


 Cite this: *Chem. Commun.*, 2022, 58, 6886

 Received 4th April 2022,
 Accepted 20th May 2022

DOI: 10.1039/d2cc01936a

rsc.li/chemcomm

Isothiourea-catalyzed formal enantioselective conjugate addition of benzophenone imines to α,β -fluorinated α,β -unsaturated esters†

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The isothiourea-catalyzed formal enantioselective conjugate addition of 2-hydroxybenzophenone imine derivatives to α,β -unsaturated *para*-nitrophenyl esters has been developed. Investigations of the scope and limitations of this procedure showed that β -electron withdrawing substituents within the α,β -unsaturated ester component are required for good product yield, giving rise to a range of β -imino ester and amide derivatives in moderate to good isolated yields with excellent enantioselectivity (20 examples, up to 81% yield and 97:3 er).

The development of methods for the enantioselective synthesis of β -amino acid derivatives^{1a} is of widespread importance due to the prevalence of this structural motif in natural products and medicinally relevant compounds.¹ Among the synthetic methods that have been developed for the preparation of β -amino acid derivatives, arguably the most simple and elegant involves the asymmetric conjugate addition of an ammonia equivalent to an α,β -unsaturated carbonyl motif. As an example of this approach, the conjugate addition of enantiomerically pure lithium amide derivatives to α,β -unsaturated esters has been developed and exploited extensively by Davies and co-workers. Conjugate addition of lithium *N*-benzyl-*N*- α -methylbenzylamide to an α,β -unsaturated ester gives the corresponding β -amino ester with high diastereoselectivity (>95:5 dr), with *N*-deprotection through hydrogenolysis giving the corresponding β -amino ester derivatives (Scheme 1a).²

Over the last two decades, several enantioselective organocatalytic approaches to amine conjugate addition have been introduced. To date, these successful approaches rely upon enals,³ enones,⁴ *N*-acyl pyrazoles,⁵ and nitro-olefins⁶ as Michael acceptors, with the use of bifunctional thiourea^{4a,5b,7,8a-c,e} or squaramide^{4,5c,8a,b,e} organocatalysts, or Lewis basic pyrrolidines^{3,8} commonplace. Catalytic enantioselective amine conjugate additions to α,β -unsaturated esters are rare, reflecting the recognized


 Scheme 1 Synthesis of β -amino ester derivatives.

recalcitrance of α,β -unsaturated esters as Michael acceptors (Scheme 1b). To date, the current state-of-the-art organocatalytic approach is represented by Seidel and co-workers⁹ demonstration of the conjugate addition of cyclic secondary amines to β -alkyl- α,β -unsaturated benzyl esters using a selenourea-thiourea catalyst **1** (Scheme 1c). Although limited to β -alkyl substituted Michael acceptors, this impressive methodology was applicable to a range of cyclic amines and the kinetic resolution of (\pm)-cyclic 2-arylamines.

Our approach to enantioselective amine conjugate addition focused upon the use of imines as nucleophiles. The conjugate addition of (diphenylmethylene)amine to α,β -unsaturated esters, nitriles and ketones in racemic form has been demonstrated by de Meijere *et al.* MeOH was optimal as a solvent and

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 † Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2cc01936a>




Scheme 2 Previous imine conjugate additions and this work.

a basic additive (such as NEt₃) led to effective product formation (Scheme 2a).¹⁰ In 2018, Alemán and co-workers successfully demonstrated an enantioselective aza-Michael addition of nucleophilic imines to enals using secondary amine catalyst **2** (Scheme 2b).¹¹ Trapping of the resultant β -imino aldehydes with a phosphorane gave the corresponding δ -imino esters in good yield and enantioselectivity. Notably, 2-hydroxybenzophenone imines showed increased reactivity and enantioselectivity compared with the parent benzophenone imine, attributed to an increase in acidity of the imine proton caused by intramolecular hydrogen bonding.^{12,13} In previous work, we and others have demonstrated a range of enantioselective Michael-addition processes of *in situ* generated α,β -unsaturated acyl ammonium species.^{14,15} Building on these precedents, we report herein the formal isothiurea-catalyzed enantioselective addition of 2-hydroxybenzophenone imines to β -fluorinated α,β -unsaturated *para*-nitrophenyl esters *via* an α,β -unsaturated acyl ammonium intermediate, giving products in up to 98 : 2 er (Scheme 2c).

