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## Efficacy of C–N Coupling Reactions with a New Multinuclear Copper **Complex Catalyst and Its Dissociation into Mononuclear Species**

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A new tetranuclear copper(I)-pyridazine (pda)/rhenate hybrid has been synthesized under hydrothermal conditions and structurally characterized by X-ray crystallography. The activity of this catalyst, as well as its dissociation into mononuclear species, was investigated in homogeneous C-N aryl-

#### Introduction

C-N coupling reactions are important and established chemical processes for the formation of many significant products, including drugs, organic materials, and optical devices.<sup>[1-3]</sup> Therefore the development of efficient catalytic systems for this reaction has attracted considerable attention in the past few years. A recent focus has been on the use of copper catalysts in place of the more toxic and expensive palladium catalysts.<sup>[2,4,5]</sup> Additional progress has been made to widen the reaction scope and to develop mild reaction conditions through the optimization of copperligand systems<sup>[6-10]</sup> and the application of other types of copper-containing catalysts, such as Cu<sub>2</sub>O-coated, soluble copper nanoparticles,<sup>[11]</sup> copper-exchanged apatites,<sup>[12]</sup> and copper-containing perovskites.<sup>[13]</sup> More recently, mechanistic investigations of Cu catalytic reactions have shown that the formation of defined copper-ligand complexes has substantial effects on the rate of C-N coupling reactions, although the isolation and full characterization of the solidstate and solution-phase structures of these copper-ligand intermediate complexes are still underdeveloped.<sup>[14]</sup>

In the search for new homogeneous and efficient catalyst systems for C-N coupling reactions, we became interested in the investigation and synthesis of new multimetallic copper complexes in which the copper atoms are held at specific distances from each other to allow the catalytic effects of multimetal-centered catalysis to be studied.<sup>[15-17]</sup> The catalytic properties of trimeric Cu<sup>I</sup>-carbene complexes in C-N coupling reactions have been investigated previously,

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ation reactions. A variety of N-arylamides and -azoles were synthesized in good to excellent yields, revealing the effect of polynuclear versus mononuclear Cu complexation in this type of coupling reaction.

and confirmed that trinuclear Cu<sup>I</sup> complexes catalyze highly efficient Ullman-type arylation reactions.<sup>[18]</sup> However, the mechanism and comparative efficacy of polynuclear Cu<sup>I</sup> complexes as catalysts in coupling reactions are still unclear and have not yet been reported. On the other hand, our current research involves the synthesis of new oxide/organic hybrids containing a combination of d<sup>10</sup> (i.e., Cu<sup>+</sup>) and d<sup>0</sup> (i.e., Re<sup>7+</sup>) transition metals, which have been explored for potential applications in areas such as smallmolecule absorption, magnetism, and catalysis.<sup>[19-21]</sup> For example, strong visible-light absorptions have been observed in Cu(pyz)ReO<sub>4</sub> and Cu<sub>3</sub>(q6c)<sub>2</sub>ReO<sub>4</sub>, both containing Cu<sup>I</sup> dimeric centers.<sup>[20]</sup> Hybrid solids in these systems can also undergo subsequent ligand-mediated structural transformations, such as found for Cu(bpy)ReO<sub>4</sub> and Cu(bpy)<sub>2</sub>ReO<sub>4</sub>·<sup>1</sup>/<sub>2</sub>H<sub>2</sub>O.<sup>[21]</sup> As part of this work, our continued interest in the coordination chemistry of pyridazine ligands led us to investigate the synthesis and characterization of a new tetranuclear copper(I)-pyridazine (pda)/rhenate hybrid and to explore its catalytic activity in C-N coupling reactions.

