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# Gold and Silver-Catalyzed Reductive Amination of Aromatic Carboxylic Acids to Benzylic Amines

Robin Coeck, Jittima Meeprasert, Guanna Li, Thomas Altantzis, Sara Bals, Evgeny A. Pidko, and Dirk E. De Vos\*



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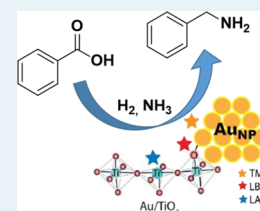
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**ABSTRACT:** The reductive amination of benzoic acid and its derivatives would be an effective addition to current synthesis methods for benzylamine. However, with current technology it is very difficult to keep the aromaticity intact when starting from benzoic acid, and salt wastes are often generated in the process. Here, we report a heterogeneous catalytic system for such a reductive amination, requiring solely  $H_2$  and  $NH_3$  as the reactants. The  $Ag/TiO_2$  or  $Au/TiO_2$  catalysts can be used multiple times, and very little noble metal is required, only 0.025 mol % Au. The catalysts are bifunctional: the support catalyzes the dehydration of both the ammonium carboxylate to the amide and of the amide to the nitrile, while the sites at the metal–support interface promote the hydrogenation of the in situ generated nitrile. Yields of up to 92% benzylamine were obtained.

**KEYWORDS:** reductive amination, gold, silver, benzylic amines, aromatic carboxylic acids, heterogeneous catalysis



## INTRODUCTION

Benzylamines are important chemical compounds with widespread applications in the textile (i.e., dyes), military, agrochemical, and pharmaceutical industries (Figure 1).<sup>1,2</sup> Classically, benzylamines are made from toluene via one of the three main pathways (Figure 2). The first method involves the chlorination of toluene to benzyl chloride, which is then reacted with ammonia to form benzylamine.<sup>2,3</sup> This method is by far the least environmentally friendly: the reaction requires dangerous chlorine gas and forms many (ring-)chlorinated side products, and salt waste is generated. Two halogen-free alternatives are the hydrogenation of benzonitrile and the reductive amination of benzaldehyde. Although both reduction reactions are highly efficient and can be performed with a wide variety of catalysts, there are some drawbacks related to the syntheses of both intermediates.<sup>4–10</sup> Benzonitrile is generally produced via ammoxidation of toluene at around 400 °C.<sup>11,12</sup> Working under these conditions requires a significant energy input, and one must be careful not to decompose or partially burn the reactants. Additionally, whereas ammoxidation processes are efficient for simple nitriles, more complex functionalized benzonitriles require hazardous cyanation reactions.<sup>13,14</sup> Alternatively, benzaldehyde is produced via oxidation of toluene. In contrast to ammoxidation, this oxidation reaction is performed under relatively mild conditions. However, with overoxidation as the main side reaction, a significant fraction of the substrate is lost to benzoic acid.<sup>15–17</sup>

In more recent years, efforts have been made to synthesize benzylamine in an efficient manner from more green and renewable sources. Aside from a few exceptions,<sup>18,19</sup> amination of benzyl alcohol has been the primarily

investigated synthesis route.<sup>20–26</sup> In these reports, benzylamine yields typically range between 66 and 86%. Currently, benzyl alcohol is produced from benzyl chloride, via hydrolysis, and in small quantities during benzaldehyde synthesis.<sup>27</sup> However, biobased synthesis routes are available.<sup>24,28</sup> Nevertheless, a synthesis route starting from benzoic acid, and its derivatives (e.g., benzamide), would be a valuable addition to existing methods; benzoic acid is readily available and a lot cheaper than benzyl alcohol. Additionally, it can be synthesized from renewable sources.<sup>29,30</sup> The direct conversion of benzoic acid to benzylamine is a fairly unexplored domain. With current technology, one has to either reduce benzoic acid to benzyl alcohol followed by amination (i.e., a multistep process)<sup>31</sup> or synthesize benzylamine via benzamide. As we recently showed, it is fairly easy to derivatize carboxylic acids to carboxamides.<sup>32,33</sup> However, the difficulty lies in reducing the carbonyl group and still keeping the aromatic ring intact. To achieve this goal, strong dehydrating agents, for example,  $P_2O_5$ , can be added to in situ generate a more easily reducible nitrile.<sup>34</sup> Alternatively, stoichiometric amounts of hydride reagents, for example,  $LiAlH_4$ , silanes, or boranes, are required for the selective reduction of the amide group.<sup>35–41</sup> Both approaches result in undesirable salt waste.

In this report, we describe two heterogeneous highly efficient catalysts, that is,  $Au/TiO_2$  and  $Ag/TiO_2$ , for the one-

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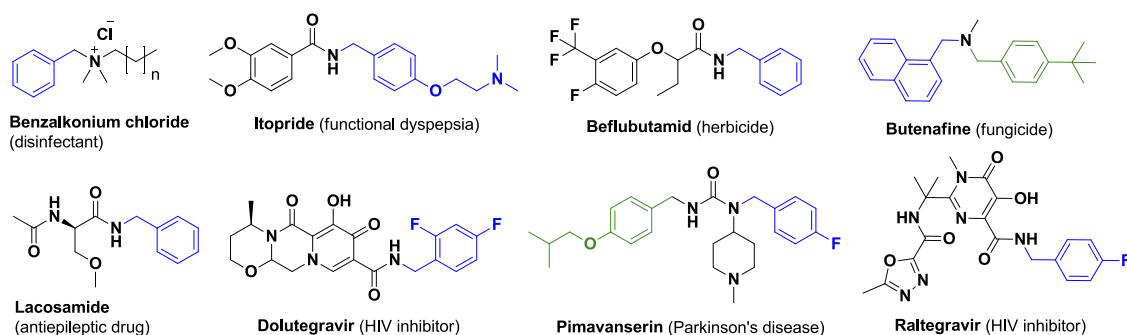


Figure 1. Pharmaceutical compounds containing at least one benzylic amine.

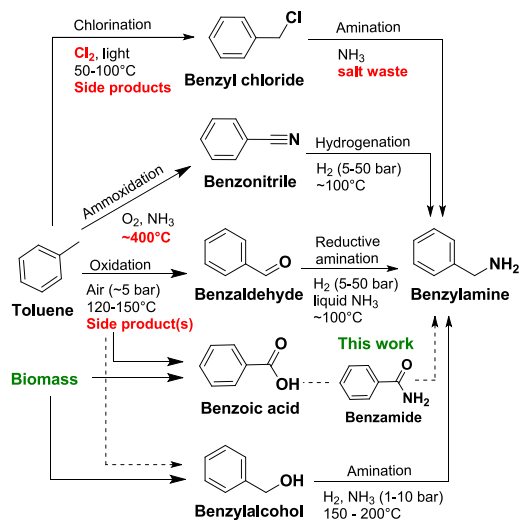


Figure 2. Synthesis methods for benzylamine.

pot catalytic conversion of benzoic acid (and its derivatives) to benzylamine. Reactions were performed using the green and benign cyclopentyl methyl ether (CPME) as the solvent, with  $\text{NH}_3$  and  $\text{H}_2$  as the only and clean reactants. Yields of up to 92% benzylamine were observed. To our knowledge, this is

the first report of an efficient (heterogeneous) reductive amination system for benzoic acid.

