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Synthesis of Secondary Amides from Thiocarbamates

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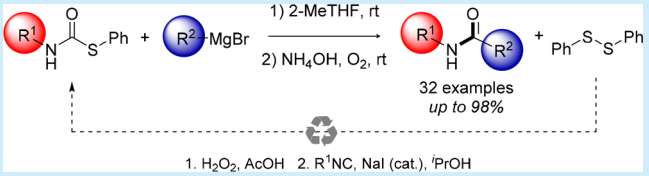
Supporting Information

ABSTRACT: The synthesis of secondary amides from readily accessible and bench-stable substituted *S*-phenyl thiocarbamates and Grignard reactants is reported. Oxidative workup allows recycling of the thiolate leaving group as diphenyl disulfide. Diphenyl disulfide can be transformed into *S*-phenyl benzenethiosulfonate, a reactant required for thiocarbamate synthesis. This amide synthesis is suitable for the preparation of challenging amides that are not or hardly accessible via classical approaches.



Amide bond formation is one of the most important reactions in organic synthesis. Amide bonds are essential to all biological systems, as they connect all amino acid building blocks to form proteins. Amide bonds also appear in a variety of natural products. Moreover, they are key structural motifs in several pharmaceuticals (e.g., lidocaine, roflumilast, atorvastatin), agrochemicals (e.g., boscalid), and polymers (e.g., nylon, chitin).[1] Amides were present in 24% of all drugs in the top 200 prescription list of 2016[2] and appeared in 60% of the newly approved drugs of 2017.[3] Traditional methods for amide synthesis are based on the coupling of amines with activated carboxylic acid derivatives. In the past decades, a plethora of stoichiometric coupling agents have been developed for the *in situ* activation of carboxylic acids.[1,4] These methods have been successful for a variety of amides, but the coupling agents are often toxic and generate a large quantity of waste, which is not always (easily) separable and typically not recoverable into the reactant. For this reason, these classical amide bond formation reactions do not score well in the context of green chemistry. As an alternative approach, amine activation has been introduced. To date, however, only a few procedures have been reported that involve the transformation of an amine into an isothiourea,[5] isocyanide,[6] iminophosphorane,[7] or *N*-(imidazolylcarbonyl)-amine.[8] Recently, several (boron-based) organo- and transition metal catalysts have also been explored to achieve the direct amidation of carboxylic acids with amines.[1c,9] However, simultaneous removal of water is required to achieve full conversion. Many other interesting procedures have been developed from precursors other than amines and/or carboxylic acids,[1d] such as transamidation,[10] catalytic amidation of unactivated esters,[1d,11] coupling of (activated) thioacids with amines[6b] or azides,[12] catalytic oxidative amidation of aldehydes,[1d,13] oxidation of *in situ*-generated aminals from alcohols and amines,[14] aminocarbonylation of alkenes or alkynes,[15] and iodonium-promoted nitroalkane-amine coupling.[16]

Despite the large number of reported methods, the majority of known amide syntheses are unfortunately not suitable for preparing challenging amides derived from sterically hindered carboxylic acids and electron-deficient and/or sterically hindered amines. This is illustrated for *N*-(1-adamantyl)-2,4,6-trimethylbenzamide (**4a**) and *N*-mesityl-2,4,6-trimethylbenzamide (**4k**). The classical approaches based on coupling/activating agents (CDI, COMU, DCC, EDC, HATU, PyBOP, T_3P) generally fail for these amide types, and therefore, their synthesis remains a challenge (see section 2 in the Supporting Information (SI)). To date, only four synthetic procedures have been reported for the synthesis of such challenging amides (Scheme 1). The Bode group reported a strategy for the synthesis of secondary amides based on the addition of Grignard reactants to isocyanates[17] or *N*-carboxyanhydrides (NCAs) (route A).[18] Although this approach proved effective for the preparation of sterically hindered and electron-deficient amides, the involvement of very reactive and unstable isocyanates is a drawback (SI section 3).[19] The Ulven group developed a method for the coupling of sterically hindered carboxylic acids with hindered or electron-deficient amines via *in situ* formation of acyl fluorides at elevated temperatures and in halogenated solvents (route B).[20] As part of our research program on amide-bond-forming reactions, we recently developed two routes for sterically hindered amides.[5,21] In the first approach, readily available and stable *N*-*tert*-butyl alkane- and (hetero)arenecarboxamidamides[22] are transformed into secondary amides via oxidative rearrangement with $PhI(OCOR^1)_2$ (route C).[21] Although very challenging amides can be obtained and the produced iodobenzene (PhI) waste can be recycled, this approach still requires the synthesis of the specific carboxylic acid-derived hypervalent iodine coupling reactant $PhI(OCOR^1)_2$, which is a drawback.[23] Our second approach is based on the use of isothiourea intermediates as

