This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the Information for Authors.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal’s standard Terms & Conditions and the Ethical guidelines still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.
Synthesis and Characterization of 1, 3-diamino-graphene as a Heterogeneous Ligand for CuI-catalyzed C-N Coupling Reaction †

Limei Zhou *, Mengyun Yin, Xiaohui Jiang, Qiang Huang, and Wencheng Lang

1, 3-diamino-graphene (NH$_2$-G-NH$_2$) materials were synthesized by a simple chemical method. The as-prepared materials were characterized by FT-IR, TG, XRD, XPS, and SEM measurements. The results revealed that 1, 3-diamino has been successfully grafted on the graphene and can immobilize CuI by coordination interaction. The NH$_2$-G-NH$_2$ materials can be used as heterogeneous ligands for CuI catalyzed C-N coupling reactions, and the desired products were obtained with good yields. The reaction system is much smoother at lower temperature compared with other previous reports. Additionally, the new method can easily realize the purification of products and recyclability of catalysts.

Introduction

Graphene, which has a two dimensional carbon plane with a thickness of one atom, attracted extensive attention in catalysis fields such as photochemistry, electrochemistry and organic catalysis for the past few years.$^{1-5}$ Graphene oxide (GO) is an oxidized form of graphene, which holds rich hydroxyl, epoxy, carbonyl and carboxyl groups on its basal planes and edges.$^{6}$ Hence, these defective structures are favourable for chemical adjustment of graphene. The obtained functionalized graphene materials commonly hold superior performance than unmodified graphene, including electrical conductivities, mechanical performance, thermal stability, and dispersibility. Many applications of functionalized graphene have been explored based on these properties, such as sensors,$^7$ carrier materials for drug$^8$ and catalysts.$^9$ Especially, amino-functionalized graphene materials as solid base catalysts$^{10, 11}$ or supports$^{12}$ have potential values which can be very promising substitutes for heterogeneous catalysts. Amino can be grafted on graphene via amino-silanes$^{13, 14}$ or n-BuLi followed by an electrophilic substitution with bromotriethylamine$^{10}$. Diamine is usually used as effective ligand in metal catalysis. Especially, 1, 3-Diamine can be used as chelating ligand$^{14-17}$ or key regent for forming di-schiff base$^{16, 17}$. However, to our best knowledge, few reports exist about synthesis of 1, 3-diamino-graphene.

Based on these researches, we intensively believed that the diamine functionalized graphene can promote the CuI-catalyzed C-N coupling reactions.

In continuation of these studies, 1,3-diamino-graphene (NH$_2$-G-NH$_2$) was prepared and used as heterogeneous ligand for copper-catalyzed C-N coupling reaction in this work. The experimental results showed that the new method can effectively overcome the hard separation of catalyst and purification of products. By using Cu as the catalyst and NH$_2$-G-NH$_2$ materials as the promoters, the C-N cross-coupling of various aryl halides with N-heterocycles under very mild conditions gave the corresponding products in good yields.

Experimental

Materials

Graphite powder was purchased from Shanghai Huaiy Company (Shanghai, China). KMnO$_4$, NaNO$_2$, H$_2$SO$_4$ (98%) and HCl (36%-38%) were obtained from Sinopharm Chemical Reagent Co. Ltd. (Shanghai China). Cuprous iodide (CuI) and malononitrile were purchased from Kelong Chemical Reagent Co. Ltd. (Chengdu China). Iodobenzene, calcium hydride and lithium aluminium hydride were obtained from Aladdin Industrial Inc. America. GO was synthesized by the oxidation of graphite powder according to our previous method. 

Materials

Graphite powder was purchased from Shanghai Huaiy Company (Shanghai, China). KMnO$_4$, NaNO$_2$, H$_2$SO$_4$ (98%) and HCl (36%-38%) were obtained from Sinopharm Chemical Reagent Co. Ltd. (Shanghai China). Cuprous iodide (CuI) and malononitrile were purchased from Kelong Chemical Reagent Co. Ltd. (Chengdu China). Iodobenzene, calcium hydride and lithium aluminium hydride were obtained from Aladdin Industrial Inc. America. GO was synthesized by the oxidation of graphite powder according to our previous method.
report. The deionized (DI) water used throughout all experiments was purified to 18.2 MΩm with the Millipore system.