## RESULTS AND DISCUSSION

**Catalyst Screening and Evaluation.** In previous research on the hydrogenation and reductive amination of aliphatic amides and carboxylic acids, it was shown that the catalytic reduction of these compounds is a green and sustainable method for the production of valuable amines.<sup>32,33</sup> However, aromatic rings do not remain stable in the presence of highly active hydrogenation catalysts based on noble metals such as Ru, Rh, Pd, and Pt (Figure S2). As a starting point for the current work, benzamide was selected as a substrate molecule, with Au and Ag as potential hydrogenation catalysts. Of these metals in particular, it is known that they can perform reductions, such as the hydrogenation of nitrobenzenes, while leaving the aromatic ring intact.<sup>42–44</sup> Therefore, several catalysts with different Ag and Au loadings were prepared on  $\text{TiO}_2$ ,  $\text{Nb}_2\text{O}_5$ , hydroxyapatite (HAP), and  $\text{ZrO}_2$ . Commonly used supports such as fumed  $\text{SiO}_2$  and carbon black were excluded because we were only interested in catalysts that could promote the dehydration of the ammonium carboxylate as well.<sup>33</sup> The commercially available AUROLite (Au/ $\text{TiO}_2$ ) was also tested. This initial catalyst

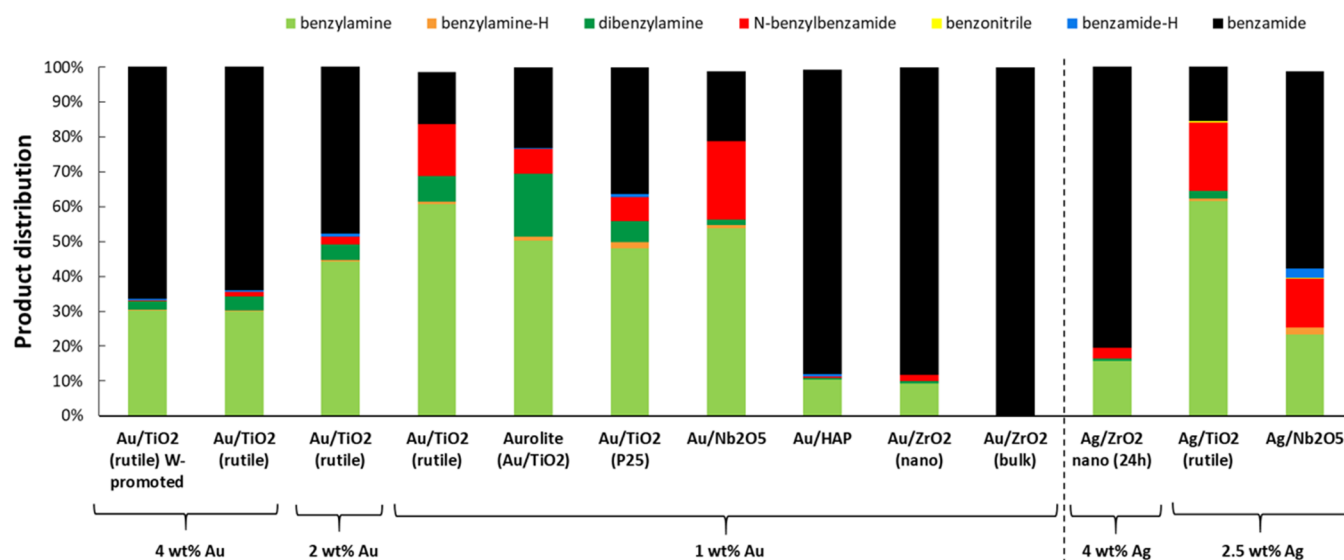


Figure 3. Catalyst evaluation for the hydrogenation of benzamide. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar  $\text{NH}_3$ , 50 bar  $\text{H}_2$ , 1 mol % Au or 5 mol % Ag, undecane (40  $\mu\text{L}$ ), CPME (20 mL), and 5 h. (Product names ending with “-H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).

Table 1. Variation of the Reaction Conditions for the Hydrogenation of Benzamide with Ag and Au Catalysts<sup>a</sup>

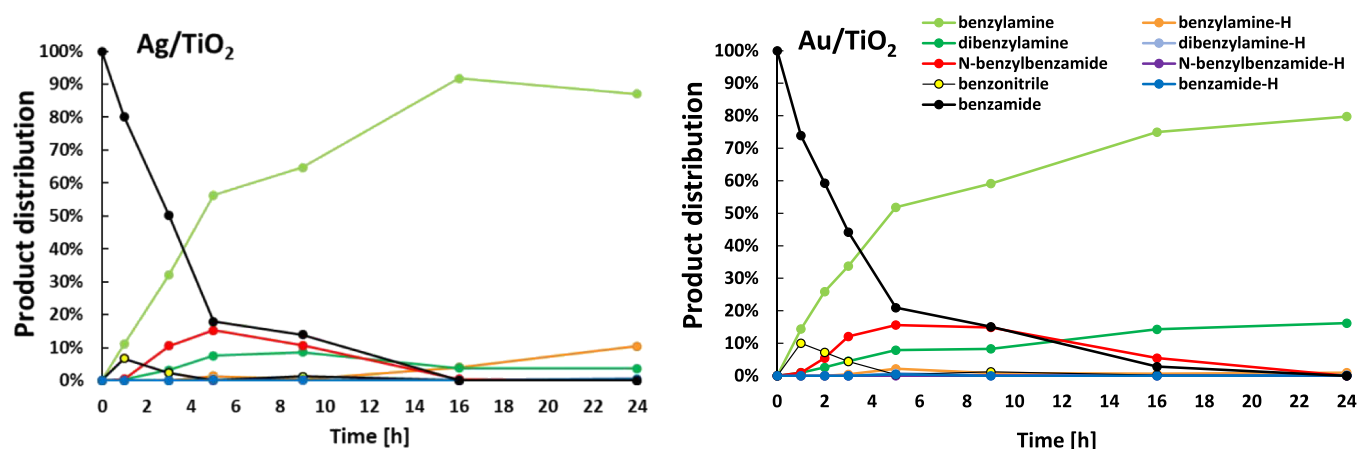
	metal	P <sub>H<sub>2</sub></sub> [bar]	P <sub>NH<sub>3</sub></sub> [bar]	T [°C]	t [h]	solvent	conversion [%]	selectivity [%]					
								BAm <sup>b</sup>	DiBAm <sup>c</sup>	BAm-H <sup>d</sup>	N-BBenz <sup>e</sup>	Bnit <sup>f</sup>	others
1	Ag	50	2	200	5	CPME <sup>g</sup>	61	42	10	2	42	1	4
2	Ag	50	4	200	5	CPME	79	50	7	1	40	1	1
3	<b>Ag</b>	<b>50</b>	<b>6</b>	<b>200</b>	<b>5</b>	<b>CPME</b>	<b>84</b>	<b>73</b>	<b>3</b>	<b>1</b>	<b>23</b>	<b>1</b>	<b>&lt;1</b>
4	Ag	25	6	200	5	CPME	77	56	3	2	33	2	3
5	Ag	10	6	200	5	CPME	60	57	4	<1	28	8	3
6	Ag	5	6	200	5	CPME	36	41	4	<1	21	34	<1
7	<b>Ag</b>	<b>50</b>	<b>6</b>	<b>200</b>	<b>16</b>	<b>CPME</b>	<b>&gt;99</b>	<b>92</b>	<b>4</b>	<b>4</b>	<b>&lt;1</b>	<b>&lt;1</b>	<b>&lt;1</b>
8	Ag	50	6	185	5	CPME	26	65	2	<1	12	18	2
9	Ag	50	6	170	5	CPME	9	37	<1	<1	<1	62	1
10	Au	50	2	200	5	CPME	79	26	11	8	41	1	14
11	Au	50	4	200	5	CPME	86	45	10	5	32	<1	7
12	Au	50	6	200	5	CPME	82	69	9	2	19	<1	2
13	<b>Au</b>	<b>30</b>	<b>6</b>	<b>200</b>	<b>5</b>	<b>CPME</b>	<b>83</b>	<b>70</b>	<b>7</b>	<b>1</b>	<b>21</b>	<b>1</b>	<b>&lt;1</b>
14	Au	20	6	200	5	CPME	79	62	7	<1	26	3	2
15	Au	15	6	200	5	CPME	70	61	7	<1	27	4	<1
16	Au	10	6	200	5	CPME	80	58	6	1	31	1	2
17	Au	5	6	200	5	CPME	49	64	5	<1	24	5	3
18	Au	50	6	200	16	CPME	>99	78	12	6	<1	1	4
19	<b>Au</b>	<b>30</b>	<b>6</b>	<b>200</b>	<b>16</b>	<b>CPME</b>	<b>97</b>	<b>77</b>	<b>15</b>	<b>1</b>	<b>6</b>	<b>&lt;1</b>	<b>2</b>
20	Au	15	6	200	16	CPME	97	73	11	2	10	<1	4
21	Au	30	6	185	5	CPME	36	60	7	<1	12	21	1
22	Au	30	6	170	5	CPME	20	42	4	<1	3	49	1
23	Au	30	6	200	5	MeCyclohex. <sup>h</sup>	71	47	46	1	4	1	1
24	Au	30	6	200	5	toluene	90	58	15	<1	24	2	<1
25	Au	30	6	200	5	TAME <sup>i</sup>	81	55	13	<1	23	7	3
26	Au	30	6	200	5	MeTHF <sup>j</sup>	80	80	5	<1	13	2	1
27	Au	30	6	200	5	DME <sup>k</sup>	72	86	3	<1	7	6	<1
28	Au	30	6	200	5	anisole	84	74	5	<1	21	1	<1
29	Au	30	6	200	5	dioxane	45	72	<1	<1	4	26	<1
30	Au	30	6	200	5	TAA <sup>l</sup>	no hydrogenation products						

