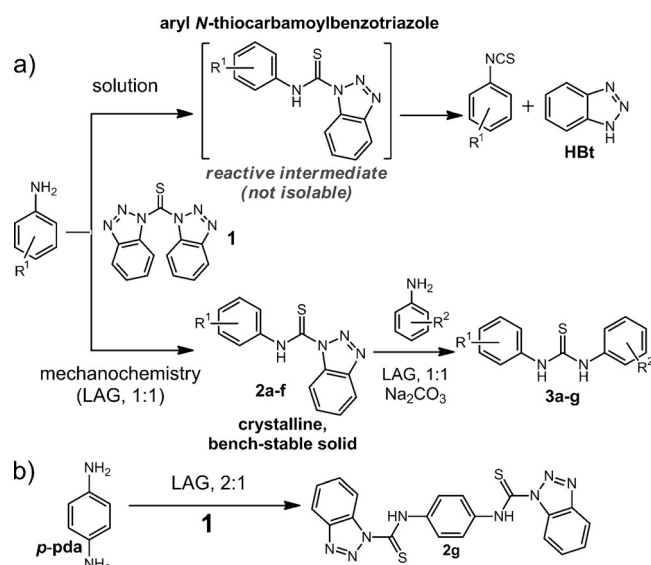


# Trapping Reactive Intermediates by Mechanochemistry: Elusive Aryl *N*-Thiocarbamoylbenzotriazoles as Bench-Stable Reagents\*\*

Vjekoslav Štrukil,\* Davor Gracin, Oxana V. Magdysyuk, Robert E. Dinnebier, and Tomislav Friščić\*

**Abstract:** Monitoring of mechanochemical thiocarbamoylation by in situ Raman spectroscopy revealed the formation of aryl *N*-thiocarbamoylbenzotriazoles, reactive intermediates deemed unisolable in solution. The first-time isolation and structural characterization of these elusive molecules demonstrates the ability of mechanochemistry to access otherwise unobtainable intermediates and offers a new range of masked isothiocyanate reagents.

Mechanochemistry has emerged as an efficient means for rapid, solvent-free, and energy-efficient synthesis.<sup>[1]</sup> In organic synthesis,<sup>[2]</sup> neat and liquid-assisted grinding (LAG)<sup>[3]</sup> has provided rapid and clean access to a number of transformations, excellent control of reaction stoichiometry, and previously unknown reactivity.<sup>[4–6]</sup> We now demonstrate the ability of mechanochemistry to access reactive intermediates considered unisolable in solution. We describe the first synthesis and isolation of aryl *N*-thiocarbamoylbenzotriazoles (**2a–g**, Scheme 1) as bench-stable solids by milling bis(benzotriazolyl)methanethione (**1**)<sup>[7]</sup> with anilines (Table 1). Mechanochemical isolation of **2a–g** allows their



**Scheme 1.** a,b) In contrast to solution chemistry,<sup>[14–16]</sup> mechanochemical reactions of **1** and anilines give *N*-thiocarbamoylbenzotriazoles (**2a–g**) as stable solids which, upon milling with anilines and a base, afford thioureas (**3a–g**).

[\*] Dr. V. Štrukil, Prof. T. Friščić  
Department of Chemistry, McGill University  
801 Sherbrooke Street West, Montreal, H3A 0B8 (Canada)  
E-mail: tomislav.frischic@mcgill.ca

Dr. V. Štrukil, Dr. D. Gracin  
Ruđer Bošković Institute  
Bijenička cesta 54, 100002 Zagreb (Croatia)  
E-mail: vstrukil@irb.hr

Dr. O. V. Magdysyuk, Prof. Dr. R. E. Dinnebier  
Max Planck Institute for Solid State Research  
Heisenbergstrasse 1, 70569 Stuttgart (Germany)

Dr. O. V. Magdysyuk  
Diamond Light Source Ltd.  
Harwell Science and Innovation Campus, OX11 0DE Didcot (UK)