Synthesis of 1, 3-diamo-no-graphene (NH₂-G-NH₂)

40 mg GO was dispersed into 30 mL dry THF by sonication to obtain homogeneous suspension, and marked as A solution. Next, 70 mg CaH₂ and 200 mg malononitrile were mixed in 20 mL dry THF by continuously stirring at 0 °C, and labeled as B solution. Then, solution B was dropwise added into solution A by stirring at 60 °C for 24 h. After completion of the reaction, the solid was filtrated and washed by HCl, deionized water 3 times and ethanol 2 times to thoroughly remove the Ca²⁺.

30 mg malononitrile-functionalized graphene oxide (CN-GO) was dispersed into 20 mL anhydrous THF, and 150 mg LiAlH₄ was dissolved into 20 mL anhydrous THF. Next, the LiAlH₄ solution was added into the graphene derivatives suspension by continuously stirring at room temperature for 24 h. The obtained product was filtrated and washed by HCl, deionized water 3 times and ethanol 2 times to thoroughly remove the residual Li⁺ and Al³⁺. Finally, the 1, 3-diamo-no-graphene (NH₂-G-NH₂) was dried under high vacuum.

General procedure for the catalytic C-N coupling reaction

10 mg NH₂-G-NH₂, 1.2 mmol nitrogen heterocycles, 2.0 mmol base and 0.05 mmol CuI were added into a 10 mL reaction vessel fitted with a stir bar. Then 1.0 mmol aryl halide and 2 mL anhydrous DMSO was added into the vessel with the protection of nitrogen. The reaction mixture was stirred for a specified period of time at required temperature, and the progress of the reaction was monitored with thin layer chromatography. Next, the obtained product was diluted with 20 mL H₂O and extracted with 3×15 mL ethyl acetate. The organic layers were combined together and dried overnight with anhydrous Na₂SO₄. Finally, the product was purified by flash chromatography using dichloromethane and methanol as the eluent, and the solvent was evaporated under vacuum.

Characterization

The samples were characterized by Fourier Transform Infrared Spectroscopy (FT-IR, Nicolet 6700, USA), Scanning Electron Microscopy equipped with an energy dispersive X-ray spectrometer (SEM, ARIEL JSM-6510LV, JAPAN), Thermogravimetric analyses (TGA, Netzsch STA 449F3, Germany), X-Ray Photoelectron Spectroscopy (XPS, Thermo ESCALAB 250XI, USA), and X-Ray Diffraction (XRD, D/MAX Ultima IV, JAPAN).

Results and discussion

NH₂-G-NH₂ materials were prepared according to the following procedure. Firstly, the reaction of malononitrile with GO was chosen and then the reduction of malononitrile functionalized graphene oxide was carried out by LiAlH₄ in THF (Scheme 1). The obtained materials were characterized and used as heterogeneous ligand for Cul-catalyzed C-N coupling reaction.

Scheme 1 Illustration of the synthesis of NH₂-G-NH₂ materials.

Fig. 1 FT-IR analysis of GO, CN-GO and NH₂-G-NH₂.

Next, the thermal stability of GO and NH₂-G-NH₂ were measured using TGA in Ar atmosphere and the results are shown in Fig. 2. The first weight loss was observed below 200 °C for GO materials, corresponding to the evaporation of water. The second weight loss was observed between 200 and 500 °C, and the loss is due to the pyrolysis of COOH and carbonyl groups. The weight loss above 500 °C may be caused by the decomposition of hydroxyl and epoxide groups. In contrast, the mass loss of NH₂-G-NH₂ material is obviously lower than that of GO, which indicates that the NH₂-G-NH₂ material is more stable. A significant weight loss was observed at 200 °C for NH₂-G-NH₂ material. In order to study the functional groups on the NH₂-G-NH₂ material around 200 °C, the sample after treating by TG in Ar atmosphere at 200 °C (NH₂-G-NH₂-200 °C) was measured by FT-IR (Fig. S1, ES1†). It can be seen that there is no obvious change between the FT-IR spectra of NH₂-G-NH₂ and NH₂-G-NH₂-200 °C, but the relative intensity of υ(NH) at 3421 cm⁻¹ is weakened for NH₂-G-NH₂-200 °C sample, which may be caused by the evaporation of water. So the first weight loss below 200 °C for NH₂-G-NH₂ material can be ascribed to the evaporation of water. The weight loss in the range of 200-500 °C can be attributed to the pyrolysis of a small amount of COOH and carbonyl groups which were unreduced by LiAlH₄. The weight loss above 500 °C may be caused by the decomposition of 1, 3-diamo-no and hydroxyl groups.
Fig. 2 TG analysis of GO and NH$_2$-G-NH$_2$.