Preliminary investigations used β -CF₃-substituted α,β -unsaturated *para*-nitrophenyl ester **4** (1.0 equiv.) in toluene as standard. Given the moderate reactivity of α,β -unsaturated acyl ammonium ions, imine **3** (2.0 equiv.) bearing an electron donor 4-OMe-substituent was postulated to enhance nucleophilicity (Table 1). Attempted isolation of the *para*-nitrophenyl ester product led to low and irreproducible product yields, so addition of pyrrolidine to give the isolable amide **5** was adopted. Screening of isothiurea catalysts **6–8** (10 mol%) at 1 : 2 substrate ratio of ester **4**: imine **3** (entries 1–3) showed that tetramisole **6** and BTM **7** gave promising product yield (~50%) whereas HyperBTM **8** showed poor catalytic activity (<10% yield). Excellent enantioselectivity (96 : 4 er) was observed using BTM **7**. Altering the

Table 1 Reaction optimisation

| Entry | Catalyst (mol%) | Temp. (°C) | Solvent | 3 : 4 | Yield ^a (%) | er ^b |
|-----------------|-----------------|------------|---------------------------------|---------|------------------------|-----------------|
| 1 ^c | 6 (10) | rt | Toluene | 1 : 2 | 50 | 12 : 88 |
| 2 ^c | 7 (10) | rt | Toluene | 1 : 2 | 54 | 96 : 4 |
| 3 ^c | 8 (10) | rt | Toluene | 1 : 2 | <10 | 68 : 32 |
| 4 ^c | 7 (10) | rt | Toluene | 1 : 1.5 | 42 | 95 : 5 |
| 5 ^c | 7 (10) | rt | Toluene | 1.5 : 1 | 38 | 97 : 3 |
| 6 ^c | 7 (10) | 40 | Toluene | 1 : 2 | 52 | 94 : 6 |
| 7 ^c | 7 (10) | 60 | Toluene | 1 : 2 | 47 | 91 : 9 |
| 8 ^c | 7 (2.5) | rt | Toluene | 1 : 2 | <10 | 91 : 9 |
| 9 ^c | 7 (5.0) | rt | Toluene | 1 : 2 | 18 | 96 : 4 |
| 10 ^c | 7 (20) | rt | Toluene | 1 : 2 | 71 ^d | 96 : 4 |
| 11 ^c | 7 (20) | rt | THF | 1 : 2 | 31 | 96 : 4 |
| 12 ^c | 7 (20) | rt | Et ₂ O | 1 : 2 | 30 | 96 : 4 |
| 13 ^c | 7 (20) | rt | CH ₂ Cl ₂ | 1 : 2 | 37 | 96 : 4 |
| 14 ^e | 7 (20) | rt | Toluene | 1 : 2 | 31 | 98 : 2 |
| 15 ^f | 7 (20) | rt | Toluene | 1 : 2 | 42 | 96 : 4 |
| 16 ^g | 7 (20) | rt | Toluene | 1 : 2 | 36 | 96 : 4 |

^a Using ¹H NMR spectroscopic analysis and 1,3,5-trimethoxybenzene as internal standard. ^b Ratio of (R):(S) enantiomers determined by HPLC analysis on a chiral stationary phase. ^c Ar = 4-NO₂C₆H₄. ^d Isolated yield. ^e Ar = 2,4,6-Cl₃C₆H₂. ^f Ar = C₆F₅. ^g Ar = 3,5-(CF₃)₂C₆H₃.

reaction stoichiometry (entries 4 and 5) led to reduced product yield. A detrimental effect on product enantioselectivity (91 : 9 er) was observed when the reaction temperature was increased to 40 °C or 60 °C (entries 6 and 7). Lowering the catalyst loading showed a significant decrease in product yield and enantioselectivity (entries 8 and 9), while using 20 mol% BTM **7** gave increased yield (71% yield, 96 : 4 er, entry 10). Screening of an alternative solvents gave high product enantioselectivity but reduced yields (entries 11–13). Further optimisation probed the effectiveness of alternative electron-deficient aryl esters. Comparison of *para*-nitrophenyl with 2,4,6-trichlorophenyl, pentafluorophenyl, and 3,5-bis(trifluoromethyl)phenyl esters (entries 14–16) showed that excellent enantioselectivities were observed in each case (up to 98 : 2 er), with the *para*-nitrophenyl ester leading to the best product yield (71%).

