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Cu(I)−NHC Catalyzed Asymmetric Silyl Transfer to Unsaturated Lactams and Amides

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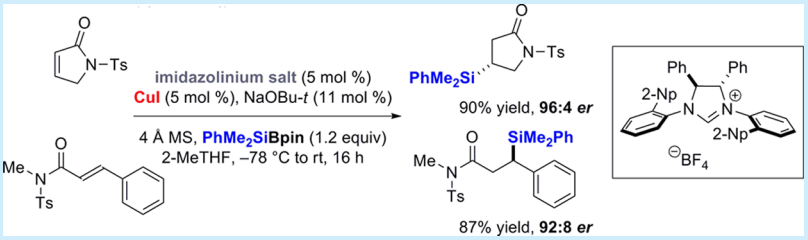
Supporting Information



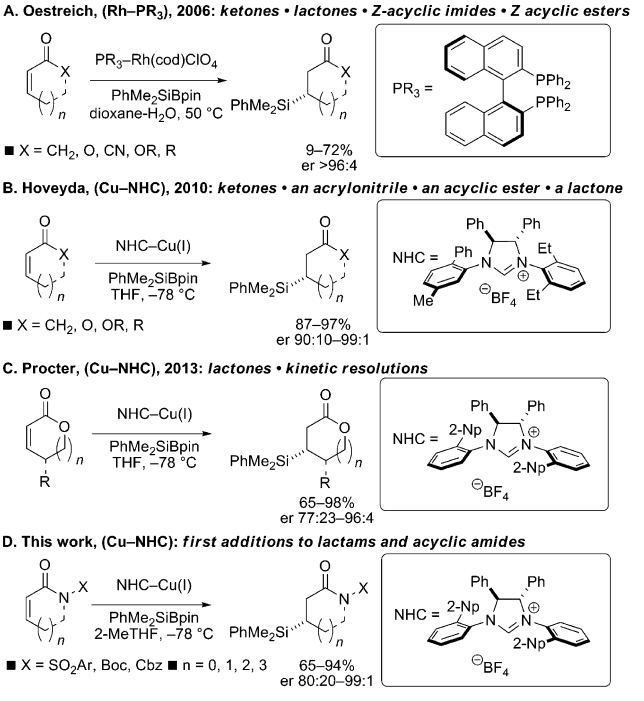
ABSTRACT: The first asymmetric silylation of unsaturated lactams and amides using Cu(I)−NHC catalysts and $PhMe_2SiBpin$ has been accomplished. The method has been exploited in an expedient asymmetric synthesis of the (*R*)-enantiomer of the nootropic drug oxiracetam.

Silicon directly connected to an asymmetric carbon atom is a versatile functional group in organic synthesis.[1] Since the pioneering studies by Fleming and Tamao, the motif is widely used as a stereodefined placeholder for the hydroxyl group.[2] α-Chiral silanes are also valuable substrates in C−C bond-forming reactions.[3] These applications have stimulated studies into the installation of the silicon group in an enantioselective fashion. Inspired by Fleming's conjugate addition of silylcuprates,[2a−c,g,4] Hayashi's seminal Pd-catalyzed 1,4-disilylation of enones represented a breakthrough although the procedure has clear limitations in scope.[5] A major development in the field was achieved by Oestreich who exploited the activation of the Si−B bond in Suginome's $PhMe_2SiBpin$ reagent[6] by Rh(I)-phosphine catalysts in efficient asymmetric silyl transfer to cyclic and acyclic α,β-unsaturated ketones, esters, imides, and lactones[7] (Scheme 1A). In a further major advance, Hoveyda recently reported Cu(I)−NHC (*N*-heterocyclic carbene)[8] catalyzed activation of the Si−B bond in $PhMe_2SiBpin$ in asymmetric silyl transfer to cyclic and acyclic α,β-unsaturated ketones with single examples of additions to an acrylonitrile, acyclic ester, and lactone (Scheme 1B).[9]

Hoveyda found that NHC ligands derived from C_1-symmetric imidazolinium salts gave the best results.[9a] We have since studied the asymmetric silyl transfer to unsaturated lactones, which are challenging substrates for these transformations, using Hoveyda's protocol and a C_2-symmetric NHC ligand.[10,11] Furthermore, we reported the kinetic resolution of racemic 5-substituted butenolides mediated by Cu(I)−NHC silyl transfer from $PhMe_2SiBpin$ (Scheme 1C).[11,12]