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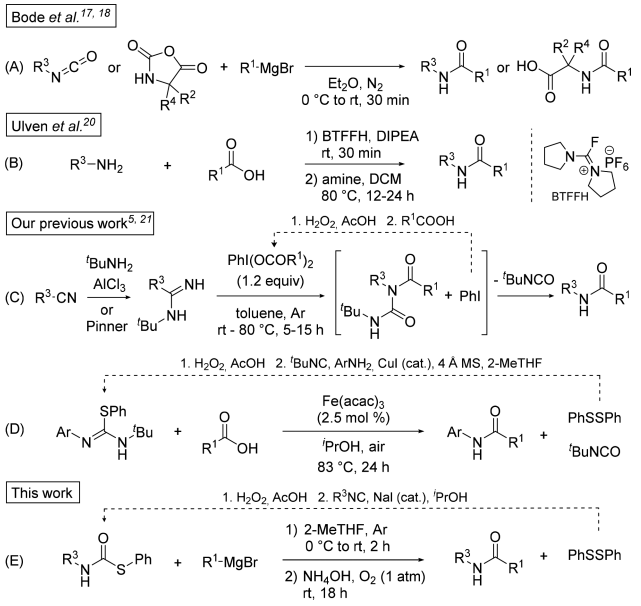
Scheme 1. Strategies for Sterically Hindered and/or Electron-Deficient Secondary Amides

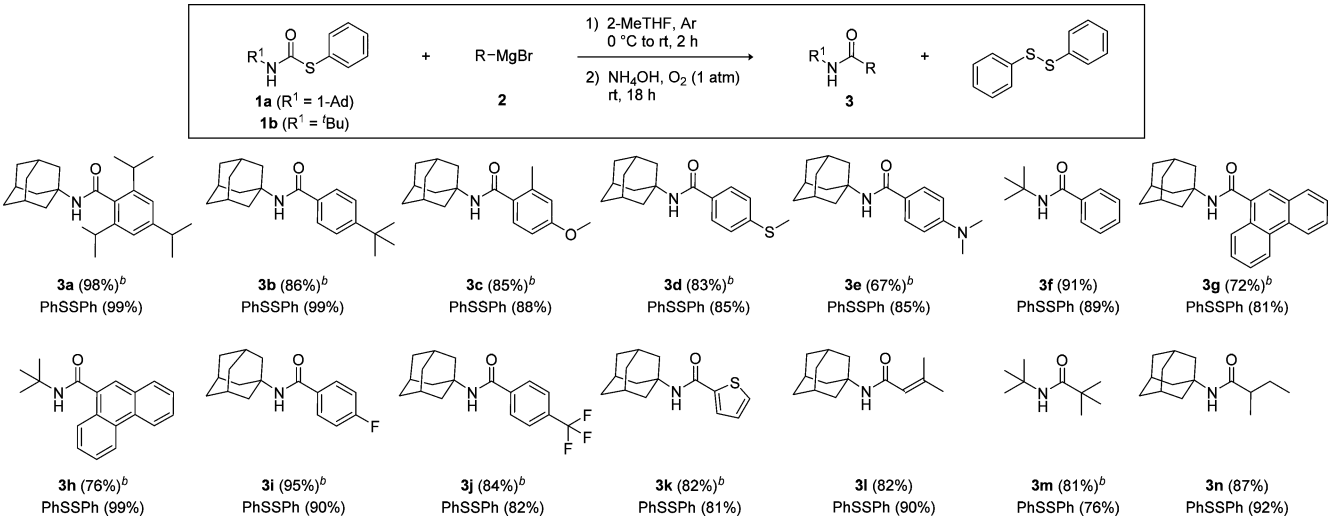


activated amines (route D).[5] The protocol is suitable for the synthesis of very challenging sterically hindered *N*-(hetero)-arylamides under mild reaction conditions, of which the (hetero)aromatic amine moiety can also be electron-deficient. Unfortunately, our three-component reaction toward isothioureas[24] does not tolerate aliphatic amines, so the corresponding *N*-alkylamides could not be obtained via this second approach. We therefore envisioned an alternative strategy for challenging amides based on the addition of Grignard reactants to thiocarbamates (route E). Both *N*-alkyl- and *N*-(hetero)arylthiocarbamates can be easily prepared under very mild reaction conditions via an iodide-catalyzed three-component reaction of readily available isocyanides, thiosulfonates, and isopropanol recently reported by our group.[25] In addition to being readily accessible, thiocarbamates are bench-stable, and thermogravimetric analysis confirmed their thermal stability (SI section 3).