<sup>a</sup>Reaction conditions: Au/TiO<sub>2</sub> (1 mol %) or Ag/TiO<sub>2</sub> (5 mol %), benzamide (2 mmol) in solvent (20 mL), and undecane standard (40 μL) with NH<sub>3</sub> and H<sub>2</sub>. <sup>b</sup>Benzylamine. <sup>c</sup>Dibenzylamine. <sup>d</sup>Benzylamine-H (i.e., aminomethylcyclohexane). <sup>e</sup>N-benzylbenzamide. <sup>f</sup>Benzonitrile. <sup>g</sup>Cyclopentyl methyl ether. <sup>h</sup>Methylcyclohexane. <sup>i</sup>tert-Amyl methyl ether. <sup>j</sup>2-Methyltetrahydrofuran. <sup>k</sup>1,2-Dimethoxyethane. <sup>l</sup>tert-Amyl alcohol.

screening was performed at 200 °C, with 6 bar NH<sub>3</sub>, 50 bar H<sub>2</sub>, 1 mol % Au, or 5 mol % Ag, in CPME (Figure 3).

From this catalyst screening, several observations can be made. First, virtually all Au and Ag catalysts have at least some hydrogenation activity with very little overhydrogenation of the aromatic ring (below 5%). In addition to the formation of the desired product (up to 65%), significant amounts of dibenzylamine and N-benzylbenzamide are formed as well. Second, whereas Ru catalysts can be modified with WO<sub>x</sub> to improve their amide hydrogenation activity, this strategy does not seem effective for Au.<sup>32,33</sup> Finally and most importantly, the catalyst support seems to play a very important role in the overall conversion. In particular, catalysts with low metal loadings and sufficient Lewis acid sites on the support are very active, for example, TiO<sub>2</sub> and Nb<sub>2</sub>O<sub>5</sub>.<sup>45–49</sup> Catalysts with supports that are only mildly Lewis acidic to even basic, for example, ZrO<sub>2</sub> and HAP, performed poorly. This observation comes to no surprise because it is generally known that Lewis acid sites help to adsorb the amide to the catalytic surface.<sup>32,33,41,50–57</sup> The quantity of the catalyst support plays a remarkably prominent role in the final product yield. A reference reaction with only a catalyst support reveals that an intermediate product, that is, benzonitrile, is formed (Figure S3). This dehydration reaction from amide to nitrile is significantly faster on a TiO<sub>2</sub> (rutile) surface in comparison

with the employed ZrO<sub>2</sub>. The importance of a sufficient quantity of the support becomes clear when comparing the results for Au/TiO<sub>2</sub> (rutile) with a 1, 2, and 4 wt % Au loading (Figure 3). For all three reactions, an equal amount of gold (thus a different amount of support) was added; there is a clear increase in the product yield when the metal loading is decreased, that is, when the amount of the support is increased. Because differences in the Au nanoparticle (NP) size and dispersion between these catalysts were minor, these results suggest that the reaction proceeds via two consecutive reactions: starting molecule A (the amide) is converted to molecule B (nitrile intermediate) at the catalyst support, and B is converted to C (amine product) at the gold surface. To further test this hypothesis, experiments were performed with a fixed weight of the catalyst, rather than with the same amount of Au or Ag (Figure S4). Even with four times less gold present, a 1 wt % Au catalyst (Au/TiO<sub>2</sub>) still performed slightly better than the 4 wt % Au catalyst, proving that at least for the 1–4 wt % Au/TiO<sub>2</sub> catalysts, the amount of Au is largely sufficient; rather the amount of the support determines the rate of the slowest step in the sequence, viz. the dehydration of the amide. For the Ag/TiO<sub>2</sub> catalyst, however, this did not seem to be the case. Replacing a 2.5 wt % Ag catalyst with a 1 wt % Ag catalyst (same catalyst weight) resulted in a clear drop in the product yield. Thus, for the Ag



**Figure 4.** Time profiles for the hydrogenation of benzamide with Ag/TiO<sub>2</sub> (left) and Au/TiO<sub>2</sub> (right). Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar NH<sub>3</sub>, 30 bar H<sub>2</sub> (Au) or 50 bar H<sub>2</sub> (Ag), 1 mol % Au (1 wt % Au catalyst) or 5 mol % Ag (2.5 wt % Ag catalyst), undecane (internal standard, 40 μL), and CPME (20 mL). (Product names ending with “-H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety.)

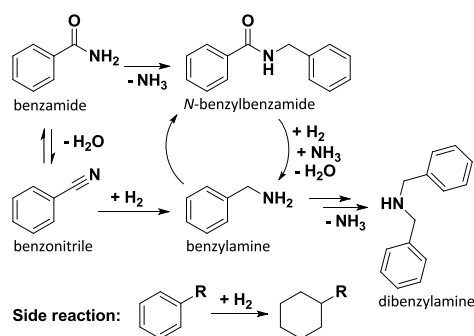
catalyst, the hydrogenation on the metal surface seems to be significantly slower. Au/TiO<sub>2</sub> (rutile, 1 wt % Au) and Ag/TiO<sub>2</sub> (rutile, 2.5 wt % Ag) were selected as the best catalysts. At first glance, it appears that Au/Nb<sub>2</sub>O<sub>5</sub> (1 wt % Au) is an excellent catalyst as well. However, reactions performed with a longer reaction time revealed that this material easily catalyzed the overhydrogenation of the aromatic ring (Figure S5). Note also that Ag/Nb<sub>2</sub>O<sub>5</sub> performed rather poorly. This is likely also the result of a different catalyst preparation: in contrast to the Au catalysts, the Ag catalyst requires activation at 600 °C (calcination). At temperatures above 400 °C, Nb<sub>2</sub>O<sub>5</sub> is known to start losing its active sites.<sup>45</sup>

**Optimization of the Reaction Conditions.** Reaction conditions were optimized for both Ag/TiO<sub>2</sub> (2.5 wt % Ag) and Au/TiO<sub>2</sub> (1 wt % Au; Table 1). The favorable influence of the NH<sub>3</sub> pressure on the selectivity for benzylamine is expected: high concentrations of NH<sub>3</sub> decrease the formation of secondary amine and secondary amides where, in both cases, an extra NH<sub>3</sub> molecule is generated (entries 1–3 and 10–12). Interestingly, more NH<sub>3</sub> also increases the reaction rate itself, although this effect is more pronounced with Ag than with Au. In particular for the Au catalyst, NH<sub>3</sub> has an additional positive effect on the selectivity by hindering the overhydrogenation of the aromatic ring (14% of the initial substrate was overreduced after a reaction with only 2 bar NH<sub>3</sub>). It is suggested that NH<sub>3</sub> is competitive for the adsorption sites on which an aromatic ring can adsorb (they are both Lewis bases). An excess of NH<sub>3</sub> will therefore dominate these adsorption sites, thus keeping the aromatic rings relatively safe from overhydrogenation. For the Ag catalyst, only traces of the overreduced product were detected under the same reaction conditions. This decreased hydrogenation activity, in comparison with the Au catalyst, was also very noticeable when varying the H<sub>2</sub> pressure (entries 3–6 and 12–20). For Ag/TiO<sub>2</sub>, there is a clear drop in the product yield and reaction rate with decreasing H<sub>2</sub> pressure (entries 3–6). The amount of residual benzonitrile increases as well. For Au/TiO<sub>2</sub>, however, there is nearly no decrease in the product yield or reaction rate with decreasing H<sub>2</sub> pressure (entries 12–20). Only when reducing the H<sub>2</sub> pressure from 10 to 5 bar, there is a clear drop. This again illustrates that for the Au catalyst, not the hydrogenation but the dehydration of