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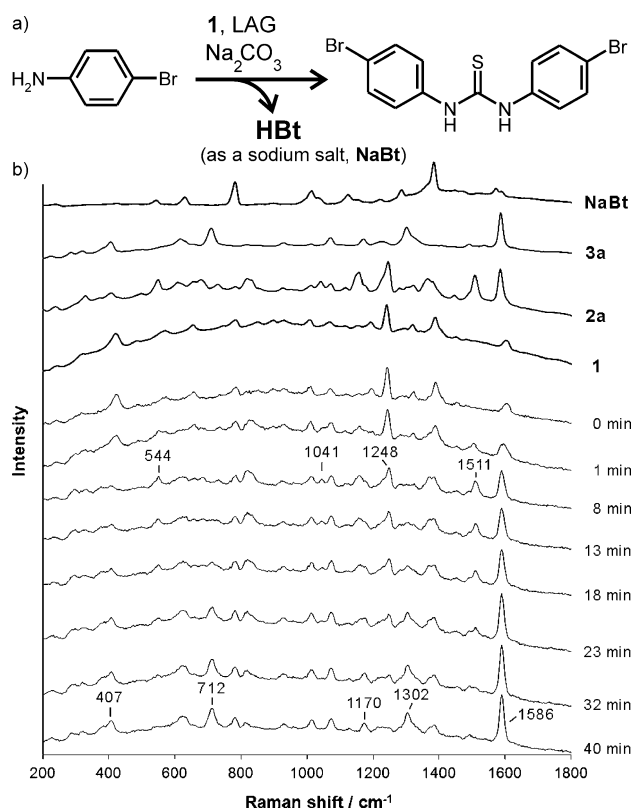
**Table 1:** LAG synthesis of aryl *N*-thiocarbamoylbenzotriazoles **2a–g** and thioureas **3a–g**.<sup>[a]</sup>

| Compound                 | R <sup>1</sup>     | R <sup>2</sup>     | Yield of isolated product [%] |
|--------------------------|--------------------|--------------------|-------------------------------|
| <b>2a</b>                | 4-Br               | –                  | 99                            |
| <b>2b</b>                | 4-Cl               | –                  | 98                            |
| <b>2c</b>                | 4-CH <sub>3</sub>  | –                  | 98                            |
| <b>2d</b>                | 4-OCH <sub>3</sub> | –                  | 99                            |
| <b>2e</b>                | 2-NH <sub>2</sub>  | –                  | 98                            |
| <b>2f</b>                | 4-NH <sub>2</sub>  | –                  | 99                            |
| <b>2g</b> <sup>[b]</sup> | 4-NH <sub>2</sub>  | –                  | 99                            |
| <b>3a</b>                | 4-Br               | 4-Br               | 97 <sup>[c]</sup>             |
| <b>3b</b>                | 4-Cl               | 4-Cl               | 97                            |
| <b>3c</b>                | 4-CH <sub>3</sub>  | 4-CH <sub>3</sub>  | 98                            |
| <b>3d</b>                | 4-OCH <sub>3</sub> | 4-OCH <sub>3</sub> | 98                            |
| <b>3e</b>                | 4-OCH <sub>3</sub> | 4-Cl               | 97 <sup>[d]</sup>             |
| <b>3f</b>                | 4-Cl               | 4-Br               | 99 <sup>[c,d]</sup>           |
| <b>3g</b>                | 4-Br               | 2-NH <sub>2</sub>  | 98 <sup>[d,e]</sup>           |

[a] 10 min LAG with CH<sub>3</sub>CN ( $\eta = 0.25 \mu\text{L mg}^{-1}$ ), 10 mm ball. [b] 2 equiv of **1**. [c] 45 min LAG. [d] Two-step synthesis. [e] 30 min LAG.

use as reagents for the controlled solvent-free synthesis of thioureas (**3a–g**) without using corrosive isothiocyanates.