#### **Results and Discussion**

The crystalline compound [Cu<sub>2</sub>(pda)<sub>3</sub>(ReO<sub>4</sub>)<sub>2</sub>] (I) was synthesized by the hydrothermal reaction of pda with Cu<sub>2</sub>O and  $\text{Re}_2O_7$  (see the Experimental Section). We have previously demonstrated a similar pathway in the syntheses of a number of silver(I) and copper(I) hybrids.<sup>[19-21]</sup> X-ray analysis of the synthesized crystals showed that the resultant hybrid consists of tetranuclear Cu<sup>I</sup> atoms in the same plane with one rhenate counteranion (ReO<sub>4</sub>-) bonded to each Cu<sup>I</sup> center. As shown in Figure 1, each Cu atom exhibits a distorted tetrahedral geometry and is coordinated to three N atoms from three different pda rings and one O

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atom from a ReO<sub>4</sub><sup>-</sup> counteranion. Each of their bond lengths [i.e., Cu–N  $\approx$  1.953(6)–2.024(6) Å] are slightly larger than those in the reported Cu<sup>I</sup>-pyrazole tetranuclear cluster  $[Cu(\mu-3-tBu-5-iPrpz)]_4$  (Cu-N  $\approx 1.84$  Å)<sup>[22]</sup> in which the central copper atoms are two-coordinated in a nearly linear arrangement, similar to other known polynuclear CuI-pyrazole complexes.<sup>[23,24]</sup> However, for the values reported therein, it seems evident that three significant strains are present in I, for example, the very rare and quite long Cu<sup>I</sup>-O bonds [ $\sim 2.251(5)$  and 2.306(5) Å], which suggests a weak interaction, which is potentially important in its catalytic chemistry.<sup>[20]</sup> Furthermore, the geometry of  $\{CuN_3\}$  is nearly trigonal planar with N-Cu-N bond angles of ~120° (as listed in Figure 1). The sums of the N-Cu-N bond angles are very close to 360° [357.4(2)° and 355.3(2)° for Cu1 and Cu2, respectively] and are in excellent agreement with the electronic requirements of a trigonal-planar-coordinated Cu<sup>I</sup> center, which indicates only weak contributions of Cu-O to the Cu geometries, as confirmed by bond valence sum calculations (Table S1). Furthermore, the arrangement of Cu and pda is fundamentally different to those of reported polynuclear complexes in which the Cu/ligand ratio is 1:1. In I, the tetranuclear cluster  $[Cu]_4$  is a new type of structure with the uncommon composition  $[Cu_2(pda)_3]_2$  and can be viewed as two symmetric face-to-face Cu<sub>2</sub>(pda)<sub>3</sub> subunits. Each of the Cu<sub>2</sub>(pda)<sub>3</sub> subunits is comprised of [Cu<sub>2</sub>-(pda)<sub>2</sub>] in the same plane with one additional pda at the site-bridging position connected to the other neighboring symmetric Cu<sub>2</sub>(pda)<sub>3</sub> subunits. The intramolecular Cu…Cu distances (neighboring Cu1···Cu2) are 3.18(1) and 3.24(1) Å, which are close to the normal coplanar Cu-Cu distances in polynuclear complexes.<sup>[22,23]</sup> This tetranuclear complex is air-stable and thermogravimetric analysis (Figure S1) shows that the complex I is stable up to around 220 °C. In solution, the UV/Vis absorption spectrum of I exhibits a strong absorption at around 330 nm (Figure S2), typical of a Cu(d<sup>10</sup>)-to-ligand ( $\pi^*$ ) transition.<sup>[17]</sup> Noticeably absent is the copper(d<sup>10</sup>)-to-rhenate(d<sup>0</sup>) transition in solution. In contrast, the solid-state diffuse reflectance spectrum (Figure S3) displays an optical absorption onset at around 2.20 eV, which is similar to that of CuReO<sub>4</sub> and CuReO<sub>4</sub>(ligand) hybrids<sup>[20,21]</sup> and stems from an optical excitation from the valence to the conduction bands that corresponds to charge transfer between  $Cu(d^{10})$  and  $Re(d^0)$ , with smaller contributions from the ligand-based orbitals.