the amide is determining the overall rate. For Au/TiO<sub>2</sub>, a H<sub>2</sub> pressure of 30 bar was selected as the optimum. At this point, there is more than enough H<sub>2</sub> for a smooth reaction, but not as much as would result in an overreduction of the aromatic ring (entries 18–20). Next the reaction temperature was varied (entries 3, 8, 9, 13, 21, and 22). Reducing the reaction temperature resulted in a clear drop in product conversion. Not only the endothermic dehydration of the amide is hindered, but the hydrogenation as well; indeed an increasing amount of benzonitrile is present after reaction at lower reaction temperature. Finally, the solvent tolerance was determined (entries 13 and 23–30). In general, the reaction can be performed in any ether or hydrocarbon solvent, resulting in similar conversions. However, the selectivity for benzylamine differs strongly. This is mainly the influence of the amount of dissolved NH<sub>3</sub>. Condensation reactions, such as secondary amine and amide formation, are prevented in solvents that dissolve more NH<sub>3</sub> (at 6 bar NH<sub>3</sub>, Figures S6 and S7). Therefore, a higher benzylamine yield can be expected. Nevertheless, one should not add an excessive amount of NH<sub>3</sub>. A clear drop in the reaction rate is observed for a reaction in dioxane where the reaction mixture consists of approximately 33 wt % of NH<sub>3</sub> (at 6 bar NH<sub>3</sub>). Although low quantities of benzonitrile were detected, no hydrogenation products were observed when performing this reaction in an alcohol solvent (entry 30). It is advisable to perform the reaction in either CPME or anisole, as both solvents are recommended in green solvent guides.<sup>58,59</sup> CPME has the advantage to ensure an energy-efficient product isolation, because of its low heat of evaporation. Anisole, however, ensures a slightly higher benzylamine yield: it dissolves more NH<sub>3</sub> at 6 bar and more favorably suppresses the competing reduction of the aromatic ring.

**Unraveling the Reaction Network.** After optimization of the reaction conditions, a time profile was made for the Ag and Au catalysts (Figure 4). The reaction proceeds very similarly on both catalysts. The first products are benzonitrile and benzylamine, with benzonitrile as the intermediate as discussed earlier. Soon after, two additional products are formed: dibenzylamine and N-benzylbenzamide. Both are consecutive condensation products of benzylamine. While dibenzylamine is a dead-end product under the conditions of

this catalytic reaction, *N*-benzylbenzamide is not. It can be converted into benzylamine. An additional experiment starting from *N*-benzylbenzamide showed that the secondary amide bond can be broken again by ammonolysis, yielding 15% benzamide and 47% benzylamine after a reaction time of 2 h (Figure S8). This observation is surprising because silver catalysts have been reported to catalyze the hydrogenolytic C–N cleavage of secondary amines resulting in primary amines and alcohols.<sup>41</sup> In none of our experiments was benzyl alcohol detected, nor is the catalyst capable of aminating benzyl alcohol to benzylamine (Figure S8). This experiment also confirmed that *N*-benzylbenzamide is not hydrogenated directly toward dibenzylamine either. For Ag/TiO<sub>2</sub>, an excellent yield of 92% benzylamine was obtained after a reaction time of 16 h (full conversion). It is advisable to stop the reaction in time to prevent overreduction and secondary amine formation. The Au catalyst yielded 80% benzylamine after a reaction time of 24 h, with 18% dibenzylamine as the main side product (full conversion). The global reaction scheme is shown in Figure 5.



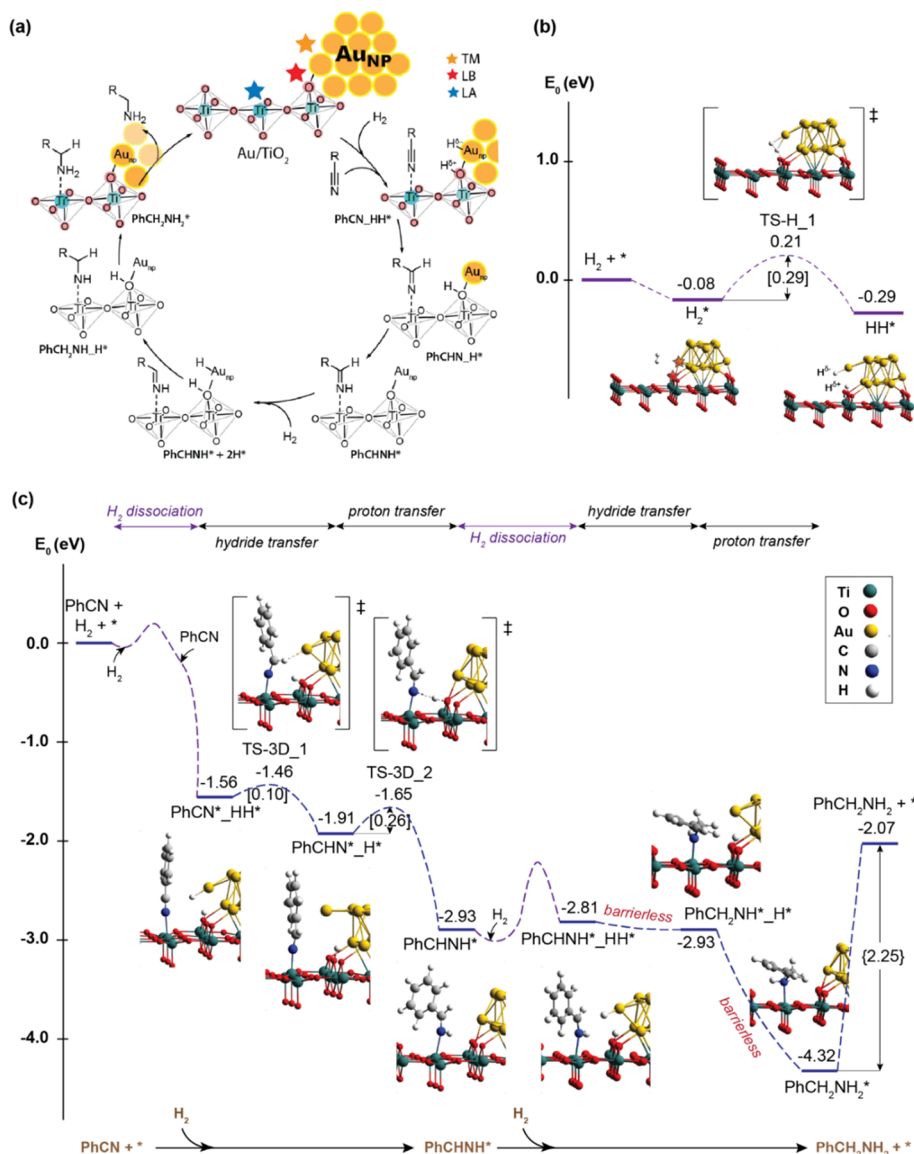
**Figure 5.** Reaction scheme for the hydrogenation of benzamide to benzylamine.