As part of our interest in the mechanosynthesis of ureas and thioureas,<sup>[8,9]</sup> we applied the recently introduced technique of in situ Raman spectroscopy monitoring of mecha-



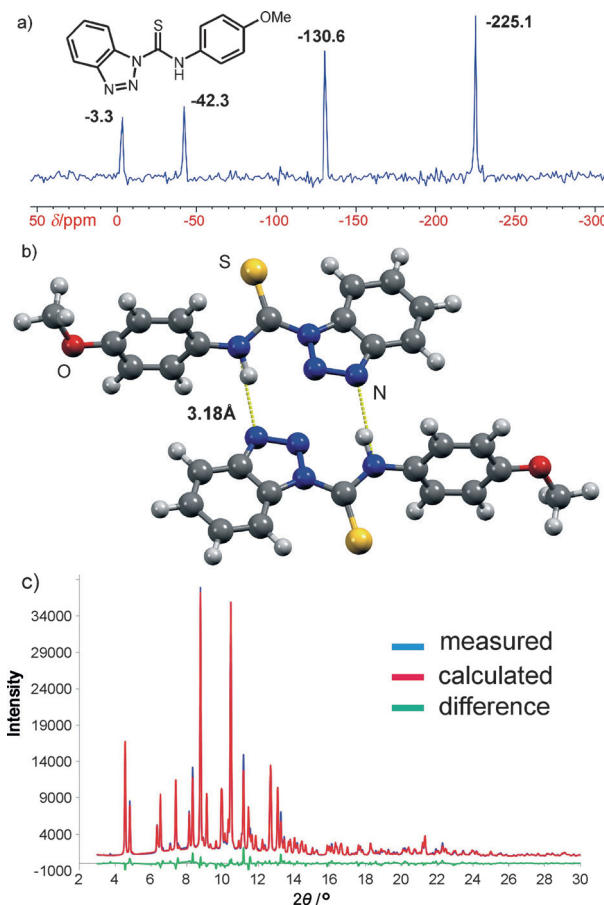
**Figure 1.** a) Mechanochemical base-assisted reaction of **1** and *p*-bromoaniline to form the thiourea **3a** and b) in situ collected Raman spectra for this reaction.

nochemical reactions<sup>[10–13]</sup> to the mechanochemistry of **3a** by milling **1** with two equivalents of 4-bromoaniline in the presence of  $\text{Na}_2\text{CO}_3$  (Figure 1a). While **1** is a known reagent for base-catalyzed thioacylations and thiocarbamoylations in solution,<sup>[7,14]</sup> thereby giving benzotriazole (HBt) as a by-product, its mechanochemical reactivity is still unexplored. Monitoring the reaction in situ reveals that characteristic bands of **1** are completely replaced with those of **3a** (e.g. 407, 712, 1170, 1302  $\text{cm}^{-1}$ , Figure 1b) within 40 min. A characteristic band of the by-product HBt sodium salt also appears at 1380  $\text{cm}^{-1}$ . However, the spectra also revealed an unknown intermediate with bands at 544, 1041, 1159, 1248, and 1511  $\text{cm}^{-1}$ , appearing about 2 min into milling and disappearing concomitantly with the appearance of **3a**.

Katritzky et al. proposed that **1** reacts with anilines in solution via reactive aryl *N*-thiocarbamoylbenzotriazole intermediates that are not isolable due to their rapid fragmentation into isothiocyanates (Scheme 1).<sup>[14–16]</sup>

Speculating that the herein observed intermediate might be the elusive *N*-thiocarbamoylbenzotriazole, we repeated the milling without a base, and with only one equivalent of aniline. Under these conditions the intermediate was obtained as the only product (see the Supporting Information). Solution  $^1\text{H}$  NMR spectroscopy and thin-layer chromatography revealed this product deteriorates quickly in organic solvents into HBt and 4-bromophenylisothiocyanate. However, a  $^1\text{H}$  NMR spectrum recorded immediately after dissolution was consistent with the generation of *N*-thiocar-

