



HAL
open science

d -Glucose: An Efficient Reducing Agent for a Copper(II)-Mediated Arylation of Primary Amines in Water

Maud Bollenbach, Patrick Wagner, Pedro Aquino, Jean-Jacques Bourguignon, Frédéric Bihel, Christophe Salomé, Martine Schmitt

► **To cite this version:**

Maud Bollenbach, Patrick Wagner, Pedro Aquino, Jean-Jacques Bourguignon, Frédéric Bihel, et al.. d -Glucose: An Efficient Reducing Agent for a Copper(II)-Mediated Arylation of Primary Amines in Water. ChemSusChem, 2016, 9 (22), pp.3244-3249. 10.1002/cssc.201600801 . hal-02368856

HAL Id: hal-02368856

<https://hal.science/hal-02368856>

Submitted on 28 Jan 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

D-glucose : An efficient reducing agent for a Cu(II) mediated arylation of primary amines in water

Maud Bollenbach,^[a] Patrick Wagner,^[a] Pedro Aquino,^[a,b] Jean-Jacques Bourguignon,^[a] Frédéric Bihel,^[a] Christophe Salomé^[a,c] and Martine Schmitt*^[a]

Abstract: A copper-catalyzed Ullmann-type amination with primary amines in water is reported using a combination of Cu(OTf)₂, dipivaloylmethane and D-glucose. The mild conditions, the use of

inexpensive catalyst and renewable feedstock (D-glucose, TPGS-750-M) make this protocol a safe and convenient strategy for efficient of C-N bonds formations.

Introduction

Transition metal-catalyzed reactions have a prominent place in the arsenal of synthetic chemists.^[1] These reactions have traditionally been carried out in conventional organic solvents. Currently, the design of sustainable protocols involving green catalysis is emphasized.^[2] The use of water as a solvent has many advantages because it is the most economical, safe and environmentally friendly solvent.^[3] The presence of micelles formed *via* non-ionic amphiphile polyoxyethanyl- α -tocopheryl succinate (TPGS-750-M) helps solubilize the organic reagents.^[4a] The viability of this surfactant-promoted chemistry was demonstrated by Lipshutz *et al.* Indeed, since 2008, they reported the use of this new methodology for metathesis^[4] and important cross-coupling reactions such as Suzuki-Miyaura,^[4a,d-e,5] Heck,^[4d-f,6] C-H activation,^[4a,e] Sonogashira^[4a,7] and Buchwald-Hartwig reactions.^[4a,e,8] Recently, our group further investigated the Buchwald-Hartwig reaction^[9] since the formation of the C-N bond is one of the most useful reaction types in medicinal chemistry and materials science.^[10] Thus we reported a universal catalytic system for Buchwald-Hartwig reactions acting under micellar conditions.^[11] However, industrial use of these methods may be limited by the high cost, rarefaction and toxicity of palladium. As an alternative, copper-based Ullmann aminations attracted our attention due to their low cost, low toxicity and the high abundance of copper.

Copper-mediated arylation was discovered several decades before the Buchwald-Hartwig reaction, but its use was limited for a long time due to several drawbacks that restrict its industrial application. Indeed, originally, it required stoichiometric amounts of copper, high reaction temperatures and high-boiling point polar

solvents.^[12] Moreover, the scope of the reaction was also restricted to electron-poor aromatic substrates.^[13a-c] In 2001, the discovery of new copper/bidentate ligand systems led to a spectacular renewed interest in Ullmann reactions.^[10b,13] The milder conditions of the new copper-catalyzed aminations enlarged the scope in terms of substrate tolerance, chemoselectivity and enantioselectivity.^[13e, 14] Despite the emergence of green chemistry, the copper-catalyzed coupling reactions using water as solvent have been rarely described. Only few examples of copper-catalyzed *N*-arylation in aqueous media have been reported with heterocyclic amines,^[15a-l] aliphatic amines,^[15g-h,l,n] amino acids^[15h,m] or ammonia^[15n-o]. To be efficient, these reactions required temperatures between 80 °C and 130 °C. Herein, we describe an efficient and highly selective copper-catalyzed *N*-arylation or heteroarylation with primary amines under micellar conditions at much lower temperature (room temperature (*rt* = 25 °C) or 50 °C).

Results and Discussion

In our initial screening experiments, 3-iodotoluene **1a** and 3-phenylpropylamine **2** were used as a prototypical substrates to establish the most suitable conditions (Figure 1). Seven commercially available classical ligands such as β -diketones, diamines or phenanthroline were tested using CuI (10%) as the catalyst. NaOt-Bu was selected as a suitable base, and the reactions were carried out in water supplemented with the TPGS-750-M (2 wt%) as the surfactant. In the absence of ligand (W/L), no reaction was observed, while the nitrogen-based ligands (L3-L7) were poorly active or inactive. Both β -diketones L1 and L2 showed a promising effect with about 25% yield. To explain this modest yield, we could consider the possible oxidation of copper(I) leading to an inactive copper(II) in water. To validate this hypothesis, a reducing agent was added to regenerate the copper(I) catalyst *in situ*. Sodium ascorbate (NaAsc) was chosen for its ability to reduce copper(II) and its well-known use in the “click” reaction.^[16] It is also often used for cross-coupling arylations with ammonia,^[15o] amides,^[17] and disulfides.^[18] A significant improvement in yields (50%) was obtained in the presence of NaAsc with the β -diketone ligands L1 and L2 (Figure 1). This result encouraged us to favor the use of copper(II) catalysts in the presence of reducing agents.