**Density Function Theory (DFT) Calculations.** To understand in more detail the mechanism of the selective nitrile hydrogenation on the Au/TiO<sub>2</sub> catalyst, we next turned to periodic DFT calculations using Au<sub>13</sub>/TiO<sub>2</sub> as a model catalyst.<sup>66,67</sup> The detailed description of the computational models and results is summarized in the [Supporting Information](#), while the key findings are presented in Figure 6. The reaction mechanism for the catalytic reaction is schematically presented in Figure 6a. DFT calculations reveal the synergistic role of the Lewis acid and base sites of the titania support and the metallic Au NP to establish a low-energy reaction path for the heterolytic cleavage of H<sub>2</sub> and subsequent selective hydrogenation of the polar nitrile moiety. The DFT calculations reveal that the Lewis-acidic 5-fold coordinated Ti surface sites (Ti<sup>5c</sup>) preferentially adsorb and additionally polarize the CN moiety of the benzonitrile substrate (Figures S16 and S17), while the Au-O<sup>2c</sup> Lewis acid–base pair at the Au/TiO<sub>2</sub> interface promotes the H<sub>2</sub> dissociation. Heterolytic H<sub>2</sub> cleavage over the Au-O<sup>2c</sup> pair site produces a couple of proton (H<sup>+</sup>) and hydride (H<sup>-</sup>) via an exothermic reaction ( $\Delta E = -0.21$  eV) with a small activation energy ( $E_a = 0.29$  eV, Figure 6b). The combination of the facile heterolytic cleavage of H<sub>2</sub> and the polarization of the substrate molecules by Lewis-acidic sites at the Au–TiO<sub>2</sub> interface is key for a high selectivity toward the hydrogenation of the CN functional group. Previous studies of H<sub>2</sub> dissociation on bare rutile TiO<sub>2</sub> (110)<sup>63</sup> and Au/TiO<sub>2</sub>

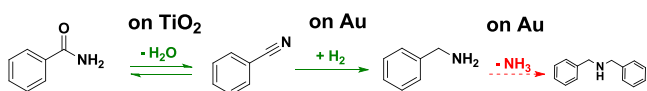
(110)<sup>64,65</sup> found that the heterolytic dissociation is favored in comparison with the homolytic H<sub>2</sub> activation. Therefore, here only the former mechanism is considered. Our calculations confirmed that the H<sub>2</sub> dissociation at the Ti<sup>5c</sup>-O<sup>2c</sup> pair site on the support is both thermodynamically and kinetically less favorable than at the interface Au-O<sup>2c</sup> site (Figure S18). The hydrogenation of benzonitrile (PhCN) to benzylamine (PhCH<sub>2</sub>NH<sub>2</sub>) proceeds in four consecutive hydride and proton transfer reaction steps (Figure 6c). Our results indicate the H<sub>2</sub> activation to be the most energy-demanding reaction step. The end-on coordination of benzonitrile to the Lewis-acidic Ti<sup>5c</sup> site polarizes and activates the CN moiety facilitating thus the hydride transfer step. Indeed, once the H<sup>δ+</sup>...H<sup>δ-</sup> pair is generated at the interface site, the subsequent benzonitrile hydrogenation is energetically favorable and proceeds with very small activation barriers of 0.10 and 0.26 eV for the hydride and proton transfer steps, respectively. Further reduction of the benzylimine intermediate (PhCHNH) to benzylamine (PhCH<sub>2</sub>NH<sub>2</sub>) is barrierless. However, the desorption of the PhCH<sub>2</sub>NH<sub>2</sub> product and the regeneration of the Lewis-acidic Ti site are quite endothermic by 2.25 eV. By accounting for the translational and rotational entropy gains because of the product desorption at 200 °C, we estimate the Gibbs free energy for this final step to be only 1.11 eV, which is comparable to the overall free energy barriers estimated for the H<sub>2</sub> activation steps (Figure S20). These DFT results indicate that the synergetic action of the multisite environment at the Au–TiO<sub>2</sub> interface is the key for the selective nitrile hydrogenation.

**Reducing the Au Loading of the Catalyst.** Gold is a very valuable and expensive metal. For this reason, it is highly recommended to work with as little gold as possible. Initial experiments suggested that with a 1 wt % Au catalyst on a TiO<sub>2</sub> support, the Au does not limit the product formation, but rather the TiO<sub>2</sub> support affecting the dehydration of the amide does (Figures 3 and 7, and Figure S4). Therefore, the Au loading was further decreased, and hydrogenation experiments were performed with the same weight of the catalyst (Figure 8). From these experiments, two main conclusions arise. First, down to a 0.01 wt % Au loading of the catalyst, the benzamide conversion remains constant. Below this critical point, the activity of the catalyst dropped drastically with decreasing Au loading. Second, the selectivity for dibenzylamine decreases with decreasing gold loading. This results in an increase in benzylamine selectivity and yield. As less gold is present, there are fewer active sites that catalyze secondary amine formation (requiring metal catalysis).<sup>32,33,60</sup> The Au/TiO<sub>2</sub> catalyst with a 0.025 wt % Au metal loading was selected as the optimal catalyst. This catalyst displays both a good activity and selectivity for the desired product. A hydrogenation experiment with benzamide and this 0.025 wt % Au catalyst for 16 h, with only 0.025 mol % Au, resulted in a yield of 92% benzylamine (Figure S5). This is identical to the result initially obtained for Ag/TiO<sub>2</sub> (2.5 wt % Ag). Both catalysts are therefore very suitable and relatively cheap hydrogenation catalysts; gold is 70 times more expensive than silver, but 110 times less (metal) weight is required (0.025 mol % Au vs 5 mol % Ag).

**Increasing the Volumetric Productivity and the Influence of Water.** To make this catalytic system more interesting for application, it may be useful to work under as concentrated conditions as possible. For this reason, the



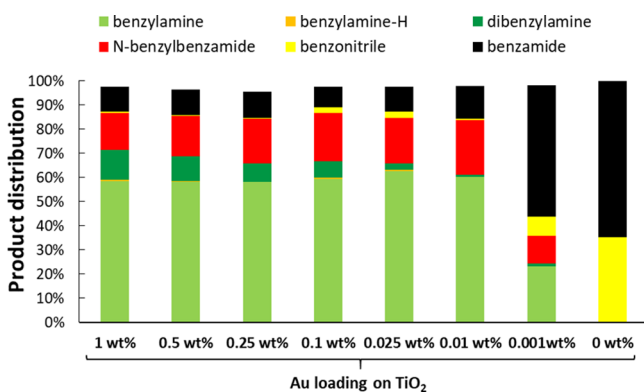
**Figure 6.** Mechanistic analysis by periodic DFT calculations. (a) Mechanism of benzonitrile hydrogenation at the Au/TiO<sub>2</sub> interface and the respective DFT-computed reaction energy diagrams for (b) heterolytic H<sub>2</sub> activation at the bare interface site and (c) catalytic reduction of benzonitrile to benzylamine on the Au<sub>13</sub>/TiO<sub>2</sub> model catalyst surface. (The details of the H<sub>2</sub> activation steps are omitted for clarity. The full reaction energy profiles are provided in the Supporting Information, Figure S20).



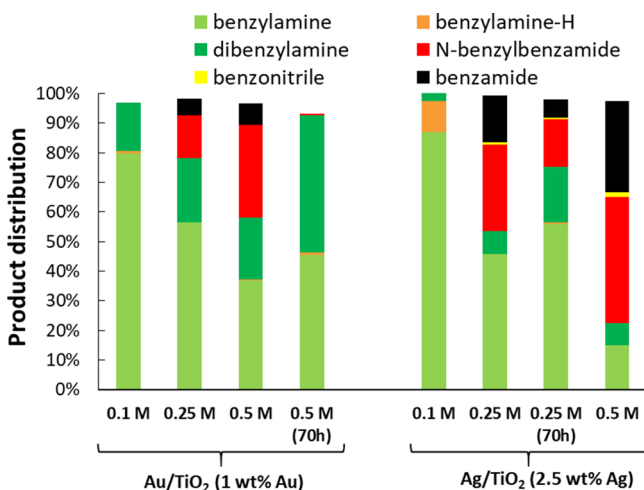
**Figure 7.** Simplified reaction scheme for the hydrogenation of benzamide to benzylamine.