The importance of aza-heterocyclic motifs in natural products and biologically active compounds led us to consider whether an analogous Cu(I)−NHC-catalyzed asymmetric silyl transfer could be applied for the first time to α,β-unsaturated lactams. As highlighted recently by Alexakis, such substrates are problematic Michael acceptors and present a significant challenge for the development of new methods.[13] In fact, the

Scheme 1. Asymmetric Silyl Transfer from $PhMe_2SiBpin$ to α,β-Unsaturated Carbonyls: (A) Rh-Catalyzed Transfer, (B) Cu-Catalyzed Transfer, (C) Cu-Catalyzed Transfer to Lactones, and (D) This Work



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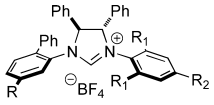
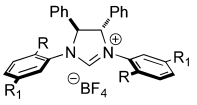
nonasymmetric silylcuprate addition to lactams remains essentially unexplored.[14] Analogous additions of silicon nucleophiles to acyclic amides are known, but asymmetric variants rely on chiral auxiliary control[15,16] and the development of a catalytic asymmetric variant represents a significant challenge. Here we report our investigations on the Cu(I)–NHC-catalyzed silyl asymmetric transfer to α,β-unsaturated lactams and amides (Scheme 1D). The method has been used in the catalytic asymmetric synthesis of the (*R*)-enantiomer of the nootropic drug oxiracetam.

We selected pyrrolidinone **1** bearing an electron-withdrawing protecting group on nitrogen as our model substrate. The use of C_1-symmetric imidazolinium **L1**, a salt that has previously been employed successfully in conjugate silyl transfer to carbocyclic substrates (Table 1, entry 1),[9a] gave low enantiocontrol.

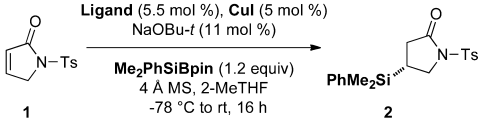
Table 1. Screening of NHC–Cu(I) Complexes in Silyl Transfer to Lactam 1 (conv 89–99% by ^{1}H NMR)



C_1-symmetric imidazolinium salts **L1-L5**



C_2-symmetric imidazolinium salts **L6-L10**



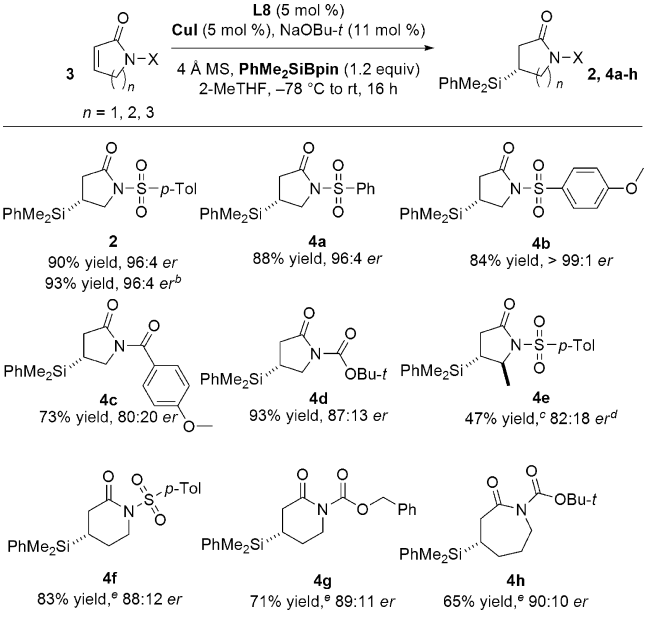
entry	ligand	type	R	R_1	R_2	*er*
1	**L1**	C_1	Me	Et	H	62:38
2	**L2**	C_1	H	Et	H	64:36
3	**L3**	C_1	*i*-Pr	Et	H	54:46
4	**L4**	C_1	H	Me	Me	69:31
5	**L5**	C_1	Me	Me	Me	65:35
6	**L6**	C_2	H	Ph	–	93:7
7	**L7**	C_2	Me	Ph	–	83:17
8	**L8**	C_2	**2-naphthyl**	**H**	–	**96:4**[a]
9	**L9**	C_2	2-naphthyl	*i*-Pr	–	58:42
10	**L10**	C_2	2-anthryl	H	–	94:6
11	**L8**	C_2	2-naphthyl	H	–	93:7[b]

[a]90% Isolated yield. [b]THF was used as the solvent.