[a] M. Bollenbach, P. Wagner, P. Aquino, Dr. J.-J. Bourguignon, Dr. F. Bihel, Dr. C. Salomé, Dr. M. Schmitt
Laboratoire d'Innovation Thérapeutique
University of Strasbourg
74 route du Rhin, BP60024, 67401 Illkirch, France.
E-mail: mschmitt@unistra.fr

[b] P. Aquino
Laboratório de Pesquisa em Recursos Naturais
Universidade Federal de Alagoas
Maceió, AL, Brazil.

[c] Dr. C. Salomé
SpiroChem AG, c/o ETH-Zürich
Vladimir-Prelog-Weg 3, 8093 Zürich, Switzerland.

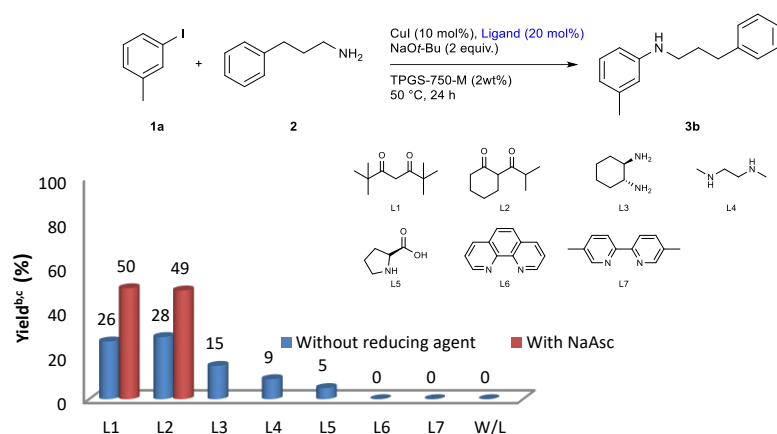


Figure 1. Copper catalyzed amination of 3-iodotoluene in TPGS-750-M: Impact of various ligands in presence or absence of NaAsc. ^aReaction conditions: CuI (10 mol%), ligand (20 mol%), NaOt-Bu (2 equiv.), 3-iodotoluene (1 equiv.), 3-phenylpropylamine (1.2 equiv.), TPGS-750-M (2 wt%), 50 °C, 24 h. ^bAverage yield of 2 experiments. ^cYields were determined by HPLC/UV using benzophenone as an external standard. W/L: without ligand.

The influence of eight different copper(II) salts and leaving groups were studied in combination with either dipivaloylmethane (THMD) L1 or 2-isobutyrylcyclohexanone L2 (Figure 2). Surprisingly, using L1, bromo derivatives appeared systematically more reactive than the corresponding iodo ones. This result was quite unexpected because bromoaryls are generally less reactive in Ullmann-type reactions than iodo derivatives. In contrast, L2 appeared systematically more effective with the 3-iodotoluene **1a** versus 3-bromotoluene **1b**.

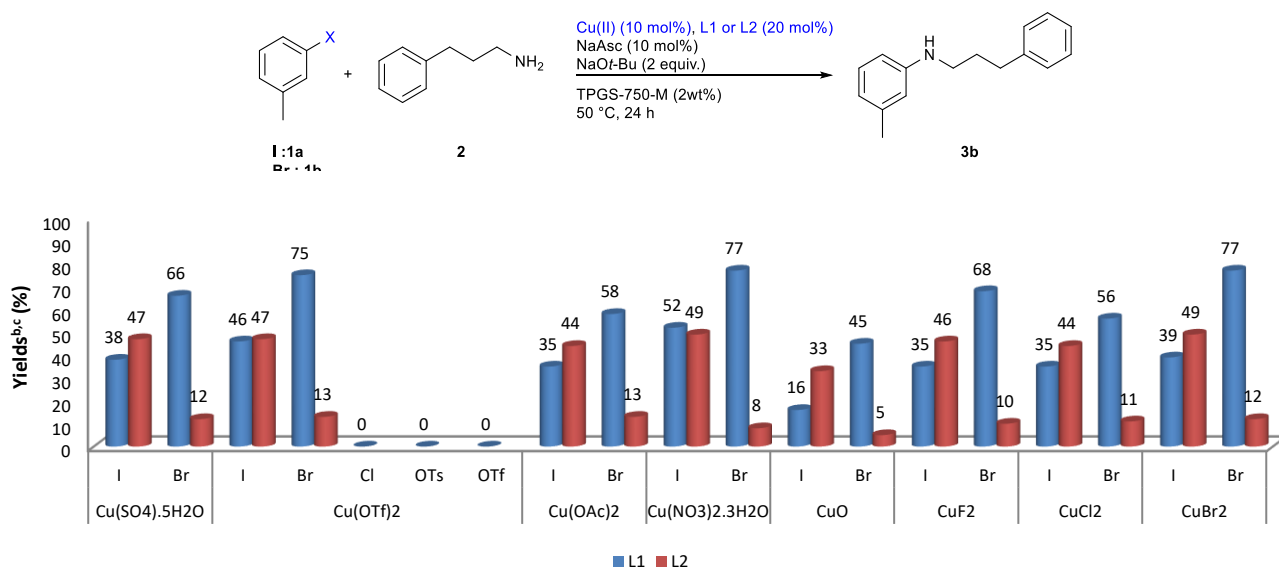
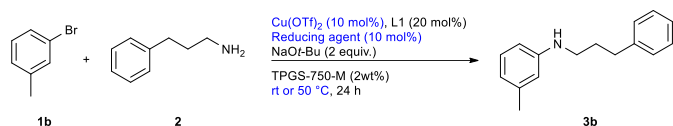