concentration of the substrate was increased, while the ratio of the substrate to catalyst was kept constant (Figure 9). Two main observations could be made. First, although the substrate to catalyst ratio is constant, we see a clear drop in conversion with increasing substrate concentration. This is caused by the hindering effect of extra water, which is formed during the reaction (Figure 10). Indeed, water accumulation will influence the dehydration equilibrium. More water pushes the equilibrium to the amide, making the reverse reaction (i.e., the hydration of the nitrile) more pronounced. Certainly with catalysts for which the hydrogenation was already limiting, this hindering effect is very noticeable, for example, for the 2.5 wt

% Ag catalyst (Figure 9). Additionally, water also adsorbs to the catalyst.<sup>33</sup> This appears to slow down hydrogenation; observable amounts of benzonitrile were formed with even three equivalents of water (Figure 10). We typically find such benzonitrile accumulation at the very beginning of a reaction (Figure 4). This hindering effect is not surprising because alcohols (i.e., hydroxyl-bearing solvents) have a similar effect (Table 1, entry 30). Second, by increasing the substrate concentration, the ratio of substrate to NH<sub>3</sub> increases. This has clear implications for the product selectivity. With relatively less NH<sub>3</sub> present, condensation reactions occur more frequently. Therefore, more dibenzylamine and *N*-benzylbenzamide are formed; for instance, with a 1 wt % Au catalyst at nearly full conversion a yield of 47% benzylamine and 47% dibenzylamine was obtained based on initial benzamide (Figure 9). Industrially, controlled amounts of liquid NH<sub>3</sub> can be added to the reactor to mitigate this selectivity issue. In general, it is definitely possible to work



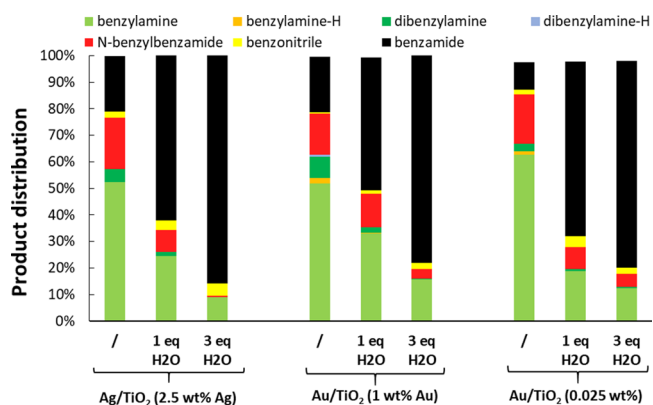
**Figure 8.** Variation of the gold loading on a  $\text{TiO}_2$  support during the hydrogenation of benzamide. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar  $\text{NH}_3$ , 30 bar  $\text{H}_2$ , 0.60 g Au catalyst, undecane (internal standard, 40  $\mu\text{L}$ ), CPME (20 mL), and 5 h. (Product names ending with “-H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).



**Figure 9.** Hydrogenation of benzamide in more concentrated reaction mixtures. Reaction conditions: benzamide, 200 °C, 6 bar  $\text{NH}_3$ , 30 bar  $\text{H}_2$  (Au) or 50 bar  $\text{H}_2$  (Ag), 1 mol % Au (1 wt % Au catalyst) or 5 mol % Ag (2.5 wt % Ag catalyst), undecane (internal standard, 40  $\mu\text{L}$ ), CPME (20 mL), and 24 h. (Product names ending with “-H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).

with more concentrated reaction mixtures. However, it is advisable to work in the presence of as little water as possible to improve the catalyst’s activity. Increasing the metal loading also improves the overall reaction rate by increasing the hydrogenation rate; this is shown by comparing reactions with the 1 wt % Au catalyst with those using the 2.5 wt % Ag catalyst. These observations were taken into account when conducting experiments with benzoic acid instead of benzamide (Table 2).

**Catalyst Characterization and Recycling Test.** To characterize the catalyst and check the catalysts’ stability, high-angle annular dark-field–scanning transmission electron microscopy (HAADF–STEM) imaging was performed along with energy-dispersive X-ray spectroscopy (EDS) elemental mapping and a recycling test (Figures 11–13, Table S1, and Figures S9–S13). Overall, the Au catalysts were found to be very catalytically stable, with the catalysts having an average Au NP size ranging from 6 to 10 nm (0.025 and 1 wt % Au



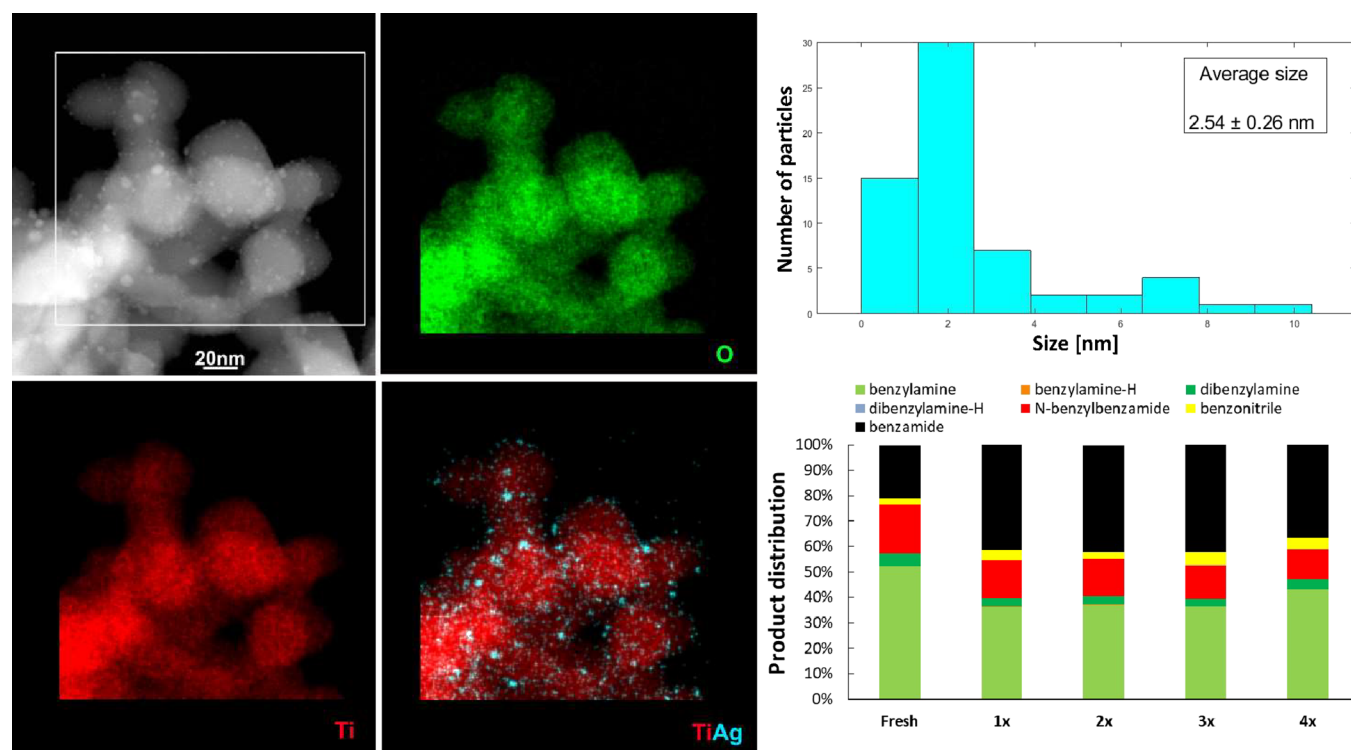
**Figure 10.** Influence of water on the hydrogenation of benzamide with Au and Ag catalysts. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar  $\text{NH}_3$ , 30 bar  $\text{H}_2$  (Au) or 50 bar  $\text{H}_2$  (Ag), 0.40 g Au catalyst (1 or 0.025 wt %) or 5 mol % Ag (2.5 wt % Ag catalyst), undecane (40  $\mu\text{L}$ ), CPME (20 mL), variable amount of water expressed in equivalent in comparison with the amount of substrate, and 5 h. (Product names ending with “-H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).

catalyst, respectively), with the NPs well dispersed over the catalyst support (Table S1). After using them once, the mean Au NP size increased very slightly. This stability is also noticeable in the recycling test (Figures 11 and 12). The activity of both the 0.025 and 1 wt % Au catalyst is retained over multiple runs. Characterization of  $\text{Au}/\text{ZrO}_2$  (1 wt % Au) again illustrated the importance of the catalyst support. While the catalyst has a higher number of surface Au atoms, with an average Au NP size of 6 nm versus 9 nm for 1 wt % Au on  $\text{TiO}_2$ , it still performed very poorly because of a low amide dehydration rate (Figure 3).