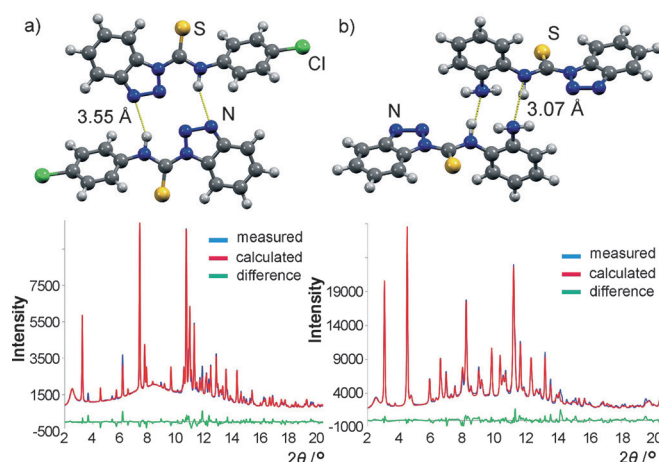
bamoylbenzotriazole **2a** (Scheme 1, Table 1). Intrigued by the possibility of mechanochemically accessing such elusive molecules, we conducted LAG of **1** with a series of substituted anilines (Table 1, Scheme 1a,b). In all cases, LAG followed by simple aqueous washing gave crystalline solids, which were identified as *N*-thiocarbamoylbenzotriazoles **2a–g** by cross-polarization magic angle spinning (CP-MAS)  $^{13}\text{C}$  and  $^{15}\text{N}$  solid-state NMR spectroscopy (SSNMR, Figure 2a), ther-



**Figure 2.** a)  $^{15}\text{N}$  NMR CP-MAS SSNMR spectrum of **2d**; b) a centrosymmetric pair of **2d** molecules in the crystal structure, based on PXRD data; and c) final Rietveld fit for the crystal-structure determination of **2d** by PXRD.

mogravimetric analysis (TGA), differential scanning calorimetry (DSC), and, where possible, structure determination from synchrotron powder X-ray diffraction (PXRD) data (Figure 2b,c and Figure 3a–d). Solid-state characterization was mandated by the instability of **2a–g** in solution: the  $^1\text{H}$  NMR spectra in  $\text{CDCl}_3$ ,  $[\text{D}_6]\text{DMSO}$ , or  $\text{CD}_3\text{CN}$  reveals degradation to isothiocyanates in minutes (see the Supporting Information). The 2-amino derivative **2e** decomposed in solution into 2-mercaptobenzimidazole (**4**) and HBt. In contrast, the compounds were stable in the solid state: FTIR-ATR spectra of mechanochemically prepared **2a–d** did not change after storage for more than 1 year.<sup>[17]</sup>

The CP-MAS  $^{13}\text{C}$  SSNMR spectra of **2a–g** reveal the signal of the thiocarbonyl group shifted downfield by about 2–



**Figure 3.** Centrosymmetric arrangement of molecules (top) and the final Rietveld fits (bottom) for the crystal structures of a) **2b** and b) **2e**, determined from PXRD data.

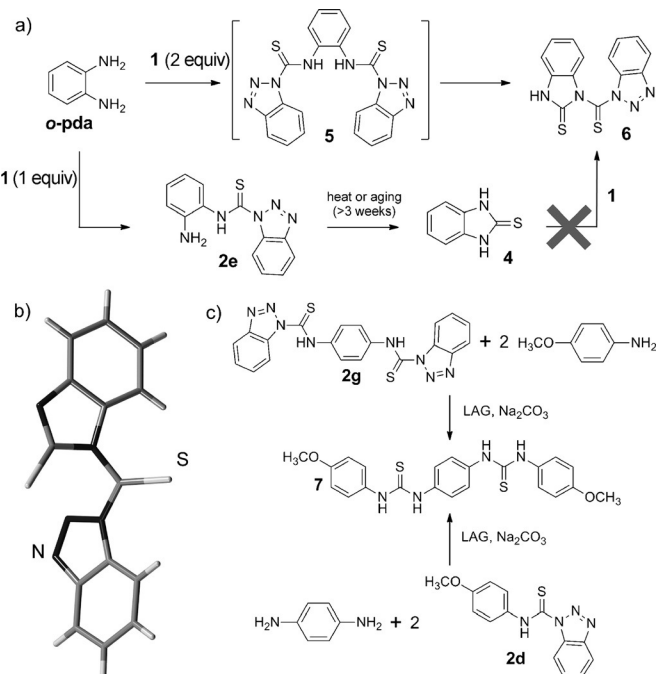
5 ppm relative to that of **1**. The spectrum of **2f** reveals signal twinning, thus suggesting  $Z' = 2$ .<sup>[18]</sup> With the exception of **2f**, the  $^{13}\text{C}$  SSNMR spectra for all the compounds are consistent with one molecule per asymmetric unit ( $Z' = 1$ ).