Figure 2. Impact of copper(II) salts and leaving groups in combination with either L1 or L2. ^aReaction conditions: Copper(II) (10 mol%), L1 or L2 (20 mol%), NaAsc (10 mol%), NaOt-Bu (2 equiv.), ArX (1 equiv.), 3-phenylpropylamine (1.2 equiv.), TPGS-750-M (2 wt%), 50 °C, 24 h. ^bAverage yield of 2 experiments. ^cYields were determined by HPLC/UV using benzophenone as an external standard.

However, it is important to note that the yields using L2 never exceeded 50%, while L1 led to yields higher than 70%. Further explorations revealed the non-efficacy of chloro, *O*-triflate and *O*-tosylate as leaving groups. While copper(II) oxide showed a modest activity, the other copper(II) salts afforded good yields - up to 75% yield with Cu(OTf)₂, Cu(NO₃)₂·3H₂O and CuBr₂. Based on these results, we selected 3-bromotoluene **1b** with the dipivaloylmethane L1 in combination with Cu(OTf)₂, Cu(NO₃)₂·3H₂O or CuBr₂ to continue our study.

We have previously highlighted the importance of reducing agents in this copper-catalyzed amination under micellar conditions. Without a reducing agent, no reaction was observed using the copper(II) catalyst (SI Figure S2). To optimize this parameter, three classical reducing agents were used (sodium ascorbate, hydroquinone and tris (2-carboxyethyl)phosphine (TCEP)) as well as three reducing sugars (D-glucose, D-fructose and D-galactose), at two different temperatures (room temperature and 50 °C, Figure 3 and SI Figure S1). In presence of Cu(OTf)₂, no reaction was observed with TCEP at both temperature, nor with NaAsc at room temperature. All the other reducing agents led to the desired product **3b** in moderate to excellent yields - even at room temperature. In particular, D-glucose afforded the desired product with 84% yield at room temperature. Similar results were obtained with Cu(NO₃)₂·3H₂O and CuBr₂ in presence of sodium ascorbate and D-glucose. However, the catalytic system Cu(OTf)₂/L1/D-glucose was the best combination for this green-Ullmann-type amination. To the best of our knowledge, D-glucose has rarely been used as reducing agent in organic chemistry. It has been reported for the one-pot assembly of *N*-fused imidazoles^[19], the reductive homocoupling of aryl halides^[20] and the formation of quinolines involving a three-steps cascade.^[21] Therefore, this seems to be



the first report of D-glucose used as a reducing agent in a copper-catalyzed reaction in aqueous medium. Its abundance and non-toxicity make D-glucose the perfect additive for sustainable chemistry approaches. This aspect is strengthened by the efficiency of the catalytic system Cu(OTf)₂/L1/D-glucose at room temperature, which is a positive parameter in terms of energy saving.

Several other parameters were further evaluated including different bases (SI Figure S3), various β-diketones (SI Figure S4), Cu/ligand ratio (SI Figure S5), catalyst loading (SI Figure S5), reducing agent molar ratio (SI Figure S2), surfactants (SI Figure S6), quantity of surfactant (SI Figure S7) and the atmosphere (SI Figure S8). Based on all these experiments, a combination of Cu(OTf)₂ (10 mol%), L1 (20 mol%), D-glucose (10 mol%) and NaOt-Bu (2 equiv.) was selected as the best catalytic system to perform this Ullmann-type amination at room temperature in an aqueous medium supplemented with TPGS-750-M (2 wt%).

With the optimal conditions in hand, the scope of the reaction was investigated using a diverse set of substituted amines and