Modification of the aryl substituents on nitrogen in a series of C_1-symmetric imidazolinium salts did not increase the enantioinduction (Table 1, entries 2–5). A significant improvement was achieved upon switching from C_1-symmetric to C_2-symmetric ligands (entries 6–11). Pleasingly, the use of imidazolinium salt **L8**, which provided the best results for 5-membered lactone substrates,[10,11] proved to be optimal for asymmetric silyl transfer to pyrrolidinone **1**, and **2** was formed in 90% yield and with an *er* of 96:4. In the study, 2-MeTHF was used as an attractive alternative to THF,[17] although the use of THF gave very similar yields and selectivity (Table 1, entry 8 vs 11). Attractively, the experimental protocol does not require the use of a glovebox.

With optimized conditions in hand, we next studied the scope of the reaction (Scheme 2). Five-membered lactam substrates bearing an arylsulfonyl substituent on nitrogen underwent efficient asymmetric silyl transfer to give β-silyl adducts **2**, **4a**, and **4b** in high yield and with an *er* up to >99:1. Importantly, the catalytic asymmetric silyl transfer could be scaled up and was

Scheme 2. Cu(I)–NHC Catalyzed Asymmetric Silyl Transfer to 5-, 6-, and 7-Membered Unsaturated Lactams[a]



[a]Yields are for isolated products. [b] Reaction run on a 5.0 mmol scale. [c] 0.70 equiv of $Me_2PhSiBpin$ used. [d] Selectivity factor, s = 9. [e] **L1** was used in place of **L8**.

performed without loss of efficiency on a 5.0 mmol scale (formation of **2** from **1**). Increasing the steric demand of the arylsulfonyl substituent led to a decrease in yields and the level of enantiocontrol.[18] Substrates bearing *p*-methoxybenzoyl and *tert*-butoxycarbonyl groups on nitrogen underwent high yielding silyl transfer although enantioselectivities were lower (<87:13 *er*) (**4c** and **4d**). In line with our observations on Cu–NHC catalyzed silyl transfer to racemic lactone substrates,[11] the kinetic resolution of racemic lactams was also possible: **4e** was obtained in 47% yield (maximum 50%) and 82:18 *er*. (The added steric congestion caused by the methyl substituent in the 5-position of the pyrrolidinone unit causes a drop in enantioselectivity.) When a substrate bearing a less activating phenyl substituent on nitrogen was investigated, a dramatic decrease in conversion and enantioselectivity was observed.[19] Importantly, imidazolinium salt **L8** gave the best yields and selectivities for all of the 5-membered lactam substrates studied (cf. Table 1).

In contrast, for 6-membered lactam substrates, Hoveyda's C_1-symmetric imidazolinium salt **L1**[9a] gave the best results: asymmetric silyl transfer gave *N*-tosylpiperid-2-one **4f** and *N*-Cbz-piperid-2-one **4g** in good yields and with selectivities up to 89:11 *er*. A similar observation was made in the preparation of *N*-Boc-caprolactam **4h** (65% yield, 90:10 *er*) using imidazolinium salt **L1**. These results clearly show that the ring size and the identity of the activating nitrogen substituent in lactam substrates are crucial when selecting the ligand for the asymmetric silyl transfer.

We next extended the protocol to linear *N*-tosyl α,β-unsaturated amides.[20] Pleasingly, employing imidazolinium salt **L8** gave efficient silyl transfer, and good levels of enantioinduction were observed (up to 92:8 *er*) (Scheme 3). The process was found to be compatible with substrates bearing β-aryl, heteroaryl, and alkyl substituents on the electron-deficient alkene.[21]

The synthetic value of the protocol was showcased in an expedient asymmetric synthesis of the (*R*)-enantiomer of

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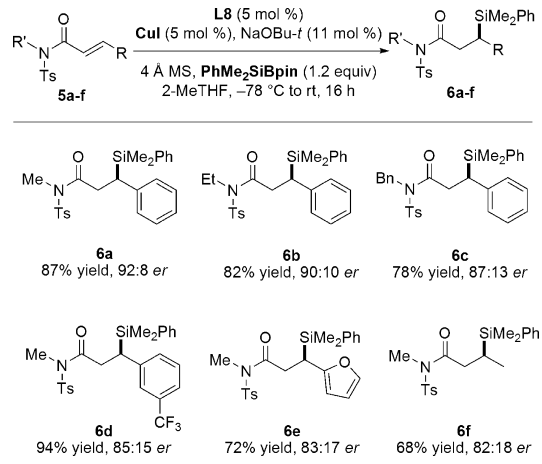
Scheme 3. Cu(I)−NHC Catalyzed Asymmetric Silyl Transfer to *N*-Tosyl *α,β*-Unsaturated Amides[a]