To better understand the role of NH$_2$-G-NH$_2$ in the C-N coupling reactions, we carried out a reaction between CuI (0.05 mmol) and 10 mg NH$_2$-G-NH$_2$ in 2 mL of anhydrous DMSO in a sealed tube under stirring for 20 h at 90 °C. After reaction, solid material was obtained by filtration. The obtained material was denoted as CuI/NH$_2$-G-NH$_2$. Further characterizations were carried out by XRD, XPS, and SEM.

The X-ray diffraction patterns of GO, CN-GO, NH$_2$-G-NH$_2$, and CuI/NH$_2$-G-NH$_2$ were shown in Fig. 3. The XRD peak of GO was observed at 2θ = 10.5°, corresponding to an average interlayer spacing of ~ 0.84 nm due to the presence of oxygen-containing functional groups attached on both sides of the graphene sheets. After grafting CN on the GO, the interlayer spacing of GO has no obvious change. However, the characteristic peak of NH$_2$-G-NH$_2$ at 10.5° disappeared, which indicates that the reduction of CN-GO was accomplished successfully. Next, the CuI/NH$_2$-G-NH$_2$ catalyst was characterized. Obviously, the crystalline CuI can be observed, which indicates the NH$_2$-G-NH$_2$ can well immobilize the Cu owing to the coordination interaction between amino groups and Cu ions.

Fig. 3 XRD analysis of GO, CN-GO, NH$_2$-G-NH$_2$, and CuI/NH$_2$-G-NH$_2$.

Fig. 4 showed the X-ray photoelectron spectra (XPS) of GO, RGO, NH$_2$-G-NH$_2$, and CuI/NH$_2$-G-NH$_2$. The C1s XPS spectrum of GO is consisted of four types of carbon: the C-C/C=C (285.0), C=O (287.0), C=O (287.8), and COOH (288.8) (Fig. 4a). When GO was reduced by LiAlH$_4$ at room temperature, the RGO material could be obtained. In the C1s XPS spectrum of RGO, the peak intensities of C=O, C=O, and COOH obviously decrease, corresponding to the reduction of epoxy, carbonyl, and carboxyl groups by LiAlH$_4$ (Fig. 4b). The signals in the Fig. 4c can be associated with C1s, O1s, and N1s, confirming the presence of nitrogen in the amino functionalized graphene. According to previous reports, that binding energy of Al2p, Al2s, and Li1s are 74.5, 119.4, and 54.8 ev, respectively. But there is no peak between 1-200 ev (Fig. 4c). Therefore, it can be concluded that a clean amino-graphene has been obtained. The C1s spectrum of NH$_2$-G-NH$_2$ (Fig. 4d) was deconvoluted into five main peaks, which is attributed to C-C/C=C, C-N, C-O, C=O and COOH, respectively. Moreover, the N1s spectrum of NH$_2$-G-NH$_2$ shows one peak at 399.8 ev, which can be ascribed to hydrogen-bonded amino groups. But CuI addition will break the hydrogen bonding. The N1s spectrum could be divided into two peaks for CuI/NH$_2$-G-NH$_2$ in Fig. 4e, one peak at 399.0 ev is ascribed to free terminal amines and another peak at 400.1 ev is attributed to amino groups coordinated to Cu metallic center. Furthermore, the copper valence state on NH$_2$-G-NH$_2$ surface was confirmed by the XPS analysis in Fig 4f. The Cu 2p1/2 peak at 932.7 ev is assigned to Cu$^+$, whereas the peak at 934.5 ev is ascribed to Cu$^2+$, which probably results from oxidation of Cu$^+$ exposure to air.