To first test the use of I as a precursor reagent of possibly either catalytic mono- or polynuclear Cu complexes in C– N arylation reactions, we selected *p*-iodoacetophenone (1) and indole (2) as coupling partners in our initial screening of optimal reaction conditions (Table 1). These two molecules were selected on the basis of their known coupling efficiency.<sup>[25,26]</sup> Initially we used 1 mol-% of I in pyridine with Cs<sub>2</sub>CO<sub>3</sub> as base at 170 °C for 3 h, which delivered the product **3** in 90% yield (Table 1, entry 1). Reduced reaction times, lower temperatures, and different solvents, including DMSO, THF, toluene, xylene, glyme, and dioxane, led to greatly diminished yields (Table 1, entries 2–7). However, reducing the amount of catalyst to 0.5 mol-% still gave sim-



Figure 1. Molecular structure of [Cu<sub>2</sub>(pda)<sub>3</sub>(ReO<sub>4</sub>)<sub>2</sub>] (I) showing the planar tetranuclear Cu<sup>I</sup> unit with symmetry unique atoms labelled. Red ellipses are O, blue are N, white are C, yellow are Re, and light-blue are Cu. Hydrogen atoms have been omitted for clarity. Probability thermal ellipsoids are drawn at the 80% level. Selected bond lengths [Å], angles [°], and torsion angles [°]: Cu1-N1 2.002(5), Cu1-N3 1.994(6), Cu1-N4 1.988(5), Cu1-O8 2.306(5), Cu2-N2 1.998(5), Cu2-N5 1.953(6), Cu2-N6 2.024(6), Cu2-O1 2.251(5), Re1-O1 1.757(5), Re1-O2 1.656(5), Re1-O3 1.686(8), Re1-O4 1.714(7), Re2-O5 1.804(10), Re2-O6 1.629(10), Re2-O7 1.691(9), Re2-O8 1.667(6), Cu1-Cu2 3.179(1), Cu1-Cu2' 3.237(1); N1-Cu1-N4 116.8(2), N1-Cu1-N3 118.0(2), N1-Cu1-O8 94.8(2), N3-Cu1-O8 90.9(2), N3-Cu1-N4 122.6(2), N4-Cu1-O8 100.5(2), N2-Cu2-N5 129.5(2), N2-Cu2-N6 103.3(2), N2-Cu2-O1 93.6(2), N5-Cu2-N6 122.5(2), N5-Cu2-O1 106.4(2), N6-Cu2-O1 88.7(2), Cu1-Cu2-Cu1'-Cu2' 0, N1-N3-N4-Cu1 11.3(1), N2-N5-N6-Cu2 11.4(1).

ilar yields (see the Supporting Information). Thus, the turnover number of the reaction can reach up to 45, which is larger than that of previously reported Cu<sup>I</sup>/ligand catalysts (ca. 10–20).<sup>[2–4,7,8]</sup> Omitting Cs<sub>2</sub>CO<sub>3</sub> (Table 1, entry 8) or using the amine bases TEA and DBU (Table 1, entries 9 and 10) provided **3** in low yields. On the other hand, the application of K<sub>3</sub>PO<sub>4</sub> as a base produced **3** in an excellent yield of 92% (Table 1, entry 11). The high yields obtained from the application of inorganic bases may be due to their high thermodynamic strength in aprotic solvents coupled with their low solubility and thus low concentration.<sup>[7]</sup> The

Table 1. Optimization of the conditions for the coupling reactions between p-iodoacetophenone (1) and indole (2) catalyzed by I.