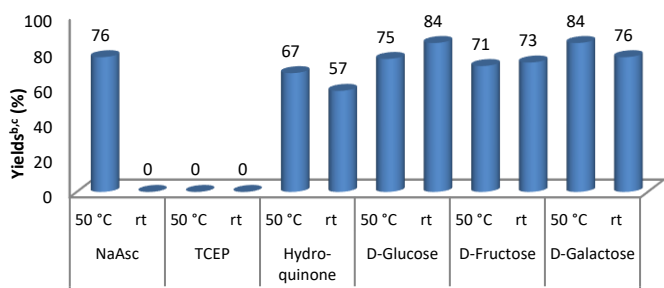
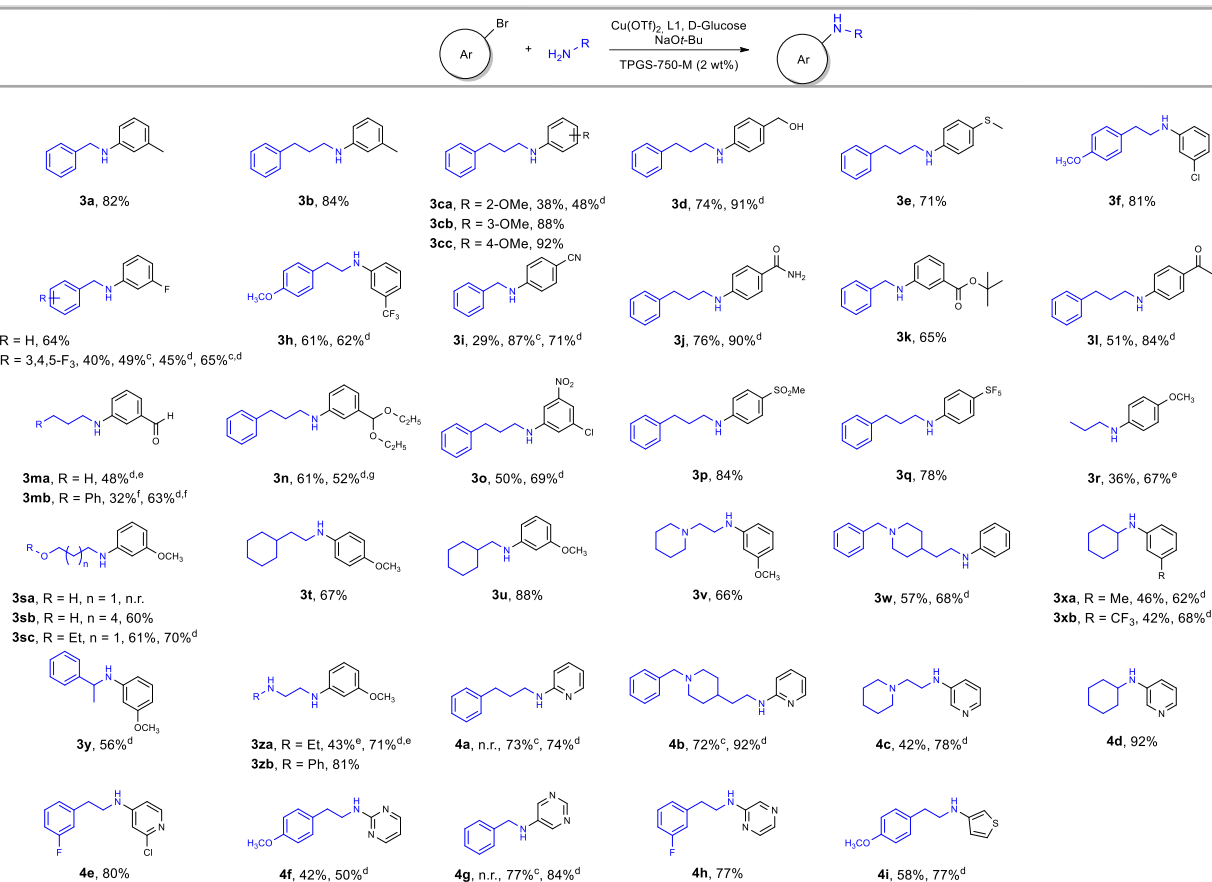


Figure 3. Screening of reducing agents. ^aReaction conditions: Cu(OTf)₂ (10 mol%), L1 (20 mol%), Reducing agent (10 mol%), NaOt-Bu (2 equiv.), 3-bromotoluene (1 equiv.), 3-phenylpropylamine (1.2 equiv.), TPGS-750-M (2 wt%), 50 °C or rt, 24 h. ^bAverage yield of 2 experiments. ^cYields were determined by HPLC/UV using benzophenone as an external standard.

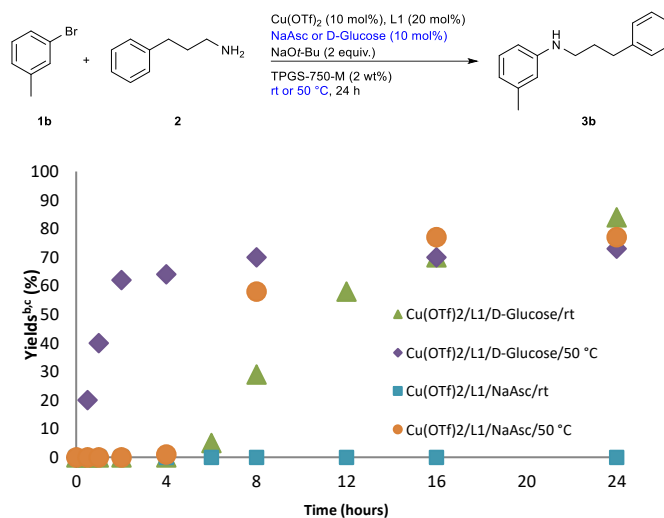
Table 1 Expanded scope of amination with arylbromides^{a,b}