Fig. 4 XPS analysis of GO, RGO, NH$_2$-G-NH$_2$, and CuI/NH$_2$-G-NH$_2$. (a) C1s XPS spectrum of GO. (b) C1s XPS spectrum of RGO. (c) Full range XPS spectrum of NH$_2$-G-NH$_2$. (d) C1s XPS spectrum of NH$_2$-G-NH$_2$. (e) N1s XPS spectrum of NH$_2$-G-NH$_2$ and CuI/NH$_2$-G-NH$_2$. (f) Cu2p XPS spectrum of CuI/NH$_2$-G-NH$_2$.

Finally, the morphology of the typical products was investigated by the SEM. From Fig. 5, it can be clearly seen that the NH$_2$-G-NH$_2$ sheets exhibit a typical rippled and crumpled morphology and paper-like structure with single or very thin layers. However, the agglomeration of CuI/NH$_2$-G-NH$_2$ catalyst is discovered after the CuI was supported. In order to identity the elementary composition of the agglomeration, four arbitrary little agglomerations were measured by energy dispersive X-ray spectrometer (EDS). The results of EDS images and analysis showed that these agglomerations are CuI/NH$_2$-G-NH$_2$ catalysts (Fig. S2-S5, ESI†). So it may be reasonable that the coordination interaction between Cu
and amino on the graphene sheets caused the agglomeration of amino-graphene sheets.

Generally, it is of great significance to research utilization range of a novel material in the practical application like electronchemistry and catalysis areas. Hence, to evaluate the NH$_2$-G-NH$_2$ materials in organic synthesis, C-N coupling reactions of imidazole with iodobenzene was investigated. A preliminary survey of reaction conditions was conducted including the effects of copper source, base, temperature and the amount of graphene. By using the NH$_2$-G-NH$_2$ as the promoter, the results showed that the system containing 2 mmol KOH, 90 °C, 5 mol% of CuI and 10 mg NH$_2$-G-NH$_2$ can drive the coupling reaction, obtaining 1-phenyl-1H-imidazole in 98% (Table 1, Entry 1). To better understand the role of the 1,3-diamino-graphene in the model reactions, we evaluated GO as the heterogenous ligand in place of NH$_2$-G-NH$_2$. As can be seen, the use of GO afforded 83% yield (Table 1, Entry 11). Meanwhile, in the absence of heterogeneous ligand, the yield of the desired product was 81% (Table 1, Entry 12). These results demonstrate that the 1,3-diamino-graphene is an effective additive for CuI-catalyzed C-N coupling reaction.

**Table 1** Effect of different reaction conditions for the C-N coupling reactions of imidazole with iodobenzene

<table>
<thead>
<tr>
<th>Entry</th>
<th>Cu source</th>
<th>Graphene</th>
<th>Base</th>
<th>Temp. (°C)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>90</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>CuCl</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>90</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>CuCl$_2$</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>CuSO$_4$</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>90</td>
<td>96</td>
</tr>
<tr>
<td>5</td>
<td>Cu(OAc)$_2$</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>90</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>NaOH</td>
<td>90</td>
<td>88</td>
</tr>
<tr>
<td>7</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>LiOH</td>
<td>90</td>
<td>86</td>
</tr>
<tr>
<td>8</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>K$_2$CO$_3$</td>
<td>90</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>80</td>
<td>90, 70°, 87°</td>
</tr>
<tr>
<td>10</td>
<td>Cul</td>
<td>NH$_2$-G-NH$_2$</td>
<td>KOH</td>
<td>70</td>
<td>46</td>
</tr>
<tr>
<td>11</td>
<td>Cul</td>
<td>GO</td>
<td>KOH</td>
<td>90</td>
<td>83</td>
</tr>
</tbody>
</table>

