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One-Pot, High-Yielding, Oxidative Cyclodehydrogenation Route for N-Doped Nanographene Synthesis

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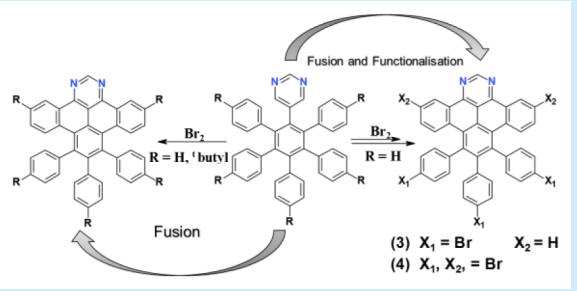
Supporting Information

ABSTRACT: An intramolecular oxidative cyclodehydrogenation via a one-pot process is described, which induces selective C−C bond formation and bromine functionalization. The application of this new route gives rise to a novel family of partially fused, selectively brominated N-doped pyrimidine graphenes.



Interest in the synthesis of N-containing polycyclic hydrocarbons (PAHs), particularly from a materials chemistry perspective, is growing exponentially.[1] The realization of multiple inter- and intramolecular bond fusions in halogenated polyphenylenes, catalyzed by Au(111),[2] Pt(111),[3] and Cu(111)[4] surfaces,[5−7] has prompted this revived research attention. Such processes offer low-energy routes to N-doped graphene nanoribbons and nanofragments, via single-source precursors.[5,6,8] Synthetic work is required, however, to improve the yield and purity of the N-doped halogenated precursors and to optimize the selectivity of their coupling reactions.

Oxidative cyclodehydrogenation in solution (the Scholl reaction) is understood to require a Lewis acid and oxidant and to occur either by a radical cation (electron transfer) or by an arenium cation (proton transfer) mechanism.[9,10] In N-containing materials, the extent of ring fusion is highly catalyst- and dopant- dependent. For one polyphenylene precursor, 1,2-dipyrimidyl-3,4,5,6-tetra(4-*tert*-butylphenyl)benzene, fully fused materials were previously obtained using $AlCl_3/CuCl_2$ as Lewis acid and oxidant, whereas a variety of incomplete ring closures are produced when $FeCl_3$ is used.[11,12] Increasing the number of N dopant atoms causes a decrease in reactivity, even in the presence of resonance-stabilizing methoxy substituents.[13] Such a lack of specificity and control has given rise to the search for alternative catalytic reagents.

The authors have an established interest in the bottom-up fabrication of N-doped graphene fragments.[12,14,15] Prompted by this and the drive to develop and test new routes to N-doped fused and partially fused materials, they decided to revisit the earlier findings of Gourdon et al. into the cyclodehydrogenation of diaza-substituted polyphenylenes.[16] This work had shown that cyclodehydrogenations using $AlCl_3/CuCl_2$ or $MoCl_5$ gave rise to insoluble polychlorinated products and had led the authors to conclude that *para* unsubstituted pendant phenyl rings promote uncontrolled oligomerization.

Using elemental bromine under controlled conditions, this new work demonstrates that it is possible to induce intramolecular bond formation at the pyrimidine rings in diaza-substituted polyphenylenes. Furthermore, it shows that controlled bromination is achievable at the *para* positions of pendant unsubstituted phenyl rings, giving a range of brominated pyrimidine-fused PAHs. Figure 1 shows the mass spectrum of the reaction mixture, comprising 1-pyrimidyl-2,3,4,5,6-pentaphenylbenzene (**1**) and elemental bromine after 10 min. At room