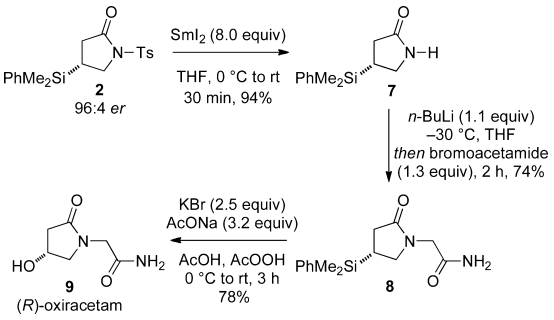


[a]Yields are for isolated products.

oxiracetam, a nootropic drug employed in the treatment of diseases related to Alzheimer's.[22]

Thus, lactam **2**, the product of Cu(I)−NHC asymmetric silyl transfer, underwent efficient removal of the *N*-tosyl group upon treatment with SmI_2 (Scheme 4).[23] The resulting *N*-H lactam **7**

Scheme 4. Asymmetric Synthesis of (*R*)-Oxiracetam



underwent *N*-alkylation to give **8** in 74% yield. Subsequent oxidation under Fleming−Tamao conditions[24] gave (*R*)-oxiracetam (α_D = +34.2 (*c* = 1.0, H_2O); lit. + 36.4 (*c* = 1.0, H_2O))[22] in 78% yield (Scheme 4).

In summary, the first Cu(I)−NHC catalyzed asymmetric silyl transfer from $PhMe_2SiBpin$ to unsaturated lactams and amides gives the corresponding *β*-silylated lactams and amides in good yields and enantioselectivities. While C_2-symmetric NHC ligands give the best results for 5-membered lactams and acyclic amides, C_1-symmetric NHC ligands work best for 6- and 7-membered lactam substrates. The protocol has been exploited in a short asymmetric synthesis of (*R*)-oxiracetam.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures, characterization data, ^1H and ^{13}C spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Reviews: (a) Oestreich, M.; Hartmann, E.; Mewald, M. *Chem. Rev.* **2013**, *113*, 402. (b) Hartmann, E.; Vyas, D. J.; Oestreich, M. *Chem. Commun.* **2011**, 7917. (c) Suginome, M.; Ito, Y. *Chem. Rev.* **2000**, *100*, 3221. (d) Hartmann, E.; Oestreich, M. *Chim. Oggi* **2011**, *29*, 34.

(2) (a) Ager, D. J.; Fleming, I. *J. Chem. Soc., Chem. Commun.* **1978**, 177. (b) Fleming, I.; Henning, R.; Plaut, H. *J. Chem. Soc., Chem. Commun.* **1984**, 29. (c) Fleming, I.; Sanderson, P. E. J. *Tetrahedron Lett.* **1987**, *28*, 4229. (d) Tamao, K.; Ishida, N.; Tanaka, T.; Kumada, M. *Organometallics* **1983**, *2*, 1694. (e) Tamao, K.; Tanaka, T.; Nakajima, T.; Sumiya, R.; Arai, H.; Ito, Y. *Tetrahedron Lett.* **1986**, *27*, 3377. For selected reviews, see: (f) Fleming, I.; Barbero, A.; Walter, D. *Chem. Rev.* **1997**, *97*, 2063. (g) Fleming, I. In *Science of Synthesis*; Fleming, I., Ed.; Thieme: Stuttgart, 2002; Vol. *4*; pp 927−946.

(3) Xu, L.-W.; Li, L.; Lai, G.-Q.; Jiang, J.-X. *Chem. Soc. Rev.* **2011**, *40*, 1777.