After the optimization researches, we aimed to explore the scope and limitations of the developed methodology. Firstly, the coupling reactions of aryl halides with N-H heterocycles were carried out. As shown in Table 2, the reactivity of aryl iodides in the C-N coupling reaction is higher than the aryl bromides and chlorides. At the same time, the influence of electronic effect of substituent is obvious in these reaction systems. For the NH$_2$-G-NH$_2$ catalytic system, aryl halides containing electron-withdrawing (EW) groups can be conducted smoothly to afford the corresponding products in good yields, while a moderate yields can be obtained for these aryl halides with electron-donating (ED) substituent. Interestingly, the steric hindrance of the substituent of reactant had a little effect for the reactions. When a nitro substituent was present in any position of the benzene ring of aryl halides, we obtained the desired compounds in 82%, 87%, and 90% yields for the NH$_2$-G-NH$_2$ system (Table 2, Entries 4-6). In the next step, the cross-couplings between iodobenzene and various nitrogen heterocycles were tested in this work. It was found that relative good reactivity was obtained with different N-heterocycles (Table 2, Entries 12-16).
Entries 1, 2, and 8). Generally, the homogenous catalysis has milder reaction conditions than heterogeneous catalysis. But, to our joy, the NH₂G-NH₂ catalysis system exhibited approximate activity compared with homogeneous ligand N,N’-dioxide (Table 4. Entries 3 and 7) and even higher activity compared with the other homogeneous ligands (Table 4. Entries 4-6, and 8).

Table 4 Comparison of different heterogeneous or homogeneous ligand for CuI-catalyzed C-N coupling reaction of iodobenzene and imidazole

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand</th>
<th>Conditions</th>
<th>Yield (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indion 770</td>
<td>Cu: 10 mol%, K₂CO₃, DMSO, 125 °C</td>
<td>94</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>Meso-N-C-1</td>
<td>Cu: 15 mol%, KOH, DMSO, 125 °C</td>
<td>88</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>N,N’-dioxide</td>
<td>Cu: 10 mol%, Cs₂CO₃, DME, 80 °C</td>
<td>95</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Metformin</td>
<td>Cu: 5 mol%, Cs₂CO₃, DMF, 110 °C</td>
<td>98</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>Tetrazole 1-acetic acid</td>
<td>Cu: 5 mol%, NaOH, DMSO, 110 °C</td>
<td>84</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>L-histidine</td>
<td>Cu: 10 mol%, K₂CO₃, DMSO, 100 °C</td>
<td>91</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>NH₂G-NH₂</td>
<td>Cu: 5 mol%, KOH, DMSO, 80 °C</td>
<td>90</td>
<td>This study</td>
</tr>
<tr>
<td>8</td>
<td>NH₂G-NH₂</td>
<td>Cu: 5 mol%, KOH, DMSO, 90 °C</td>
<td>98</td>
<td>This study</td>
</tr>
</tbody>
</table>

Conclusions

In summary, 1, 3-diamo functionalized graphene material was synthesized by a simple chemical method. FT-IR, TG, XRD, XPS, and SEM measurements revealed that 1, 3-diamo has been successfully grafted on the graphene and can immobilize CuI by coordination interaction. Notably, the as-prepared amino functionalized graphene material can be used as heterogeneous ligand for CuI catalyzed C-N coupling reactions, and the desired products were obtained with good yields. Compared with other previous reports, the reaction system is much smoother at lower temperature. In addition, the new method can easily realize the recyclability of catalysts and purification of products. Finally, we believe that 1, 3-diamo-graphene materials can also be used as heterogeneous ligand or support for other tradition meals (Ru, Pd, Rh, etc) catalysis. And the 1, 3-diamo-graphene may react with salicylaldehyde, forming di-schiff base graphene materials. Further studies for the application of 1, 3-diamo-graphene materials are currently underway in our laboratory.

Acknowledgements

The authors are grateful for financial support from the Natural Science Foundation of China (21303139).

References
ARTICLE

1,3-diamino-graphene was synthesized and used as an efficient heterogeneous ligand for 
CuI-catalyzed C-N coupling reaction.