S-Phenyl (1-adamantyl)thiocarbamate (**1a**) and *S*-phenyl *tert*-butylthiocarbamate (**1b**) were selected as model sterically hindered electrophiles. The addition of various Grignard reactants **2** to **1a** or **1b** was examined to obtain both aromatic and aliphatic secondary amides **3** (Scheme 2). The Grignard reactants **2** were either used as commercial solutions in THF or formed *in situ* from the corresponding alkyl or aryl bromides and Mg turnings in 2-MeTHF. After the addition of the Grignard reactant at 0 °C and slow warming to room temperature over 2 h, all of the reactions reached full conversion of thiocarbamate **1a** or **1b**. 2-MeTHF was selected as a solvent over THF and diethyl ether on the basis of a green solvent selection guide.[26] Interestingly, the waste resulting from the thiophenolate leaving group could be recovered as diphenyl disulfide (PhSSPh) by quenching the reaction with an aqueous ammonium hydroxide solution and stirring it for 18 h under an oxygen atmosphere (Scheme 2). The recovered diphenyl disulfide can subsequently be easily transformed into *S*-phenyl benzenethiosulfonate by selective oxidation (e.g., with H_2O_2/AcOH),[27] which can then be used as a reactant for the synthesis of thiocarbamates **1**.[25] The results in Scheme 2 show that all of the *N*-adamantyl and *N*-*tert*-butyl(hetero)-arenecarboxamides **3** were obtained in good yield, irrespective of the electronic nature and sterics of the (hetero)aromatic Grignard reactant **2**. Interestingly, vinylic and aliphatic Grignard reactants were also tolerated, as exemplified by **2l**, **2m**, and **2n**.

Next, the scope of our protocol for amide synthesis was evaluated for various substituted *S*-phenyl thiocarbamates **1** with mesitylmagnesium bromide (**2o**) as the coupling partner, as it represents a very hindered nucleophile (Scheme 3). We were pleased to observe that *N*-(1-adamantyl)-2,4,6-trimethyl-benzamide (**4a**) could be isolated in 93% yield, as this

Scheme 2. Reaction of *S*-Phenyl (1-Adamantyl)thiocarbamate (1a) or *S*-Phenyl *tert*-Butylthiocarbamate (1b) with Grignard Reactants 2[a]



[a]Reaction conditions: **1a** (0.5 mmol) or **1b** (0.25 mmol), **2** (2.2 equiv), 2-MeTHF (2 mL, dry), argon, 0 °C to rt, 2 h, then NH_4OH (3 mL), O_2 (balloon, 1 atm), rt, 18 h. Isolated yields are shown. [b]*In situ* formation of the Grignard reactant from the corresponding alkyl or aryl bromide and Mg turnings.