Reaction conditions : Cu(OTf)₂ (10 mol%), L1 (20 mol%), D-glucose (10 mol%), NaOt-Bu (2 equiv.), ArBr (1 equiv.), RNH₂ (1.2 equiv.), TPGS-750-M (2 wt%), rt, 24 h. ^aYields refer to isolated product. ^bUnpublished products were fully characterized by NMR and HR-MS data. ^cUse of TPGS-750-M (5 wt%). ^dReaction carried out at 50 °C. ^eRNH₂ (5 equiv.). ^fRNH₂ (3 equiv.). ^gPresence of 22% of **3mb**. n.r.: no reaction.

aryl or heteroaryl bromides. The results are summarized in Table 1. The reaction was efficient with aryl bromide having either electron-donating groups in ortho (**3ca**), meta (**3a**, **3b**, **3cb** and **3n**) and para (**3cc**, **3d** and **3e**) position or electron-withdrawing groups (**3f-m**, **o-q**). In presence of a sterical hindrance at the ortho-position of the aryl-bromide (**3ca**), the reaction needs to be heated at 50 °C to obtain a yield of 48%. When using an aryl ring bearing both bromine and chlorine (**3f**, **4e**) substituent, the reaction only occurred on the brominated position. It is particularly noteworthy that even in the presence of sensitive substituents (i.e. CN **3i**, CONH₂ **3j**, CO₂tBu **3k**, MeCO **3l**, CHO **3m** or nitro **3o**) the reaction proceeds successfully to provide the desired products in moderate to high yields without protection of the functional group. Starting from an acetal moiety, the aminated product **3n** was isolated as a sole product when the reaction was performed at rt. However, at 50 °C a partial deprotection of the acetal was observed with the formation of 22% of the corresponding aldehyde **3mb**. We then turned our attention to various bromoheterocyclic systems, such as pyridine (**4a-e**), pyrimidine (**4f-g**), pyrazine (**4h**) and thiophene (**4i**) which were efficiently *N*-arylated with numerous primary amines (Table 1). When the bromine atom is in the meta-position, the reaction proceeded under the classical condition (2 wt% of TPGS-750-M at rt) with good to excellent yield even with a strongly hindered amine (**4c-d**). Good yields were also obtained using 2-bromopyrazine, 2-bromopyrimidine and 3-bromothiophene (**4h**, **4f** and **4i**). Unfortunately no reaction was observed starting from an iminochloride such as 2-chloropyridine. Next, a representative series of cyclohexyl or piperidinyl-containing amines were used with different steric hindrances at the amino group (**3t-x**). As illustrated in Table 1, the reaction worked even with bulky α -branched primary amines, but it is necessary to work at 50 °C to reach 60% yields (**3x-y**). Interestingly, when starting from a substrate bearing both primary and secondary amine moieties, only the primary amine reacted (**3za**, **3zb**).

As shown in Table 1, our methodology is compatible with free hydroxyl function. Starting from 4-bromobenzyl alcohol the *N*-coupling product with phenyl-propylamine was formed in 74% yield at rt (**3d**, 74%). The yield could be slightly increased at 50 °C. Unfortunately, no reaction was observed with 3-aminopropanol, even in presence of an excess of amine. The lack of reaction may be explained by the chelation of copper to the aminoalcohol. To verify this hypothesis the same reaction was performed with 6-aminoalcohol, a higher homologue, and we were pleased to isolate the expected coupling product in a satisfactory yield (**3sb**, 60%). When the alcohol is protected as an ether group, the desired product **3sc** was obtained with a moderate yield of 61%. No reaction was observed with other amines, like anilines, secondary amines, or benzamides. Starting from 4-bromobenzonitrile, the corresponding product **3h** was formed with a yield of only 29%, due to the poor solubility of the reactant. We overcame this issue by using either 5 wt% of TPGS-750-M at rt or 2 wt% of TPGS-750-M at 50 °C – this improved the yield to 87 and 71% respectively. The same conditions were applied with 4-



(4',5',6'-trifluorophenyl)propylamine (**3f**), 2-bromopyridine (**4a-b**), and

Figure 4. Kinetic of the reaction at rt and 50 °C with D-glucose and sodium ascorbate. ^aReaction conditions: Cu(OTf)₂ (10 mol%), L1 (20 mol%), Reducing agent (10 mol%), NaOt-Bu (2 equiv.), 3-bromotoluene (1 equiv.), 3-phenylpropylamine (1.2 equiv.), TPGS-750-M (2 wt%), 50 °C or rt. ^bAverage yield of 2 runs. ^cYields were determined by HPLC/UV using benzophenone as an external standard.

5-bromopyrimidine (**4g**) to overcome the solubility issues. In contrast, starting from a highly water soluble amine, like *n*-propylamine, an excess of amine was needed (5 equiv.) to reach a yield of 67% (**3r**).

In the absence of surfactant, our model reaction was still successful with 75% yield against 85% with TPGS-750-M (2%) (see SI Figure S7). This important result shows that this copper-catalyzed reaction is likely to occur in water rather than inside the micelle. However, with crystalline educts, the surfactant was crucial to help solubilize the reactants in the aqueous media and enhance the yield of the reaction. This is particularly true for the following examples (**3i**, **4a-b**, **4g**) where 5% of TPGS-750-M was required for optimal yield. To demonstrate the efficacy of our catalytic system and thereby its potential industrial application as a “sustainable process”, the reaction was next attempted on a multigram scale. Thus, five mmoles of 3-bromotoluene **1b** and 3-phenylpropylamine **2** in TPGS-750-M (2 wt%) successfully lead to **3b** in 86% yield under our conditions.