	-1 + ()) H 2	Cu cat., base, solvent 170 °C, 3 h	
Entry	Base	Solvent	Yield [%]
1	Cs <sub>2</sub> CO <sub>3</sub>	pyridine	90
2	$Cs_2CO_3$	DMSO	trace
3	$Cs_2CO_3$	THF	48
4	$Cs_2CO_3$	toluene	32
5	$Cs_2CO_3$	xylene	13
6	$Cs_2CO_3$	glyme	46
7	$Cs_2CO_3$	dioxane	38
8	_	pyridine	trace
9	TEA	pyridine	trace
10	DBU	pyridine	26
11	K <sub>3</sub> PO <sub>4</sub>	pyridine	92

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90–92% yield of **3** compares favorably with previous reports in the literature.<sup>[2–4,7–10,27,28]</sup> In addition, the coupling reactions display substantially reduced reaction times compared with literature reports (3 h in contrast to 15– 24 h).<sup>[2–4,7–10,15,27]</sup>

By using the optimized reaction conditions (Cs<sub>2</sub>CO<sub>3</sub> in pyridine at 170 °C for 3 h), we then investigated the generality of the C–N coupling reaction. As shown in Table 2 and Table 3, a range of differently substituted aryl halides and different functional groups on the nitrogen heterocycles are tolerated, and fast and efficient catalytic C–N coupling reactions with a broad substrate scope were conducted. First, we analyzed the reactions of several aryl iodides with various electron-withdrawing and -donating substituents and three different *N*-nucleophilic substrates (Table 2) under the optimized reaction conditions. Previous reports have demonstrated that the electronic properties of the substituent on the aryl halide plays a very important role in determining its reactivity in C–N reactions.<sup>[2,28]</sup> As expected, the

Table 2. Coupling reactions of differently substituted iodobenzenes 1 and 6–9 with different N-nucleophilic substrates 2, 4, and 5.

coupling reactions of electron-withdrawing benzenes 1, 6, and 7, containing 4-acetyl or nitro groups at the 2- or 4position, proceeded to give excellent yields of 84-97% (Table 2, entries 1–3, 6–8, and 11). The coupling of 6 and 7, containing 2- and 4-NO<sub>2</sub> groups, with caprolactam (5) proved an exception due to the generation of unidentified side-products (Table 2, entries 12 and 13). Simple iodobenzene (8) underwent coupling with indole (2) or caprolactam (5) to give yields of 94 and 93%, respectively (Table 2, entries 4 and 14). In the case of the electron-donating iodobenzene 9, the yields of the reactions with 2 and 4 were lower at 58 and 45%, respectively (entries 5 and 10). However, the reactions of 5 were tolerated for aryl iodides with both electron-withdrawing and -donating substituents. As shown in Table 2 (entries 11, 14, and 15), electronic effects

Table 3. Coupling reactions between p-iodoacetophenone (2) and the heterocycles 2, 4–5, and 24–27.

R <sup>1</sup>	+	R <sub>2</sub> NH Cu cat. (4 Cs <sub>2</sub> CO <sub>3</sub> , 170 °C 2, 4-5	t mol-%) pyridine, C, 3 h	R1111 NR2 3, 10-23
Entry	R <sub>2</sub> NH	$\mathbf{R}^{1}$	Product	Yield / %
1	$\sim$	4-C(O)CH <sub>3</sub> (1)	3	90
2		4-NO <sub>2</sub> ( <b>6</b> )	10	97
3	2	2-NO <sub>2</sub> (7)	11	92
4		Н (8)	12	94
5		4-OCH <sub>3</sub> (9)	13	58
6		4-C(O)CH <sub>3</sub>	14	84
7	N N N	4-NO <sub>2</sub>	15	94
8	4	2-NO <sub>2</sub>	16	93
9		Н	17	48
10		4-OCH <sub>3</sub>	18	45
11	O.	4-C(O)CH <sub>3</sub>	19	85
12	NH	4-NO <sub>2</sub>	20	56
13	5	2-NO <sub>2</sub>	21	59
14		н	22	93
15		4-OCH <sub>3</sub>	23	87

O CH <sub>3</sub>	+ R <sub>2</sub> NH	Cu cat. (4 mol-%) Cs <sub>2</sub> CO <sub>3</sub> , pyridine, 170 °C, 3 h	
1	2,4, 5, 24-27		3,14, 19, 28-31
Entry	R <sub>2</sub> NH	Product	Yield / %
1		3	90
	2		
2	N N N N N N N N N N N N N N N N N N N	28	64
3	N N H	29	54
	25		
4	26	30	trace
5		31	81
0	4	14	84
7	NH 5	19	85

on the reactions were limited and the yields of 4-acetyl- and 4-methoxyiodobenzenes were not significantly different.