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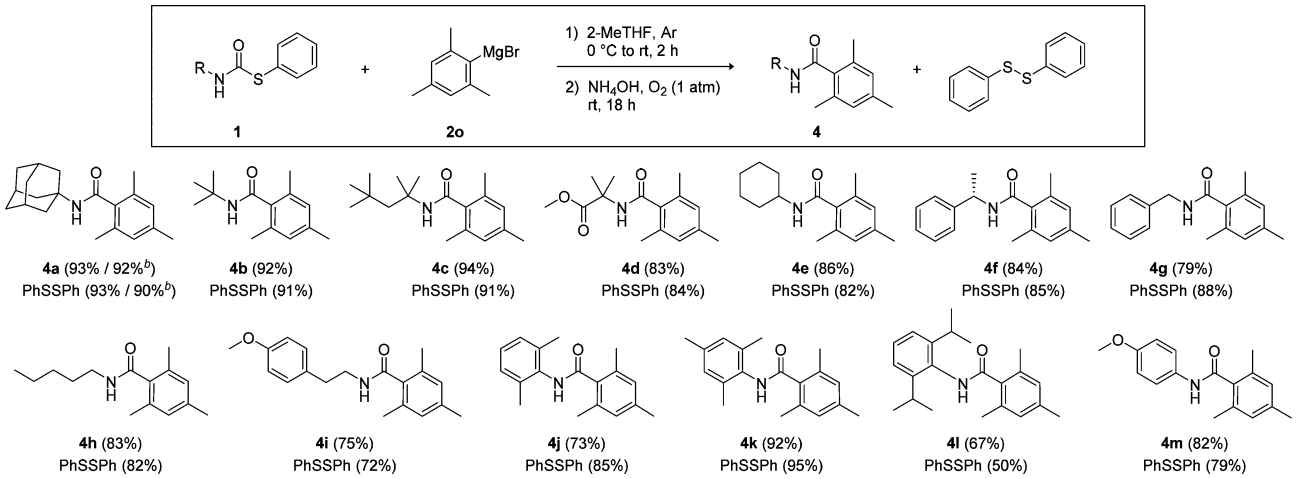
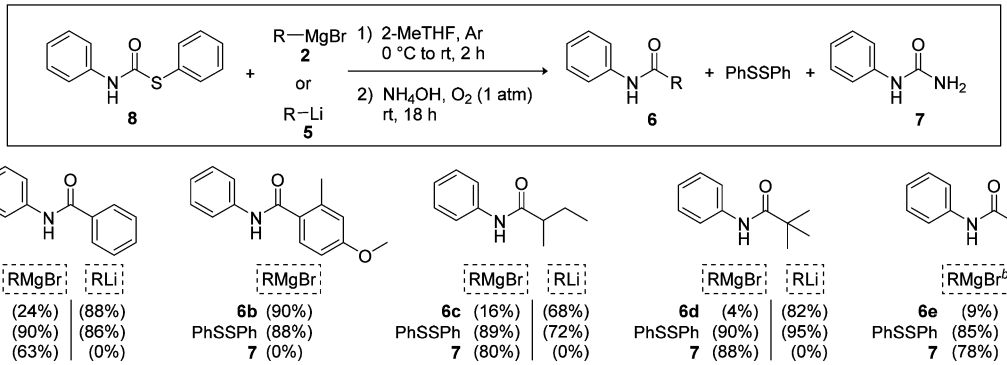
Scheme 3. Reaction of Various Substituted *S*-Phenyl Thiocarbamates 1 with Mesitylmagnesium Bromide (2o)[a]



[a]Reaction conditions: **1** (0.25 mmol), **2o** (1 M in THF, 550 μL, 0.55 mmol), 2-MeTHF (2 mL, dry), argon, 0 °C to rt, 2 h, then NH_4OH (3 mL), O_2 (balloon, 1 atm), rt, 18 h. Isolated yields are shown. [b]Reaction at the 5 mmol scale.

Scheme 4. Reaction of *N,S*-Diphenylthiocarbamate (8) with Grignard (2) or Organolithium Reactants (5)[a]



[a]Reaction conditions: **8** (0.50 mmol), **2** or **5** (1.1 mmol), 2-MeTHF (2 mL, dry), argon, 0 °C to rt, 2 h, then NH_4OH (3 mL), O_2 (balloon, 1 atm), rt, 18 h. Isolated yields are shown. [b]In situ formation of the Grignard reactant from the corresponding alkyl bromide and Mg turnings.

substrate could not be prepared in an efficient manner using classical coupling reagents (SI section 2). Amide **4a** could also easily be synthesized at the gram (5 mmol) scale without loss in yield. Other tertiary *N*-substituents on the thiocarbamate are generally well-tolerated, as was further illustrated for *tert*-butyl (**1b**), 2,4,4-trimethylpentan-2-yl (**1c**), and 3-methoxy-3-oxo-2-methylpropan-2-yl (**1d**) moieties. The corresponding amides **4b**, **4c**, and **4d** were obtained in high yield. This method is also fully compatible with secondary (**1e**, **1f**) and primary (**1g**–**i**) *N*-substituents, yielding **4e**–**i**, respectively. Interestingly, the reaction with thiocarbamates **1f** and **1g** featuring relatively acidic benzylic methylene functionalities delivered the corresponding products (*S*)-2,4,6-trimethyl-*N*-(1-phenylethyl)benzamide (**4f**) and *N*-benzyl-2,4,6-trimethylbenzamide (**4g**) in good yield. Pleasingly, a methoxy moiety (**1i** and **1m**) or even an ester moiety (**1d**) in the thiocarbamate coupling partner did not hamper the reaction. Finally, *S*-phenyl arylthiocarbamates **1j**–**m**, even the very sterically hindered ones **1j**–**l**, were well-tolerated.