(4) Alternative approaches to racemic *β*-silyl carbonyl derivatives: (a) Iannazzo, L.; Molander, G. A. *Eur. J. Org. Chem.* **2012**, 4923. (b) Lipshutz, B. H.; Sclafani, J. A.; Takanami, T. *J. Am. Chem. Soc.* **1998**, *120*, 4021. (c) Auer, G.; Weiner, B.; Oestreich, M. *Synthesis* **2006**, 2113. (d) Ito, H.; Ishizuka, T.; Tateiwa, J.-i.; Sonoda, M.; Hosomi, A. *J. Am. Chem. Soc.* **1998**, *120*, 11196. (e) Clark, C. T.; Lake, J. F.; Scheidt, K. A. *J. Am. Chem. Soc.* **2004**, *126*, 84. (f) Oestreich, M.; Weiner, B. *Synlett* **2004**, 2139. (g) Calderone, J. A.; Santos, W. L. *Org. Lett.* **2012**, *14*, 2090. (h) Xuan, Q.-Q.; Zhong, N.-J.; Ren, C.-L.; Liu, L.; Wang, D.; Chen, Y.-J.; Li, C.-J. *J. Org. Chem.* **2013**, *78*, 11076.

(5) (a) Matsumoto, Y.; Hayashi, T.; Ito, Y. *Tetrahedron* **1994**, *50*, 335. (b) Hayashi, T.; Matsumoto, Y.; Ito, Y. *J. Am. Chem. Soc.* **1988**, *110*, 5579.

(6) Reviews of Si-B chemistry: Ohmura, T.; Suginome, M. *Bull. Chem. Soc. Jpn.* **2009**, *82*, 29 and ref 1a.

(7) (a) Walter, C.; Auer, G.; Oestreich, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 5675. (b) Walter, C.; Oestreich, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 3818. (c) Walter, C.; Fröhlich, R.; Oestreich, M. *Tetrahedron* **2009**, *65*, 5513. (d) Hartmann, E.; Oestreich, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 6195. (e) Hartmann, E.; Oestreich, M. *Org. Lett.* **2012**, *14*, 2406.

(8) NHCs in metal catalysis: (a) Díez-González, S.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612. (b) Díez-González, S.; Nolan, S. P. *Aldrichimica Acta* **2008**, *41*, 43. (c) Glorius, F. *Topics in Organometallic Chemistry, N-Heterocyclic Carbenes in Transition Metal Catalysis*; Springer-Verlag: Berlin, Heidelberg, 2006; Vol. *21*, pp 1−218.

(9) (a) Lee, K.-S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2010**, *132*, 2898. (b) Lee, K.-S.; Wu, H.; Haeffner, F.; Hoveyda, A. H. *Organometallics* **2012**, *31*, 7823. Metal-free, NHC-catalyzed C−Si bond formation: (c) O'Brien, J. M.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2011**, *133*, 7712. For asymmetric allylic silylation using a Cu(I)−NHC system and $PhMe_2SiBpin$: (d) Delvos, L. B.; Vyas, D. J.; Oestreich, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 4650.

(10) Harb, H. Y.; Collins, K. D.; Altur, J. V. G.; Bowker, S.; Campbell, L.; Procter, D. J. *Org. Lett.* **2010**, *12*, 5446.

(11) Pace, V.; Rae, J. P.; Harb, H. Y.; Procter, D. J. *Chem. Commun.* **2013**, *49*, 5150.

(12) For alternative asymmetric approaches to *β*-silyl carbonyl compounds, see: (a) Ibrahem, I.; Santoro, S.; Himo, F.; Córdova, A. *Adv. Synth. Catal.* **2011**, *353*, 245. (b) Welle, A.; Petrignet, J.; Tinant, B.; Wouters, J.; Riant, O. *Chem.—Eur. J.* **2010**, *16*, 10980. (c) Lipshutz, B. H.; Tanaka, N.; Taft, B. R.; Lee, C.-T. *Org. Lett.* **2006**, *8*, 1963. (d) Shintani, R.; Okamoto, K.; Hayashi, T. *Org. Lett.* **2005**, *7*, 4757. (e) Kacprzynski, M. A.; Kazane, S. A.; May, T. L.; Hoveyda, A. H. *Org. Lett.* **2007**, *9*, 3187.