The  $^{15}\text{N}$  CP-MAS SSNMR spectra of **2d** and **2g** (Figure 2a, see also the Supporting Information) showed four signals, consistent with four non-equivalent nitrogen atoms per molecule. TGA shows **2a–d** to be stable to approximately 120 °C, with the first decomposition event corresponding to elimination of aryl isothiocyanate, followed by loss of HBT. DSC of **2a–d** reveals a melting signal at 90–105 °C. Compound **2e** also undergoes an exothermic event at 92 °C, as a result of cyclization to **4** with loss of HBT, as confirmed by TGA and PXRD (see the Supporting Information). Crystal structures of **2b**, **2d**, and **2e** were determined from synchrotron PXRD data collected at the Canadian Light Source (CLS) beamline 08B1-1 ( $\lambda = 0.6897 \text{ \AA}$ ). Indexing gave monoclinic unit cells with  $Z = 4$ . Determination of the structure using TOPAS revealed  $Z' = 1$ , in agreement with SSNMR spectroscopic analysis. **2d**, **2b**, and **2e** are nonplanar, with the angle between the phenyl and benzotriazolyl substituents being 83°, 65°, and 86°, respectively. The thione and benzotriazole groups are nearly coplanar in all cases. The molecules form centrosymmetric pairs with long N–H...N interactions between the thiocarbamoyl group and benzotriazole (**2b**, **2d**) or 2-aminophenyl (**2e**) groups of neighboring molecules (Figures 2 and 3).

Amino-substituted *N*-thiocarbamoylbenzotriazoles, such as **2e** and **2f**, are attractive as precursors for catalytically interesting aminothiureas<sup>[19]</sup> and amino-substituted isothiocyanates. Both **2e** and **2f** were readily obtained by milling **1** with one equivalent of either *ortho*- (*o*-pda) or *para*-phenylenediamine (*p*-pda). The  $^1\text{H}$  NMR spectrum of **2f** in  $[\text{D}_6]\text{DMSO}$  reveals rapid decomposition to the tentatively identified *p*-aminophenyl isothiocyanate (see the Supporting Information).<sup>[20]</sup> Although stable for weeks, solid **2f** slowly degrades on prolonged standing, as shown by  $^1\text{H}$  NMR and FTIR-ATR spectroscopy.

The bis-*N*-thiocarbamoylbenzotriazole **2g** was quantitatively obtained by LAG of *p*-pda with two equivalents of

**1** (Scheme 1b). Attempted analogous synthesis of the bis-*N*-thiocarbamoylbenzotriazole **5** from *o*-pda and two equivalents of **1** yielded the bisthiourea **6**, probably as a result of an intramolecular cyclization of the expected product (Figure 4a,b, see also the Supporting Information). The alter-



**Figure 4.** a) Mechanochemical reaction of *o*-pda with **1** in a 1:1 stoichiometric ratio yields **2e** (which slowly degrades into **4**) and milling in 1:2 ratio affords **6**, most likely by intramolecular cyclization of the expected **5**. b) Molecular structure of **6** from single-crystal X-ray diffraction. c) The use of mechanochemically prepared aryl *N*-thiocarbamoylbenzotriazoles as masked isothiocyanates.

native path, cyclization of **2e** into **4** followed by reaction with **1**, was dismissed because **1** and **4** do not react on milling.

Compounds **2a–d** represent masked aryl isothiocyanates that are useful in thiourea mechanosynthesis. Milling **2a–d** with anilines and  $\text{Na}_2\text{CO}_3$  gave **3a–g** in near quantitative yields (Table 1). Symmetrical **3a–d** were also obtained by milling **1** with two equivalents of an aniline and  $\text{Na}_2\text{CO}_3$ , while nonsymmetrical **3e–g** were obtained by a two-step one-pot procedure from **1**, thus confirming the structures of **2a–d**. Similarly, **2g** allows the synthesis of bisthioureas: milling **2g** with *p*-anisidine and  $\text{Na}_2\text{CO}_3$  gave **7** quantitatively after 3 h. The same product was obtained in 98% yield by milling **2d** and *p*-pda with  $\text{Na}_2\text{CO}_3$  for 45 min (Figure 4c).