When phenylmagnesium bromide (**2f**), *tert*-butylmagnesium bromide (**2m**), *sec*-butylmagnesium bromide (**2n**), and *n*-butylmagnesium bromide (**2p**) were coupled with *N,S*-diphenylthiocarbamate (**8**), surprisingly, only low yields of amides **6a**, **6c**, **6d**, and **6e** were obtained (Scheme 4), although diphenyl disulfide was isolated in good yield. Instead, *N*-phenylurea (**7**) was obtained in high yield. Both diphenyl disulfide and **7** are formed by decomposition of the thiocarbamate substrate with ammonium hydroxide during the workup.[28] We therefore examined the use of more nucleophilic organolithium reactants (**5**) in this amide-bond-forming strategy. Pleasingly, amides **6a** and **6c**–**e** were obtained in good yield when **8** was treated with phenyllithium (**5a**), *sec*-butyllithium (**5c**), *tert*-butyllithium (**5d**), and *n*-butyllithium (**5e**), respectively. Interestingly, it was not always necessary to use organolithiums, as exemplified by the successful reaction of 4-methoxy-2-methylphenylmagnesium bromide (**2c**) with **8**. Our methodology toward secondary amides requires 2 equiv of the Grignard reactant, of which one acts as a sacrificial base. When the Grignard reactant is derived from an expensive alkyl or aryl bromide, it would be better to use a cheaper base instead. The synthesis of **4b** was therefore selected as a model reaction to check the feasibility of premixing several bases (DBU, KHMDS, ^{n}BuLi, ^{t}BuLi, and ^{t}BuMgCl) with 1.1 equiv of mesitylmagnesium bromide (**2o**) prior to the addition of thiocarbamate **1b** (SI section 4). Pleasingly, with 1 equiv of readily available ^{t}BuMgCl as a sacrificial base, *N*-(*tert*-butyl)-2,4,6-trimethylbenzamide (**4b**) was isolated in high yield without the formation of *N*-*tert*-

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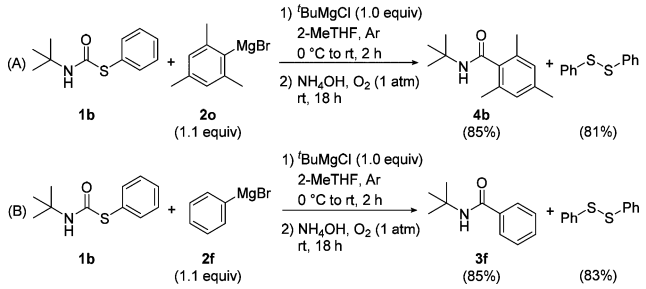
Scheme 5. Addition of Grignard Reactants (2f, 2o) to *S*-Phenyl *tert*-Butylthiocarbamate (1b) using *tert*-Butylmagnesium Chloride as a Sacrificial Base



butylpivalamide (**3m**) as a side product (Scheme 5, route A). Finally, this modified procedure was also successfully applied for the synthesis of *N*-*tert*-butylbenzamide (**3f**) using a combination of less sterically hindered phenylmagnesium bromide (**2f**) and ^{t}BuMgCl.

In summary, we have demonstrated that secondary amides can be obtained from easily accessible thiocarbamates and Grignard reactants. A combination of ^{t}BuMgCl as a sacrificial base with only 1 equiv of Grignard reactant can also be used when the latter is expensive. This protocol allows the synthesis of (sterically and electronically) challenging amides, which are not or hardly accessible via classical approaches. Recovery of the thiophenolate leaving group from *S*-phenyl thiocarbamate substrates as diphenyl disulfide reduces waste production, as diphenyl disulfide is readily transformed into *S*-phenyl benzenethiosulfonate, which is a reactant for the three-component reaction yielding *S*-phenyl thiocarbamate substrates.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b01654.

Classical coupling reagents, thermogravimetric analysis, experimental procedures, characterization of new compounds and spectral data (PDF)

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Author Contributions

All of the authors have approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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■ DEDICATION

This work is dedicated to Prof. Gordon W. Gribble on the occasion of his retirement from Dartmouth College in recognition of his outstanding scientific achievements, educational commitment, and service to the heterocyclic chemistry community.

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(28) Reaction of thiocarbamates with amines gives urea (see SI section 5).

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