The  $\text{Ag}/\text{TiO}_2$  catalyst is clearly less stable than the Au catalysts. After using  $\text{Ag}/\text{TiO}_2$  only once, the average Ag NP size increased drastically from 2.5 to 9 nm (Table S1). Agglomerates with a size even larger than 100 nm were detected (Figure S12). This decreased stability was also noticeable when performing the recycling test. A clear drop in catalytic activity was observed between the first and second runs (Figure 13). Afterward, however, the catalytic activity remained stable. Thus, although the average Ag NP size increased, the catalyst can be reused several times as well.

**Substrate Scope.** Finally, the substrate scope was explored (Table 2 and Table S2). As indicated before, the most attractive option is to perform this reaction starting from benzoic acid. The reaction was performed in a fed-batch mode, via an analogous protocol as described in our previous paper: first, the amide was formed after a reaction with  $\text{NH}_3$ .<sup>33</sup> Second,  $\text{H}_2$  was added, and the hydrogenation took place. Although this reaction, resulting in more water formation, required a longer reaction time and slightly higher gold loading, the transformation of benzoic acid to benzylamine could be performed successfully. A yield of 91% benzylamine was obtained, which is an analogous result to when the reaction is performed using benzamide (entries 1 and 2). Esters of benzoic acid, for example, methyl benzoate, are also possible reactants (entry 3). Again, the inhibitory effect of an –OH group is clearly noticeable, with methanol being released in the ammonolysis. Despite a 10-fold excess of Au in comparison with a reaction with benzamide, 26% amide remained after reaction (15% benzamide and 11% N-





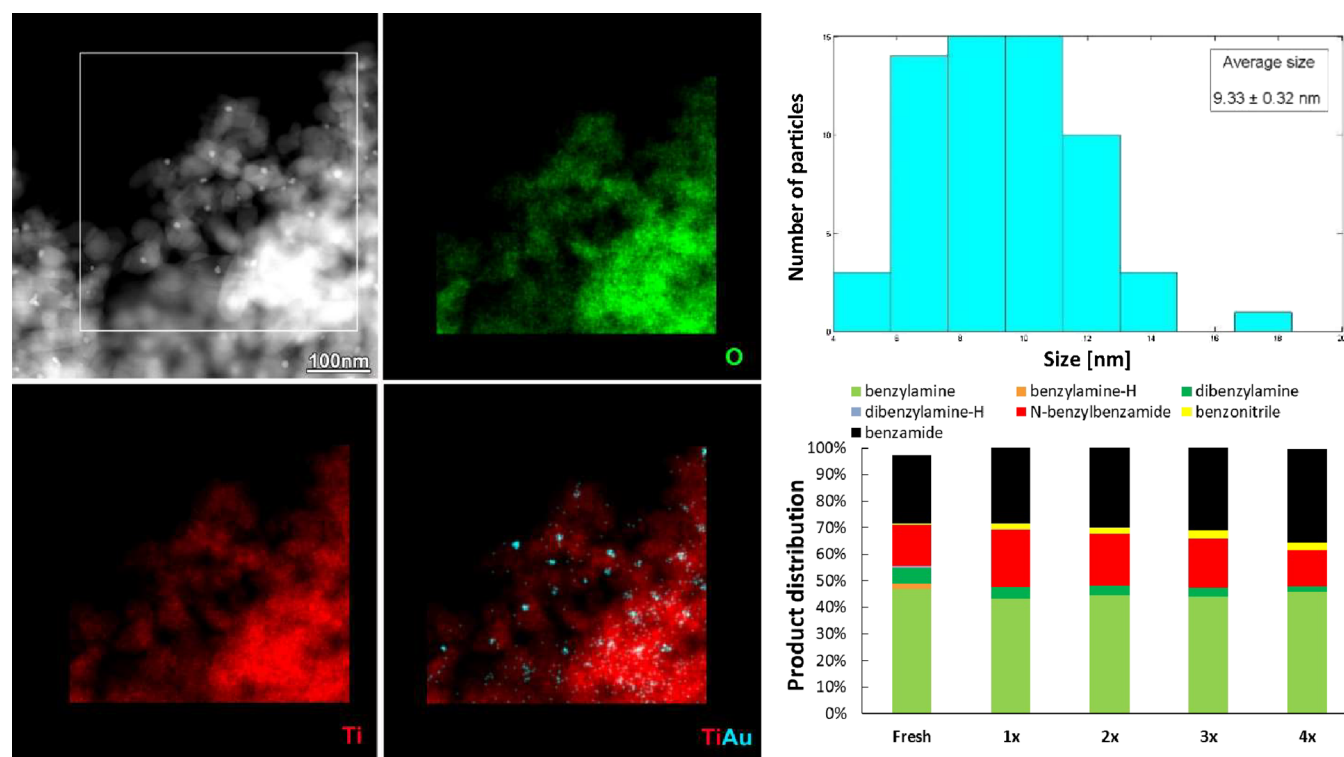
**Figure 11.** HAADF–STEM imaging and EDS elemental mapping of the Ag/TiO<sub>2</sub> (2.5 wt %, fresh) catalyst. Left: HAADF–STEM overview image of the investigated sample, together with the corresponding EDS elemental maps of Ti, O, and Ag. Top right: Size distribution of the supported Ag NPs based on 62 NPs. Bottom right: Recycling test of the investigated Ag catalyst. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar NH<sub>3</sub>, 50 bar H<sub>2</sub>, 5 mol % Ag, undecane (40 μL), CPME (20 mL), and 5 h. (Product names ending with “–H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).

benzylbenzamide). Next, the influence of substituents on the aromatic ring was investigated. Simple substituents such as methyl groups hardly seem to influence the reaction (entry 4). The same can be said for methoxy and dimethylamino groups (entries 5 and 6). These groups remain stable during the reaction, although such mesomerically donating groups appear to promote secondary amine formation. Fluorine groups pose no problem either. Although these electron-withdrawing groups make the aromatic ring less reactive, the reaction could be performed successfully with both –CF<sub>3</sub> and –F substituents on the aromatic ring (entries 7 and 8). Reactions with other halogens on the aromatic ring were less successful. Although a significant amount of 4-chlorobenzylamine is formed after a reaction with 4-chlorobenzamide, tiny amounts of dechlorination products were observed as well (2%, entry 9, and Table S2). Because Au is very sensitive to halogen-induced sintering at elevated temperatures,<sup>61,62</sup> this is not beneficial for the catalyst stability and will quickly halt the hydrogenation activity of the catalyst; after increasing the reaction time (not shown in the table), significant amounts of 4-chlorobenzonitrile still remain. The –Br and –I groups are not stable at all. The same holds for double carbon–carbon bonds outside a ring structure (entry 10). A reaction with cinnamamide resulted in the formation of 3-phenylpropanamide and 3-phenylpropanenitrile. This led to the conclusion that although nitrile formation occurs, the carbonyl group must be located directly on the ring to be susceptible to reduction to the amine. If this is not the case, no hydrogenation of the formed nitrile will take place. Not only different substituents but also different types of aromatic rings were studied (entries 11–13). The reaction was