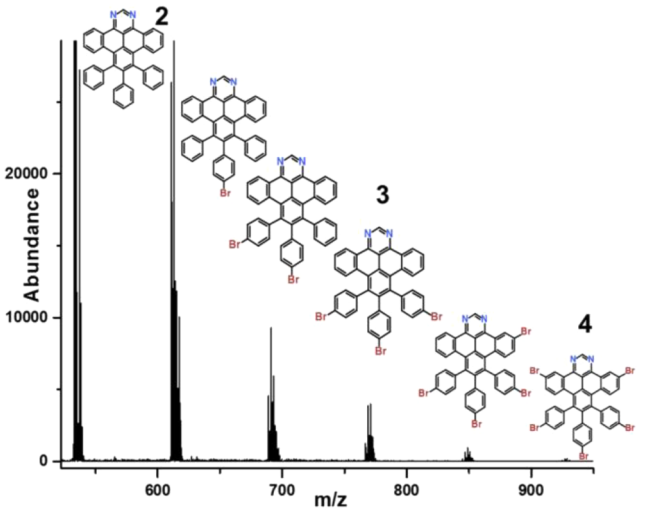


Figure 1. Mass spectrum of a sample of the reaction mixture of 1-pyrimidyl-2,3,4,5,6-pentaphenylbenzene polyphenylene (**1**) and bromine after 10 min in an open vessel at room temperature.

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temperature, no remaining uncyclized polyphenylene is observed after a reaction time of 10 min. By controlling the time and temperature of the reaction, the degree of substitution can be optimized to yield 8,9,10-tris(4-bromophenyl)-tribenzoperimidine (**3**) and 5,13-dibromo-8,9,10-tris(4-bromophenyl)tribenzoperimidine (**4**) in 80 and 50% yields, respectively.

Inspired by the one-pot reaction conditions employed by Rathore to generate hexakis(4-bromophenyl)benzene,[17] we used a 1×10^{-8} M solution of polyphenylene **1** in $CDCl_3$, with 100 equiv of reagent grade bromine. Despite the fact that the excess bromine would cause significant shifting of the NMR signals of the products, a study of the crude reaction mixture was undertaken, using in situ ^{1}H NMR spectroscopy. From this, it was possible to gain an insight into the time scale of each step of the reaction as it proceeded. The spectroscopic study, over the course of 25 min, documented the almost instantaneous nature of the cyclization between the pyrimidine ring and its neighboring phenyl rings, the stepwise bromination of the pendant phenyl rings, and finally the bromination of the fused pyrimidine core. The information garnered from the resulting ^{1}H NMR spectra (S15) suggested how we might vary the reaction conditions (reaction time, temperature, solvent, vessel conditions (open or closed)) to separately optimize the formation of each of the products.

Initially, **1** was reacted in neat bromine at room temperature for varying reaction times (5 min to 5 h) to yield different proportions of **2**, **3**, and **4**. Column chromatography using dichloromethane as eluent, followed by recrystallization from dichloromethane/methanol, allowed the isolation of each highly pure fraction. Subsequently, more direct routes to two of the major products were successfully obtained. Changing to pressure tube conditions in toluene resulted in the formation of only **2** in quantitative yields. The pure product could be crystallized directly from the reaction mixture without the need for any additional purification. Refluxing in chloroform was successful in driving the reaction to higher yields of the pentabrominated **4**. The evolution of HBr was observed in all cases. Figure 2 presents the individual spectra of the isolated materials.

^{1}H NMR spectroscopy was the primary tool for characterizing the new products. A comparison of the spectra is presented in Figure 2. Taking the spectrum of the starting material as a reference, the most dramatic change occurs upon the initial cyclization to give **2**, whereupon the resonance of proton (H1) in the pyrimidine ring of **1** shifts from 8.6 ppm to a peak at 9.8 ppm. Once this ring is fused (as in **2**, **3**, and **4**), the chemical shift of this signal remains essentially constant. The signal at 8.2 ppm (H2) in the starting material (corresponding to both protons, α to nitrogen) is now absent. From the in situ experiment, a plot was generated of the integrations of the pyrimidyl signals (e.g., H1 and H2) and their variation with reaction time. The plot is consistent with the rapid formation of the C−C intramolecular bonds (complete within 4 min). Fusion results in the significant deshielding of protons (H4) (from the multiplet at 6.9 ppm in **1**) to a doublet at 9.4 ppm in the ^{1}H NMR spectra of **2** and **3** (Figure 2). This doublet then becomes a singlet in **4** after the final bromination takes place.