Next we investigated the reactivity of different nitrogen heterocycles in the catalyzed C–N coupling reactions. As shown in Table 3, the coupling reactions of *p*-iodoacetophenone (1) proceeded in excellent yields (81-90%, Table 3, entries 1 and 5–7) with various aromatic amines, including indole (2), pyrazole (4), and imidazole (27), as well as with the lactam 5. However, the coupling of the aryl iodide 1 with 1*H*-indazole (24) and benzimidazole (25) resulted in mediocre yields of 64 and 54%, respectively (Table 3, entries 2 and 3), with the generation of unidentified side-products. Also, only a trace of the product was observed when *p*-iodoacetophenone was coupled with tetrahydroquinoline (26), probably because of its lower acidity and subsequently more difficult ionization.<sup>[8,29]</sup>

Although a precise mechanism for copper-catalyzed cross-coupling reactions has not yet been established, several literature reports have indicated the formation of Cu<sup>I</sup> and Cu<sup>III</sup> intermediates.<sup>[30]</sup> As determined by NMR spectroscopy (see the Supporting Information), the tetranuclear complex I fragments into mononuclear Cu<sup>I</sup> atoms stabilized by pyridine ligands. To understand the importance of this finding for the coupling reactions, several control experiments were carried out as shown in Table 4. First, the coupling reaction between *p*-iodoacetophenone (1) and indole (2) catalyzed by I in pyridazine as the solvent delivered the product 3 in only 37% yield (Table 4, entry 1), which indicates that maintaining the tetranuclear nature of the catalyst is a disadvantage for efficient catalysis. However, under the same conditions using either pyridine or pyrazine ligands as solvent the yields dramatically increased to 90% (Table 4, entries 2 and 3), which further indicates the importance of converting the tetranuclear species I into a mononuclear Cu<sup>I</sup> center. This is also supported by the observation that using 1 mol-% of I in THF in conjunction with 16 mol-% of pyridine led to an increase in yield from 48 (Table 1, entry 3) to 84% (Table 4, entry 4). To investigate the importance of the ReO<sub>4</sub><sup>-</sup> counterion, simple CuI was

Table 4. Investigation of the Cu<sup>I</sup>-catalyzed coupling reaction between *p*-iodoacetophenone (1) and indole (2) catalyzed by I (1 mol-%) or CuI (4 mol-%).

O CH <sub>3</sub>	) + (N) 1	2 Cu cat., $Cs_2CO_3$ solvent 170 °C, 3 h $CH_3$	3
Entry	Catalyst	Solvent	Yield [%]
1	Ι	pyridazine	37
2	Ι	pyridine	90
3	Ι	pyrazine	90
4	Ι	THF + pyridine (16 mol-%)	84
5	CuI	pyridine	92
6	CuI	pyrazine	85
7	CuI	pyridazine	22
8	CuI	pyridine + pyridazine (6 mol-%)	95

selected as the copper source and was employed in the coupling reaction in the presence of different ligands (solvents). As shown in Table 4, entries 5–8, the trends in the reaction yields are the same for both catalysts I and CuI, with the yields being substantially higher in pyridine and pyrazine than in pyridazine because the latter will presumably form or maintain the tetranuclear nature of the catalyst as shown in Figure 1.

Based on these results, we propose that the mechanism of the C–N coupling reaction catalyzed by I involves four steps (Scheme 1). Pyridine breaks up the tetranuclear complex I into the mononuclear Cu–pyridine complex 32 in the first step. The second step involves the oxidative addition of the aryl halide to  $Cu^{I}$ –pyridine to form a six-coordinated copper(III) species 33. The third step involves the N-nucleophilic substitution of I<sup>-</sup> by indole. Finally, the Cu<sup>III</sup> complex undergoes reductive elimination to give the C–N crosscoupled product. Interestingly, the PXRD patterns of complex I before and after the coupling reactions match well (Figure S6), which shows that the tetranuclear complex I can be reformed by evaporation of the solvent.