In summary, real-time monitoring revealed the utility of mechanochemistry to trap and quantitatively synthesize molecules too reactive to access in solution. Solid-state analysis enabled the first structural, physical, and chemical identification of aryl thiocarbamoylated benzotriazoles and, in combination with structure determination from PXRD data, full structural characterization of members of this compound family. In addition to providing a new family of bench-stable thiocarbamoylation reagents, this also estab-



lishes mechanochemistry as a means to circumvent solvent-induced limitations of traditional synthesis.

## Experimental Section

In a typical experiment, 200 mg of an equimolar mixture of **1** and a substituted aniline was milled for 10 min with dry CH<sub>3</sub>CN (50  $\mu$ L,  $\eta = 0.25 \text{ mL mg}^{-1}$ )<sup>[3]</sup> with a 10 mm stainless-steel ball in a Retsch MM400 mill at 30 Hz. The crude mixture was meticulously scraped from the jar and suspended in 10 mL distilled water by vigorous stirring for 30 min. The solid was filtered off, washed, and dried in air. **1** and **6** were also characterized by <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy as well as single-crystal X-ray diffraction. See the Supporting Information for PXRD, FTIR, SSNMR, TGA/DSC, TLC, MS, solution degradation, and in situ monitoring data.

Crystallographic data: **1**: monoclinic,  $P2_1/c$ ,  $a = 8.747(5)$ ,  $b = 7.370(5)$ ,  $c = 19.079(12)$  Å,  $V = 1228.6(13)$  Å<sup>3</sup>,  $Z = 4$ ,  $R_1 = 0.0338$ ,  $wR_2 = 0.0814$  (1795 data,  $I \geq 2\sigma$ ); **6**: triclinic,  $P\bar{1}$ ,  $a = 7.1962(11)$ ,  $b = 7.8855(12)$ ,  $c = 12.7962(19)$  Å,  $\alpha = 98.710(2)$ ,  $\beta = 104.144(2)$ ,  $\gamma = 93.099(2)^\circ$ ,  $V = 692.85(18)$  Å<sup>3</sup>,  $Z = 2$ ,  $R_1 = 0.0484$ ,  $wR_2 = 0.0987$  (1861, with  $I \geq 2\sigma$ ); **2b**: monoclinic,  $P2_1/n$ ,  $a = 21.7933(7)$ ,  $b = 14.7693(9)$ ,  $c = 3.9624(1)$  Å,  $\beta = 97.125(3)^\circ$ ,  $V = 1265.5(1)$  Å<sup>3</sup>,  $Z = 4$ ,  $R_{\text{exp}} = 0.40\%$ ,  $R_p = 2.73\%$ ,  $R_{\text{wp}} = 3.84\%$ ; **2d**: monoclinic,  $P2_1/n$ ,  $a = 17.6266(8)$ ,  $b = 8.9650(4)$ ,  $c = 8.6183(5)$  Å,  $\beta = 100.034(4)^\circ$ ,  $V = 1341.1(1)$  Å<sup>3</sup>,  $Z = 4$ ,  $R_{\text{exp}} = 2.00\%$ ,  $R_p = 4.98\%$ ,  $R_{\text{wp}} = 6.46\%$ ; **2e**: monoclinic,  $P2_1/c$ ,  $a = 13.0760(3)$ ,  $b = 12.0177(7)$ ,  $c = 8.1421(9)$  Å,  $\beta = 98.25(2)^\circ$ ,  $V = 1266.3(3)$  Å<sup>3</sup>,  $Z = 4$ ,  $R_{\text{exp}} = 1.64\%$ ,  $R_p = 3.85\%$ ,  $R_{\text{wp}} = 5.53\%$ . CCDC 1050984 (**1**), 1050985 (**6**), 1050986 (**2b**), 1050987 (**2d**), and 1050988 (**2e**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).

**Keywords:** mechanochemistry · reactive intermediates · thiocarbamoylation · thiourea

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