Fortunately, single-crystal X-ray diffraction was possible for most of the isolated products and gave data that were consistent with those arising through spectral characterization techniques. Diffusion of 5-(4′,5′,6′-triphenyl-[1,1′:2′,1″-terphenyl]-3′-yl)-pyrimidine into toluene solutions allowed the growth of single crystals of **2**, suitable for single-crystal X-ray diffraction

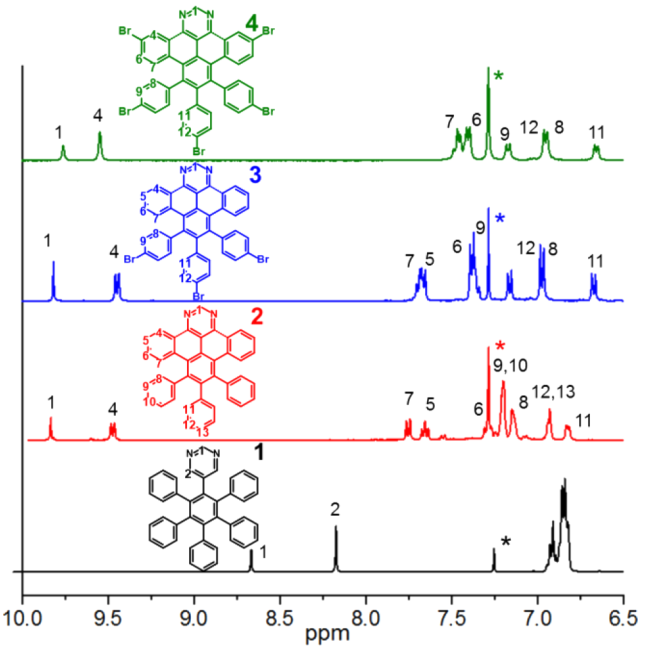

Figure 2. ^{1}H NMR spectra of **1** and the isolated products **2**, **3**, and **4** in $CDCl_3$ (solvent signal marked with an asterisk).

measurements. The molecule crystallized in the $P\bar{1}$ space group with two molecules per unit cell. Solvent molecules found in the voids could not be modeled to an acceptable level, and therefore, SQUEEZE was applied.

As a result of the ring closure, the fused phenyl and pyrimidine rings now form part of a significantly curved bowl-like structure. The strained nature of this pyrimidine section results in a curve of 20° at the extremities, relative to the plane of the central ring. The molecules pack in a head-to-tail fashion, with $\pi-\pi$ interactions between the aromatic cores resulting in intermolecular distances of 3.538 Å. Analysis of the single-crystal X-ray structure of the tribrominated **3** shows that the bromine atoms present result in only minimal changes to the molecular structure. The dimeric lateral overlap of the fused aromatic portions, however, was very much enhanced in **3**, possibly due to the presence of two dichloromethane molecules in the void, as seen in Figure 3b.

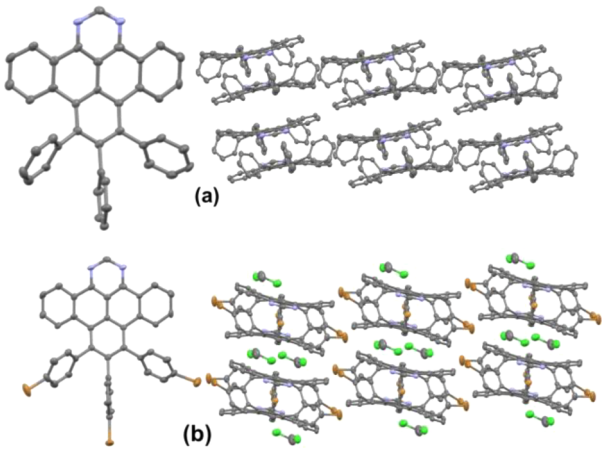

Figure 3. (a) Asymmetric unit and packing motif of **2**; (b) asymmetric unit and packing motif of **3**. Displacement ellipsoids shown at 50%. Hydrogen atoms omitted for clarity.