(13) (a) Cottet, P.; Müller, D.; Alexakis, A. *Org. Lett.* **2013**, *15*, 828. For selected examples of the use of α,β-unsaturated lactams in conjugate asymmetric additions with different nucleophiles, see: (b) Senda, T.; Ogasawara, M.; Hayashi, T. *J. Org. Chem.* **2001**, *66*, 6852 (arylboron reagents). (c) Gini, F.; Hessen, B.; Feringa, B. L.; Minnaard, A. J. *Chem. Commun.* **2007**, 710 (arylsiloxanes). (d) Smith, A. J.; Abbott, L. K.; Martin, S. F. *Org. Lett.* **2009**, *11*, 4200 (2-heteroarylzinc reagents). (e) Jin, S.-S.; Wang, H.; Xu, M.-H. *Chem. Commun.* **2011**, 7230 (arylboronic acids). (f) Pineschi, M.; Del Moro, F.; Gini, F.; Minnaard, A. J.; Feringa, B. L. *Chem. Commun.* **2004**, 1244 (organozinc and organoaluminum reagents).

(14) (a) Fleming, I.; Reddy, N. L.; Takaki, K.; Ware, A. C. *J. Chem. Soc., Chem. Commun.* **1987**, 1472. (b) Hagen, T. J. *Synlett* **1990**, 63. (c) Silylzinc additions: Barrett, A. G. M.; Head, J.; Smith, M. L.; Stock, N. S.; White, A. J. P.; Williams, D. J. *J. Org. Chem.* **1999**, *64*, 6005. See also ref 14a.

(15) Auxiliary-controlled asymmetric silyl additions to α,β-unsaturated amides: (a) Crump, R. A. N. C.; Fleming, I.; Urch, C. J. *J. Chem. Soc., Perkin Trans. 1* **1994**, 701. (b) Palomo, C.; Aizpurua, J. M.; Iturburu, M.; Urchegui, R. *J. Org. Chem.* **1994**, *59*, 240. (c) Fleming, I.; Jones, G. R.; Kindon, N. D.; Landais, Y.; Leslie, C. P.; Morgan, I. T.; Peukert, S.; Sarkar, A. K. *J. Chem. Soc., Perkin Trans. 1* **1996**, 1171. (d) Fleming, I.; Mwaniki, J. M. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1237. (e) Ahmar, M.; Duyck, C.; Fleming, I. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2721. (f) Dambacher, J.; Bergdahl, M. *J. Org. Chem.* **2005**, *70*, 580.

(16) For auxiliary-controlled asymmetric Cu-catalyzed silyl transfer from $PhMe_2SiBpin$ to α,β-unsaturated amides, see ref 12b.

(17) For selected reviews, see: (a) Pace, V.; Hoyos, P.; Castoldi, L.; Domínguez de María, P.; Alcántara, A. R. *ChemSusChem* **2012**, *5*, 1369. (b) Aycock, D. F. *Org. Process Res. Dev.* **2007**, *11*, 156.

(18) Addition to 1-naphthylsulfonyl substituted pyrrolidinone gave product in 53% yield and 78:22 *er*.

(19) Addition to *N*-phenyl substituted pyrrolidinone gave product in 11% yield and 68:32 *er*.

(20) For an example of a nonasymmetric conjugate addition of organometallics (RLi and RMgX) to *N*-tosyl α,β-unsaturated amides, see: Nagashima, H.; Ozaki, N.; Washiyama, M.; Itoh, K. *Tetrahedron Lett.* **1985**, *26*, 657.

(21) The use of primary and secondary amides (*i.e.*, NH_2 and NHTs) resulted in no conversion.

(22) Miyamoto, S.; Mori, A. *Neurosciences* **1985**, *11*, 1.

(23) Straightforward preparation of SmI_2: (a) Szostak, M.; Spain, M.; Procter, D. J. *J. Org. Chem.* **2012**, *77*, 3049. N-Ts deprotection using the reagent: (b) Knowles, H.; Parsons, A. F.; Pettifer, R. M. *Synlett* **1997**, 271. Selected reviews on the use of SmI_2 in organic synthesis: (c) Procter, D. J.; Flowers, R. A., II; Skrydstrup, T. *Organic Synthesis Using Samarium Diiodide: A Practical Guide*; RSC Publishing: Cambridge, 2009. (d) Szostak, M.; Procter, D. J. *Angew. Chem., Int. Ed.* **2012**, *51*, 9238. (e) Szostak, M.; Spain, M.; Procter, D. J. *Chem. Soc. Rev.* **2013**, *42*, 9155.

(24) Ferrarini, R. S.; Dos Santos, A. A.; Comasseto, J. V. *Tetrahedron* **2012**, *68*, 10601 and references cited therein. See also ref 2.