Finally, the kinetic parameters of this reaction were monitored (Figure 4). Firstly, at 50 °C, the reaction using D-glucose as reducing agent was faster compared to the one using NaAsc. Indeed, after 30 min, 20% conversion was already observed (purple) and the conversion reached 60% after 2 hours. In contrast, with NaAsc, a latency time of 4 hours was necessary before the formation of **3b** (orange). It is notable that after this latency time, the conversion rate is similar to the rate observed for the reaction using D-glucose. Interestingly, a latency time of 6

hours was also observed (green) when the reaction was performed with D-glucose at room temperature. We hypothesized that this period is required to reduce the inactive Cu(II) into the active Cu(I). This induction period might also suggest the formation of nanoparticles as the active catalysts

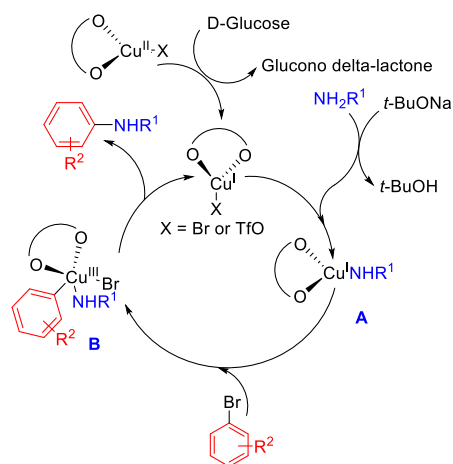


Figure 5. Proposed mechanism of the copper cross-coupling reaction in presence of D-glucose.

for 2 reasons:

- i) C-N cross coupling reaction was achieved recently with copper nanoparticles²² as catalyst.
- ii) D-glucose is known to be an excellent reducing agent for the formation of copper nanoparticles in water.²³

However, different experiments performed in our laboratory invalidate these hypotheses (see SI page S-12-13).

Finally a reasonable mechanism has been proposed to explain the different observations described in SI (see page S-14-15). Cu(I) was generated *in situ* from Cu(II) with D-glucose. Nucleophilic substitution of Cu(I) by amine leads to the formation of [Cu(I)Nu, intermediate **A**]. Then oxidative addition of the aryl halide to the intermediate **A** generates a transient Cu(III) species (**B**). Finally, the C-N bond is formed by reductive elimination from **B** leading to the aim compound and regenerating the initial copper(I) specie (Figure 5).

Conclusions

In summary, we developed the first Ullmann-type reaction at low temperature (rt or 50 °C) under micellar conditions for primary aliphatic amines. These mild conditions are simple yet robust and cheap. The use of renewable feedstocks (D-glucose and TPGS-750-M composed of vitamin E), the absence of organic solvent and the economy of energy make these conditions environmentally friendly and adaptable to industrial production. This easy-to-handle procedure is extremely competitive compared to palladium-based reactions and may be used to synthesize N-containing molecules such as drugs or OLED.

Experimental Section

General procedure: Amine (1.2 equiv.) and aryl or heteroaryl halide (1 equiv.) were added to an aqueous solution of TPGS-750-M (2 wt %, 1 mL/mmol). The mixture was degassed by bubbling Argon in through (5 min). NaOt-Bu (97% purity, 2 equiv.), Cu(OTf)₂ (10%), dipivaloylmethane (20%) and D-glucose (10%) were added and the resulting mixture was stirred (at 1200 rpm) at room temperature or 50 °C (24 h). The mixture was extracted twice with 3 mL of ethyl acetate. The combined organic layers were evaporated and the crude residue was purified by chromatographic column on silica gel using *n*-heptane and ethyl acetate as eluent.

N-Benzyl-3-methylaniline 3a

Prepared following the general procedure, using Cu(OTf)₂ (18.0 mg, 0.050 mmol), dipivaloylmethane (20.9 μL, 0.100 mmol), D-Glucose (9.0 mg, 0.050 mmol), 3-bromotoluene (60.6 μL, 0.500 mmol), benzylamine (65.6 μL, 0.600 mmol) and NaOt-Bu (99 mg, 1.00 mmol) in aqueous TPGS-750-M (2 wt %, 0.50 mL), followed by purification using column chromatography (SiO₂) and *n*-heptane/ethyl acetate (95:5), yielded **3a** as a yellow oil (81 mg, 82%). ¹H NMR (400 MHz, CDCl₃) δ 2.30 (s, 3H), 3.90 – 4.06 (br s, 1H), 4.34 (s, 2H), 6.46 – 6.59 (m, 3H), 7.09 (t, *J* = 7.5 Hz, 1H), 7.27 – 7.41 (m, 5H) ppm; ¹³C NMR (100 MHz, CDCl₃) δ 21.7, 48.4, 110.0, 113.6, 118.6, 127.2, 127.6, 128.6, 129.2, 139.1, 139.6, 148.3 ppm.