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At this point, it was decided to explore the generality of the new method and to apply it to the more challenging 4N-containing polyphenylene 1,2-dipyrimidyl-3,6-bis(4-*tert*-butylphenyl)-4,5-bis(4-bromophenyl)benzene **5**. This precursor was chosen for comparison with a system previously studied by Draper et al.[15] The difference in this case is that two *t*-butyl groups are present to block two of the *para* positions on the pendant phenyls. On heating dipyrimidyl polyphenylene precursor **5** in toluene with Br_2 for 45 min, the half-cyclized product **6** was isolated in 70% yield (Figure 4). This was a positive improvement on the reported yields of similar half-cyclized analogues that were generated by the traditional $FeCl_3$ route (e.g., 32%).[12]

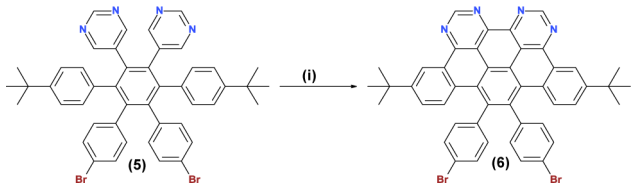

Figure 4. Schematic of the reaction to generate a fused dipyrimidyl analogue (**6**) from polyphenylene precursor (**5**): (i) Br_2, toluene, 90 °C, 1 h.

Recrystallization of **6** from CH_2Cl_2/MeOH yielded the product as a crystalline yellow solid. After filtering, no further purification was necessary, and on diffusing the product in a methanol solution, twinned crystals suitable for X-ray diffraction studies were genereated. The data were refined as a two-component twin using PLATON and HKLF 5 and were successfully integrated using a triclinic unit cell. The unit cell contains 6 H_2O molecules, which were treated as a diffuse contribution to the overall scattering without specific atom positions by SQUEEZE/PLATON. The packing motif (Figure 5) shows the head-to-tail stacking between alternating molecules, with very small interplanar distances of 3.365 and 3.349 Å.

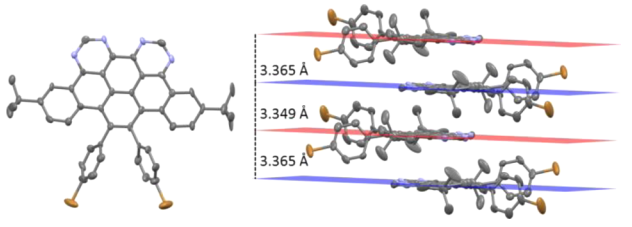

Figure 5. Asymmetric unit and packing motif of **6**. Displacement ellipsoids shown at 50%. Hydrogen atoms omitted for clarity.

For all-carbon systems, cyclodehydrogenation is not seen to occur by the route presented here. All carbon hexaphenylbenzenes are seen to only undergo *para* bromination, while precursors blocked at these sites show no reaction at all. Increasing the number of pyrimidine rings has a direct influence on the total number of C−C bond formations achieved. This can be limited, ultimately, at higher degrees of closure, at which point the twisted nature of the increasingly fused molecule possibly inhibits any further reaction. It is likely that, in the presence of nitrogen atoms, cyclodehydrogenation progresses via an arenium cation mechanism. This could be rationalized by protonation of the pyrimidine ring, thereby generating a cation at the adjacent carbons, *ortho* to both nitrogen atoms. Evidence for this is seen in the fact that cyclodehydrogenation never occurs with adjacent phenyl rings bearing electron-withdrawing substituents, such as Br. This new work supports the general consensus that for bond formation to occur, via electrophilic attack, a sufficiently electron-rich contiguous ring is required.

In summary, a gateway reaction has been demonstrated that offers an unprecedented and one-step process to partially fused and bromo-functionalized N-doped polyaromatics. These are suitable for chemical functionalization and/or further aromatization using existing routes. The work impacts recent publications that mark the point of convergence between top-down and bottom-up synthetic routes to doped nanoribbons. The arrival of an alternative reagent to brominated precursors with precise substitution patterning will provide new opportunities for the control of the symmetry and edge characteristics of graphene materials and the broadening of their potential application in electronic devices. Under the right conditions, such materials can be intermolecularly stitched to form a patchwork holey graphene sheet or nanoribbon. The new selective fusion and bromination of highly aromatic di- and tetra-aza PAHs also introduces a high-yielding methodology to deliver novel ligands. The systems isolated to date are relevant to making orthometalated or N-coordinated transition metal complexes with interesting photophysical applications.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b03312.

Additional experimental details and figures (PDF)

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Notes

The authors declare no competing financial interest.

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