **1n** with an alternative oxaziridine **3c**, which is available in both enantiomeric forms. Although the reactivity of **3c** was very low, the reaction of **1n** with (+)-**3c** proceeded with a high enantioselectivity of 81 % *ee* to produce **2n** in the matched case (Table 2, entry 18). The mismatched case using (–)-**3c** provided a trace amount of product (Table 2, entries 19). We next carried out the reaction with aryl ethyl malonate derivatives having larger substituents on the benzene ring to overcome the poor discrimination between Ph and Et esters. It should be noted that the enantioselectivity was finally improved to 88 % and 90 % *ee* by the use of larger aryl substituents, *o*-fluorophenyl ester **1o** and 1-naphthyl ester **1p**, respectively (Table 2, entries 20 and 21). The configuration of the resulting  $\alpha$ -hydroxy malonate **2** can be explained by the preferential approach of the hydroxylating agent **3** from the less hindered *Si* face of the complex formed between the substrates, a Ni<sup>II</sup> ion, and (*R,R*)-DBFOX-Ph—based on the mechanism outlined previously for the enantioselective fluorination of malonate derivatives by (*R,R*)-DBFOX-Ph/Zn<sup>II</sup> catalysis (Figure 1).<sup>[7]</sup> The octahedral complex of **1c**/(*R,R*)-DBFOX-Ph/Ni<sup>II</sup> containing a water molecule was optimized by using the PM3 program (Spartan 06)<sup>[8b]</sup> in light of the reported X-ray structure of the (*R,R*)-DBFOX-Ph/Ni<sup>II</sup> complex<sup>[10]</sup> (Figure 2).

The utility of  $\alpha$ -hydroxy malonate **2** was next demonstrated by the synthesis of chlozolinatate (**4**; Scheme 2), an important antifungal agent.<sup>[1a,11]</sup> Previously, (*R*)-**4** was synthe-

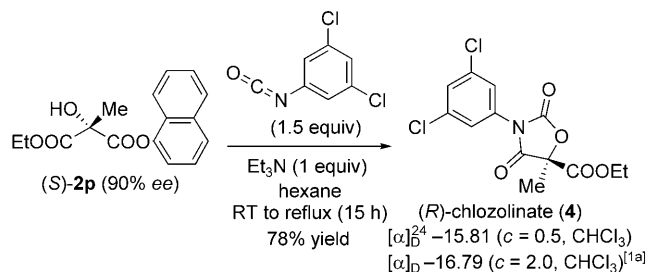


**Figure 1.** Transition-state structure for the  $(R,R)$ -DBFOX-Ph/ $\text{Ni}^{\text{II}}$ -catalyzed enantioselective hydroxylation of **1** to  $(S)$ -**2**.



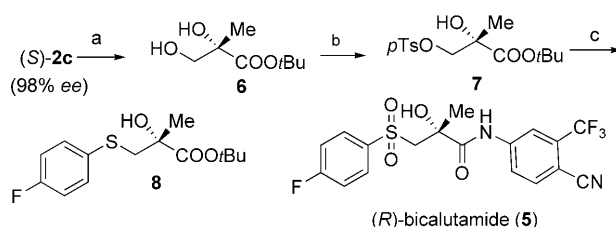
**Figure 2.** Optimized structure of the **1c**/ $(R,R)$ -DBFOX-Ph/ $\text{Ni}^{\text{II}}$  complex.

sized based on enzymatic desymmetrization.<sup>[1a]</sup> However, the synthesis requires multiple-step transformations. Our method allowed access to **4** in only two steps from the racemic malonate **1p** via chiral **2p**. Namely, treatment of  $(S)$ -**2p** (90 % ee) with 3,5-dichlorophenyl isocyanate in the presence of triethylamine afforded enantiomerically enriched  $(R)$ -chlozoline **4**.



**Scheme 2.** Synthesis of  $(R)$ -chlozoline (**4**).

We also considered the synthesis of a key intermediate for the bicalutamide derivatives.<sup>[1b,c,12]</sup> Bicalutamide (**5**; Scheme 3), which is sold under the trade name of Casodex, is a leading antiandrogen used for the treatment of prostate cancer. Bicalutamide is a racemic mixture with most of its activity residing with the  $R$  isomer. The chemoselective reduction of  $(S)$ -**2c** was successfully achieved using  $\text{LiAl}(\text{O}t\text{Bu})_3\text{H}$ <sup>[13]</sup> and gave  $(S)$ -*tert*-butyl-2-hydroxy-2-(hydroxymethyl)propanoate (**6**) in 66 % yield. The primary hydroxy group of **6** was then protected using *p*-toluenesulfonyl chloride and pyridine in  $\text{CHCl}_3$  to give the tosylate **7**. Nucleophilic substitution of **7** by sodium 4-fluorobenzene-



**Scheme 3.** Reagents and conditions: a)  $\text{LiAl}(\text{O}t\text{Bu})_3\text{H}$  (5 equiv), THF,  $-78^\circ\text{C}$  to reflux, 4 h, 66%; b)  $p\text{TsCl}$  (1.5 equiv), pyridine,  $\text{CHCl}_3$ ,  $0^\circ\text{C}$  to RT, 17 h, 49%; c)  $\text{NaH}$  (3 equiv), 4-fluorobenzene-1-thiol (3 equiv), THF,  $0^\circ\text{C}$  to RT, 3 h, 88%.

thiol furnished  $(R)$ -**8**, which should be useful as a common intermediate for the synthesis of  $(R)$ -bicalutamide as well as its derivatives.

In conclusion, we have achieved the first highly enantioselective direct hydroxylation of  $\alpha$ -hydroxy malonate **2** using the  $(R,R)$ -DBFOX/ $\text{Ni}^{\text{II}}$  complex. Based on this strategy, a dynamic kinetic asymmetric transformation in the  $\alpha$ -functionalization of racemic malonate with other electrophiles is now under investigation.

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