Scheme 1. Proposed mechanism for the *N*-arylation reaction promoted by the copper(I) complex I in pyridine.

### Conclusions

We have developed a new, air-stable, tetranuclear Cu<sup>I</sup> complex that is broken up into mononuclear species in pyridine solution thus enabling excellent catalytic efficiency in

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homogeneous C–N coupling reactions. Under the optimal reaction conditions we were able to couple a broad range of aryl iodides and various nitrogen heterocycles to the corresponding products in short reaction times. On the basis of our mechanistic investigations it appears that the tetra-nuclear Cu species needs to be converted into mononuclear units for efficient catalysis. We are currently investigating the generality of this discovery for Cu-catalyzed C–N coupling reactions.

### **Experimental Section**

**General Methods:** Unless otherwise stated, all the reagents were used without further purification. Pyridine was distilled from CaH<sub>2</sub>. The C–N coupling reactions were performed under N<sub>2</sub> in flame-dried sealed vials. All products were purified by column chromatography and the yields were determined by weight. All spectra were recorded in CDCl<sub>3</sub> and the chemical shifts are reported relative to CHCl<sub>3</sub> ( $\delta$  = 7.24 ppm for <sup>1</sup>H NMR) and CHCl<sub>3</sub> ( $\delta$  = 77.24 ppm for <sup>13</sup>C NMR).

Synthesis of the Copper Catalyst: Catalyst I was synthesized by adding Cu<sub>2</sub>O (28.8 mg, 0.20 mmol), Re<sub>2</sub>O<sub>7</sub> (96.8 mg, 0.20 mmol), pda (32.0 mg, 0.40 mmol), and deionized H<sub>2</sub>O (0.40 g, 22.2 mmol) to an FEP Teflon pouch. The pouch was heat-sealed and placed inside a 125-mL Teflon<sup>®</sup>-lined stainless steel reaction vessel which was backfilled with deionized H<sub>2</sub>O (ca. 45 mL) before closing. The reaction vessel was heated to 150 °C for 72 h inside a convection oven and slowly cooled to room temperature at 6 °C/h. Orange barshaped crystals of I were obtained in about 70% yield. The phase purities of each compound were >95% according to the powder X-ray diffraction data. Cu<sub>2</sub>(pda)<sub>3</sub>(ReO<sub>4</sub>)<sub>2</sub>·H<sub>2</sub>O (1771.62): C 16.27, H 1.59, N 9.49; found C 16.45, H 1.50, N 9.40.

Single-crystal X-ray diffraction data for compound I were collected with a Bruker–Nonius X8 Apex2 CCD diffractometer at a temperature of 296 K using Mo- $K_a$  radiation ( $\lambda = 0.71073$  Å). Selected crystal and refinement data for I: [Cu<sub>2</sub>(pda)<sub>3</sub>(ReO<sub>4</sub>)<sub>2</sub>·H<sub>2</sub>O], M =1771.62, monoclinic,  $P2_1/n$ , a = 10.5513(3), b = 16.0133(5), c =12.7303(4) Å,  $\beta = 96.150(2)^\circ$ , V = 2138.6(1) Å<sup>3</sup>, Z = 2,  $D_{calcd.} =$ 2.751 g/cm<sup>3</sup>, F(000) = 1632.0, final R1 = 0.0366, wR2 = 0.0873 [for  $I > 2\sigma(I)$ ], GOF = 1.027.

CCDC-819530 contains 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.