Keywords: C-N formation • Ullmann-type reaction • primary amines • D-glucose as reducing agent • micellar conditions

- [1] (a) M. Beller, C. Bolm, Eds., *Transition Metals for Organic Synthesis*, Wiley-VCH Verlag GmbH, Weinheim, Germany, **1998**, (b) M. Beller, C. Bolm, Eds., *Transition Metals for Organic Synthesis*, Wiley-VCH Verlag GmbH, Weinheim, Germany, **2004**.
- [2] R. A. Sheldon, I. W. C. E. Arends, U. Hanefeld, *Green Chemistry and Catalysis*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, **2007**.
- [3] (a) M.-O. Simon, C.-J. Li, *Chem. Soc. Rev.* **2012**, *41*, 1415–1427, (b) A. Chanda, F. F. Fokin, *Water in Organic Synthesis*, Georg Thieme Verlag KG, Stuttgart, **2012**, (c) J. M. DeSimone, *Science* **2002**, *297*, 799–803, (d) S. Narayan, J. Muldoon, M. G. Finn, V. V. Fokin, H. C. Kolb, K. B. Sharpless, *Angew. Chem. Int. Ed.* **2005**, *44*, 3275–3279.
- [4] (a) B. H. Lipshutz, S. Ghorai, A. R. Abela, R. Moser, T. Nishikata, C. Duplais, A. Krasovskiy, R. D. Gaston, R. C. Gadwood, *J. Org. Chem.* **2011**, *76*, 4379–4391, (b) B. H. Lipshutz, S. Ghorai, *Org. Lett.* **2009**, *11*, 705–708, (c) B. H. Lipshutz, G. T. Aguinado, S. Ghorai, K. Voigtritter, *Org. Lett.* **2008**, *10*, 1325–1328, (d) B. H. Lipshutz, S. Ghorai, *Aldrichimica Acta* **2008**, *41*, 59–72, (e) B. H. Lipshutz, S. Ghorai, *Aldrichimica Acta* **2012**, *45*, 3–16, (f) B. H. Lipshutz, S. Ghorai, W. Y. Leong, B. R. Taft, D. V. Krogstad, *J. Org. Chem.* **2011**, *76*, 5061–5073.
- [5] (a) B. H. Lipshutz, T. B. Petersen, A. R. Abela, *Org. Lett.* **2008**, *10*, 1333–1336, (b) T. Nishikata, B. H. Lipshutz, *J. Am. Chem. Soc.* **2009**, *131*, 12103–12105, (c) N. A. Isley, F. Gallou, B. H. Lipshutz, *J. Am. Chem. Soc.* **2013**, *135*, 17707–17710.
- [6] B. H. Lipshutz, B. R. Taft, *Org. Lett.* **2008**, *10*, 1329–1332.
- [7] B. H. Lipshutz, D. W. Chung, B. Rich, *Org. Lett.* **2008**, *10*, 3793–3796.
- [8] (a) B. H. Lipshutz, D. W. Chung, B. Rich, *Adv. Synth. Catal.* **2009**, *351*, 1717–1721, (b) N. A. Isley, S. Dobarco, B. H. Lipshutz, *Green Chem.* **2014**, *16*, 1480–1488.
- [9] C. Salomé, P. Wagner, M. Bollenbach, F. Bihel, J.-J. Bourguignon, M. Schmitt, *Tetrahedron* **2014**, *70*, 3413–3421.