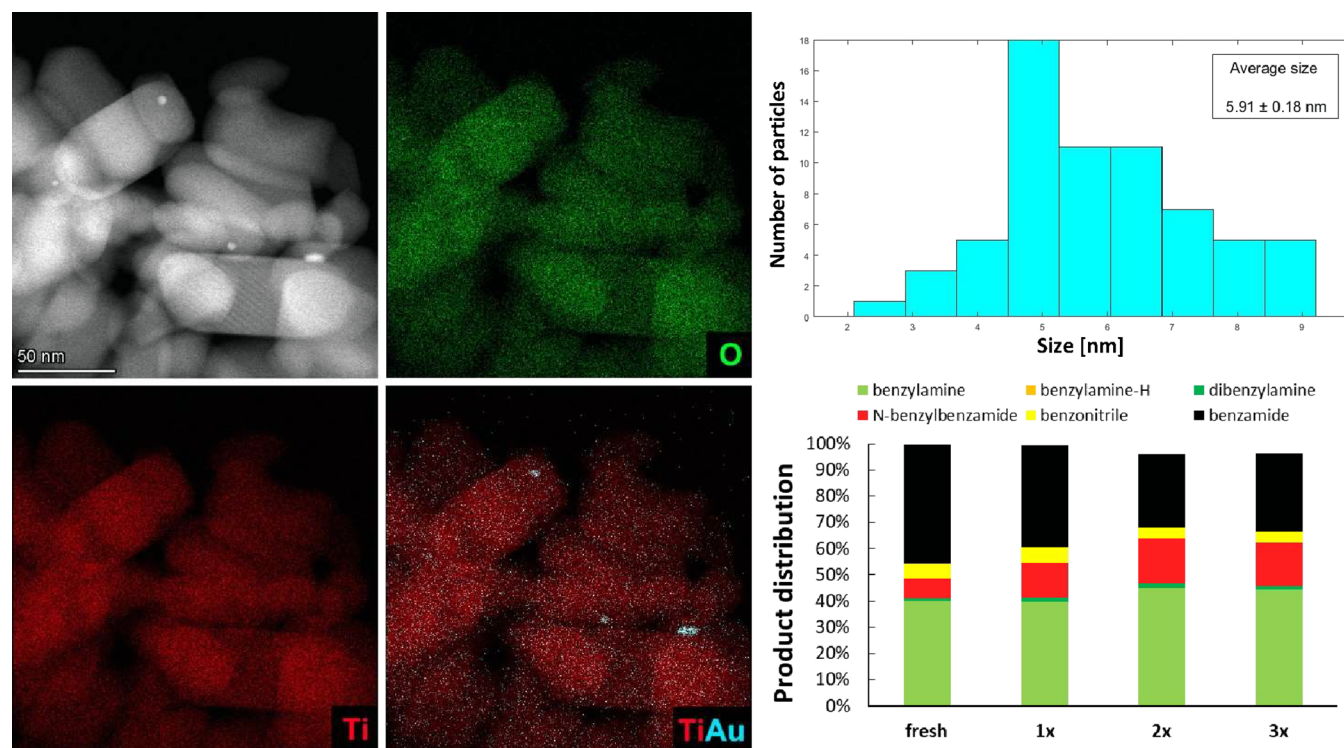
successful with polycyclic aromatic compounds such as 2-naphthoic acid (entry 11). However, such polycyclic aromatic compounds seem to be more prone to overreduction of the aromatic ring and defunctionalization (Table S2). The hydrogenation of compounds with N-heterocycles also posed no problem (entry 12). For compounds such as 2-furamide, however, that is, with an oxygen in the ring, the hydrogenation occurred extremely slowly (entry 13).

## CONCLUSIONS

In conclusion, both Ag/TiO<sub>2</sub> and Au/TiO<sub>2</sub> are excellent catalysts for the catalytic transformation of benzoic acid (and derivatives) to benzylamine: yields of up to 92% benzylamine were obtained with H<sub>2</sub> and NH<sub>3</sub> as the only reagents. Additionally, these silver and gold catalysts are reusable and relatively cheap. In the case of Au/TiO<sub>2</sub>, only 0.025 mol % Au is required. Mechanistic analysis by periodic DFT calculations indicates that the synergistic action of the multisite reaction environment at the metal–support interface plays a crucial role in the heterolytic cleavage of H<sub>2</sub> and selective polarization and reduction of the CN moiety. We also demonstrated that this reaction can be performed in any ether or hydrocarbon solvent; however, we recommend CPME or anisole to establish a green catalytic process. Reactions could be performed with highly concentrated reaction mixtures, although adjustments had to be made (e.g., longer reaction time) to drive the reaction to completion. This is caused by the hindering effect of water. Finally, an extensive substrate scope investigation was performed. The catalyst seemed to be suitable for a significant variety of substrates, resulting in good yields and selectivities for the corresponding primary amine.



**Figure 12.** HAADF–STEM imaging and EDS elemental mapping of the Au/TiO<sub>2</sub> (1 wt %, fresh) catalyst. Left: HAADF–STEM overview image of the investigated sample, together with the corresponding EDS elemental maps of Ti, O, and Au. Top right: Size distribution of the supported Au NPs based on 61 NPs. Bottom right: Recycling test of the investigated Au catalyst. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar NH<sub>3</sub>, 30 bar H<sub>2</sub>, 1 mol % Au, undecane (40 μL), CPME (20 mL), and 5 h. (Product names ending with “–H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).



**Figure 13.** HAADF–STEM imaging and EDS elemental mapping of the Au/TiO<sub>2</sub> (0.025 wt %, fresh) catalyst. Left: HAADF–STEM overview image of the investigated sample, together with the corresponding EDS elemental maps of Ti, O, and Au. Top right: Size distribution of the supported Au NPs based on 66 NPs. Bottom right: Recycling test of the investigated Au catalyst. Reaction conditions: benzamide (2 mmol), 200 °C, 6 bar NH<sub>3</sub>, 30 bar H<sub>2</sub>, 0.025 mol % Au, undecane (40 μL), CPME (20 mL), and 5 h. (Product names ending with “–H” have at least one aromatic ring that is hydrogenated toward a cyclohexyl moiety).

Table 2. Substrate Scope for the Synthesis of Aromatic Amines with the Au Catalyst<sup>a,b,c,d</sup>

	Catalyst	t <sup>a</sup> [h]	Substrate	X <sup>b</sup> [%]	Main product	S <sup>c</sup> [%]	Side product	S <sup>c</sup> [%]
1	0.025 wt% Au 0.025 mol% Au	16		97		95		3
2 <sup>d</sup>	0.1 wt% Au 0.35 mol% Au	70		99		91		4
3	0.25 wt% Au 0.25 mol% Au	16		74		75		10
4	0.025 wt% Au 0.038 mol% Au	16		> 99		89		10
5	0.025 wt% Au 0.038 mol% Au	16		93		73		26
6 <sup>d</sup>	0.1 wt% Au 0.3 mol% Au	72		97		82		15
7	0.025 wt% Au 0.038 mol% Au	16		74		89		11
8	0.025 wt% Au 0.05 mol% Au	16		40		99	/	/
9	0.025 wt% Au 0.05 mol% Au	16		31		63		7
10 <sup>d</sup>	0.025 wt% Au 0.038 mol% Au	16		> 99		65		31
11	0.1 wt% Au 0.3 mol% Au	72		> 99		33		12
12	0.025 wt% Au 0.038 mol% Au	5		68		93		5
13	0.025 wt% Au 0.038 mol% Au	16		10		97	/	/

<sup>a</sup>Reaction time. <sup>b</sup>Conversion, with both primary and secondary amides counted as the leftover reagent. <sup>c</sup>Selectivity. Reaction conditions: Substrate (2 mmol), 200 °C, 6 bar NH<sub>3</sub>, 30 bar H<sub>2</sub>, Au catalyst on TiO<sub>2</sub> support, undecane (40 μL), and CPME (20 mL). <sup>d</sup>Reactions with carboxylic acids were performed in a fed-batch mode where first a dehydration of the carboxylic acid to the amide was performed for several hours under solely NH<sub>3</sub>. Then, the reactor is pressurized with H<sub>2</sub> for the giving reaction time.

Thus, we developed an effective (heterogeneous) reductive amination system for benzoic acids, yielding benzylamines selectively.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acscatal.1c01693>.

Detailed experimental procedures, additional experimental data, characterization data, gas chromatography–mass spectrometry spectra of all compounds, and DFT calculations (PDF)

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## Notes

The authors declare no competing financial interest.

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