The scope and limitations of the developed process was explored through variation of the nucleophilic imine reaction component (Fig. 1). Variation of the electronic bias of the 4-aryl substituent within the imine component showed that decreased product yield was observed upon changing from an electron-donating 4-MeO- (**5**, 70% yield) to 4-Me (**9**, 49% yield), 4-H (**11**, 36% yield) and electron-withdrawing 4-Br substituent (**10**, 24% yield) all with >96 : 4 er. This is consistent with increasing





Fig. 1 0.10 mmol scale. Isolated product yield; er determined by HPLC analysis on a chiral stationary phase; [a] 40 °C for step i; [b] DMAP 20 mol% in step ii.

electron density within the imine component leading to increased product yield. Interestingly, comparing the yield and er of products **11** and **12** indicates that the 2-hydroxy-substituent within the imine is essential for high product er, but does not affect product yield. The incorporation of an additional electron-donating 4-MeO substituent led to product **13** in reduced yield but maintained high product er. Variation of the β -substituent within the α,β -unsaturated ester indicated that the incorporation of polyhalogenated or ester electron-withdrawing groups was necessary for reactivity as alkyl, aryl, ketone and amide substituted acceptors gave no significant product formation. For example, the introduction of halogenated (CF_2H) and polyhalogenated



Scheme 3 Gram scale synthesis of product **5**.

substituents (CF_2Cl , CF_2Br , and C_2F_5) led to products **14–17** in up to excellent yields with high enantioselectivity (40% to 81%; >96:4 er), while the incorporation of ester substituents gave **18–19** in poor 20% product yield in up to 96:4 er. Variation of the post catalysis nucleophilic component (Nuc-H) to incorporate alcohols as well as cyclic secondary and acyclic primary amines gave a range of ester and amide products **20–24** in good yield (42% to 64%) and excellent enantioselectivity ($\geq 96:4$ er).

To further demonstrate the synthetic utility of this transformation, it was applied to the gram-scale synthesis of product **5** with consistent yield and enantioselectivity (67%, 96:4 er, Scheme 3). Hydrolysis gave the free β -amino amide product **26** in high yield and enantioselectivity (95%, 96:4 er).¹⁶

A proposed mechanism of this transformation is shown in Scheme 4. Reversible acylation of the isothiourea with the α,β -unsaturated ester **1a** generates the key α,β -unsaturated acyl isothiuronium ion pair **26**.



Scheme 4 Proposed reaction mechanism.



An intramolecular chalcogen 1,5-S··O interaction ($n_{\text{O}} \rightarrow \sigma^*_{\text{S-C}}$)¹⁷ provides a plausible stabilising effect and conformational lock. Hydrogen bonding between the 2-hydroxy-substituent and the imine N serves to conformationally restrict this functionality and facilitate deprotonation.^{11–13} Subsequent conjugate addition to the *s-cis* conformation of the α,β -unsaturated acyl isothiuronium **26 anti-** to the stereodirecting phenyl substituent of the isothiurea catalyst generates the ammonium enolate intermediate **27**. Proton transfer generates the β -imino acyl isothiuronium intermediate **28**, with catalyst turnover facilitated by the aryloxide counterion to form the product and release the isothiurea catalyst BTM **7**.¹⁸

In summary, enantioselective organocatalytic conjugate addition of 2-hydroxybenzophenone imines to α,β -unsaturated esters using the isothiurea BTM as an organocatalyst gives enantioenriched β -imino amides in modest to good yield (20–81%) and excellent enantioselectivity (typically >95:5 er).¹⁹

The DOST-SEI and DOST-Foreign Graduate Scholarship Program of the Philippines are thanked for a PhD scholarship (J. E. L.) and the Royal Society for a Newton Fellowship (C. S.).

Conflicts of interest

There are no conflicts of interests to declare.

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