- [10] (a) G. Evano, M. Toumi, A. Coste, *Chem. Commun.* **2009**, 4166–4175, (b) G. Evano, N. Blanchard, M. Toumi, *Chem. Rev.* **2008**, *108*, 3054–3131, (c) T. P. Bender, J. F. Graham, J. M. Duff, *Chem. Mater.* **2001**, *13*, 4105–4111, (d) H. B. Goodbrand, N.-X. Hu, *J. Org. Chem.* **1999**, *64*, 670–674, (e) M. Negwer, H.-G. Scharnow, *Organic Chemical Drugs and Their Synonyms*, Wiley-VCH, Weinheim, **2001**, (f) T. Eicher, S. Hauptmann, A. Speicher, *The Chemistry of Heterocycles: Structures, Reactions, Synthesis, and Applications 3rd, Completely Revised and Enlarged Edition*, Wiley-VCH, Weinheim, **2012**, (g) S. D. Roughley, A. M. Jordan, *J. Med. Chem.* **2011**, *54*, 3451–3479, (h) M. S. Butler, *J. Nat. Prod.* **2004**, *67*, 2141–2153.
- [11] P. Wagner, M. Bollenbach, C. Doebelin, F. Bihel, J.-J. Bourguignon, C. Salomé, M. Schmitt, *Green Chem.* **2014**, *16*, 4170–4178.
- [12] C. Reichardt, T. Welton, in *Solvents and Solvent Effects in Organic Chemistry*, Wiley-VCH Verlag GmbH & Co. KGaA, **2010**, pp. 65–106.
- [13] (a) C. Sambiagio, S. P. Marsden, A. J. Blacker, P. C. McGowan, *Chem. Soc. Rev.* **2014**, *43*, 3525–3550, (b) F. Monnier, M. Taillefer, *Angew. Chem. Int. Ed.* **2009**, *48*, 6954–6971, (c) F. Monnier, M. Taillefer, in *Amination Form. Sp² C-N Bonds* (Eds.: M. Taillefer, D. Ma), Springer Berlin Heidelberg, **2013**, pp. 173–204, (d) G. Evano, N. Blanchard, *Copper-Mediated Cross-Coupling Reactions*, John Wiley & Sons, New Jersey, **2014**, (e) S. Buchwald, A. Klapars, J. Antilla, G. Job, M. Wolter, F. Kwong, G. Nordmann, E. Hennessy, *Copper-Catalyzed Formation of Carbon-Heteroatom and Carbon-Carbon Bonds*, **2002**, WO02085838 (A1), (f) H.-J. Cristau, C. Bouchitte, M. Taillefer, J.-F. Spindler, T. Schlama, *Method for Preparing a Polyaromatic Compound*, **2001**, WO0158834 (A1).
- [14] M. Taillefer, H. J. Cristau, P. Cellier, J. F. Spindler, *Formation of Carbon-Carbon or Carbon-Heteroatom Bonds Comprises Reaction of an Unsaturated Compound with a Nucleophile in the Presence of a Metal-Bidentate Ligand Catalyst*, **2003**, FR2833947 (A1).
- [15] (a) D. Wang, F. Zhang, D. Kuang, J. Yu, J. Li, *Green Chem.* **2012**, *14*, 1268–1271, (b) C. Mukhopadhyay, P. K. Tapaswi, R. J. Butcher, *Org. Biomol. Chem.* **2010**, *8*, 4720–4729, (c) F.-F. Yong, Y.-C. Teo, S.-H. Tay, B. Y.-H. Tan, K.-H. Lim, *Tetrahedron Lett.* **2011**, *52*, 1161–1164, (d) S. Liu, J. Zhou, *New J. Chem.* **2013**, *37*, 2537–2540, (e) Y. Wang, Z. Wu, L. Wang, Z. Li, X. Zhou, *Chem. – Eur. J.* **2009**, *15*, 8971–8974, (f) J. Peng, M. Ye, C. Zong, F. Hu, L. Feng, X. Wang, Y. Wang, C. Chen, *J. Org. Chem.* **2011**, *76*, 716–719, (g) K. Swapna, S. N. Murthy, Y. V. D. Nageswar, *Eur. J. Org. Chem.* **2010**, 6678–6684, (h) X. Li, D. Yang, Y. Jiang, H. Fu, *Green Chem.* **2010**, *12*, 1097–1105, (i) Z.-J. Liu, J.-P. Vors, E. R. F. Gesing, C. Bolm, *Green Chem.* **2011**, *13*, 42–45, (j) L. Liang, Z. Li, X. Zhou, *Org. Lett.* **2009**, *11*, 3294–3297, (k) J. Engel-Andreasen, B. Shimpukade, T. Ulven, *Green Chem.* **2013**, *15*, 336–340, (l) X. Zhu, L. Su, L. Huang, G. Chen, J. Wang, H. Song, Y. Wan, *Eur. J. Org. Chem.* **2009**, 635–642, (m) S. Röttger, P. J. R. Sjöberg, M. Larhed, *J. Comb. Chem.* **2007**, *9*, 204–209, (n) J. Jiao, X.-R. Zhang, N.-H. Chang, J. Wang, J.-F. Wei, X.-Y. Shi, Z.-G. Chen, *J. Org. Chem.* **2011**, *76*, 1180–1183, (o) Z. Quan, H. Xia, Z. Zhang, Y. Da, X. Wang, *Chin. J. Chem.* **2013**, *31*, 501–506.
- [16] Z.-J. Quan, Q. Xu, Z. Zhang, Y.-X. Da, X.-C. Wang, *Tetrahedron* **2013**, *69*, 881–887.
- [17] Z.-J. Quan, H.-D. Xia, Z. Zhang, Y.-X. Da, X.-C. Wang, *Tetrahedron* **2013**, *69*, 8368–8374.
- [18] M. Martinek, M. Korf, J. Srogl, *Chem. Commun.* **2010**, *46*, 4387.
- [19] S. K. Guchhait, A. L. Chandgude, G. Priyadarshani, *J. Org. Chem.* **2012**, *77*, 4438–4444.
- [20] A. Monopoli, V. Calò, F. Ciminale, P. Cotugno, C. Angelici, N. Cioffi, A. Nacci, *J. Org. Chem.* **2010**, *75*, 3908–3911.
- [21] N. Anand, T. Chanda, S. Koley, S. Chowdhury, M. S. Singh, *RSC Adv.* **2015**, *5*, 7654–7660.
- [22] (a) M. B. Gawande, A. Goswami, F.-X. Felpin, T. Asefa, X. Huand, R. Silva, X. Zou, R. Zboril, R. S. Varma, *Chem. Rev.* **2016**, *116*, 3722–3811, (b) A. R. Hajipour, F. Dordahan, F. Rafiee, M. Mahdavi, *Appl. Organomet. Chem.* **2014**, *28*, 809–813.
- [23] (a) M. Sabbaghan, J. Beheshtian, R. N. Liarjdame, *Mater. Lett.* **2015**, *153*, 1–4, (b) J. Mondal, A. Biswas, S. Chiba, Y. Zhao, *Sci. Rep.* **2015**, *5*, 8294.