General Procedure for the C-N Coupling Reaction: The NH-containing substrate (0.15 mmol), Cs<sub>2</sub>CO<sub>3</sub> (0.2 mmol), and the Cu complex I (1 mol-%) were added to a solution of the aryl halide (0.1 mmol) in dry pyridine (1 mL) under nitrogen. The vial was sealed and heated at 170 °C for 3 h in an oil bath, cooled to room temperature, filtered, and the filtrate was concentrated under vacuum. The product was purified by column chromatography on SiO<sub>2</sub> and eluted with hexanes/ethyl acetate to deliver 1-[4-(1H-indol-1yl)phenyl]ethanone (3),<sup>[25]</sup> 1-(4-nitrophenyl)-1H-indole (10),<sup>[31]</sup> 1-(2-nitrophenyl)-1*H*-indole (11),<sup>[31]</sup> 1-phenyl-1*H*-indole (12),<sup>[32]</sup> 1-(4methoxyphenyl)-1*H*-indole (13),<sup>[33]</sup> 1-(4-pyrazol-1-ylphenyl)ethanone (14),<sup>[10]</sup> 1-(4-nitrophenyl)-1*H*-pyrazole (15),<sup>[10]</sup> 1-(2-nitrophenyl)-1*H*-pyrazole (16),<sup>[34]</sup> 1-phenyl-1*H*-pyrazole (17),<sup>[32]</sup> 1-(4methoxyphenyl)-1*H*-pyrazole (18),<sup>[32]</sup> *N*-(4-acetylphenyl)caprolactam (19),<sup>[35]</sup> N-(4-nitrophenyl)caprolactam (20),<sup>[36]</sup> N-phenylcaprolactam (22),<sup>[35]</sup> N-(4-methoxyphenyl)caprolactam (23),<sup>[35]</sup> 1-[4-(1H- benzimidazol-1-yl)phenyl]ethanone (**29**),<sup>[37]</sup> 4-(imidazol-1-yl)acetophenone (**31**)<sup>[38]</sup> (all literature-known), as well as *N*-(2-nitrophenyl)caprolactam (**21**) and 1-[4-(1*H*-indazol-1-yl)phenyl]ethanone (**28**).

*N*-(2-Nitrophenyl)caprolactam (21): Eluted with hexanes/ethyl acetate (2:1, 1:1, 1:2); yield 59%. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  = 7.91 (d, *J* = 8.0 Hz, 1 H), 7.59 (t, *J* = 8.0 Hz, 1 H), 7.38 (t, *J* = 8.0 Hz, 1 H), 7.27 (d, *J* = 8.0 Hz, 1 H), 3.87 (br., 1 H), 3.69 (br., 1 H), 2.64 (br., 1 H), 2.74–1.65 (m, 6 H) ppm. <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>):  $\delta$  = 175.8, 138.1, 134.1, 128.97, 127.8, 125.2, 53.5, 37.6, 30.2, 28.8, 23.0 ppm. MS: calcd. for C<sub>12</sub>H<sub>14</sub>N<sub>2</sub>NaO<sub>3</sub> [M + Na]<sup>+</sup> 257.1; found 257.1.

**1-[4-(1***H***-Indazol-1-yl)phenyl]ethanone (28):** Eluted with hexanes/ ethyl acetate (6:1); yield 64%. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  = 8.23 (s, 1 H), 8.12 (d, J = 8.4 Hz, 2 H), 7.87 (d, J = 8.4 Hz, 2 H), 7.84–7.80 (m, 2 H), 7.47 (t, J = 8.0 Hz, 1 H), 7.26 (t, J = 8.0 Hz, 1 H), 2.64 (s, 3 H) ppm. <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>):  $\delta$  = 197.1, 144.2, 138.8, 136.9, 134.8, 130.1, 128.0, 126.1, 122.4, 121.8, 121.7, 110.8, 26.8 ppm. MS: calcd. for C<sub>15</sub>H<sub>13</sub>N<sub>2</sub>O[M + H]<sup>+</sup> 237.1; found 237.1.

**Supporting Information** (see footnote on the first page of this article): Bond valence sums and additional analytical data for I and NMR spectra of new compounds.

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