

New palladium catalysed reactions of bromoporphyrins: synthesis and crystal structures of nickel(II) complexes of primary 5-aminoporphyrin, 5,5'-bis(porphyrinyl) secondary amine, and 5-hydroxyporphyrin†

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Primary aminoporphyrin, secondary bis(porphyrinyl)amine and hydroxyporphyrin complexes have been isolated and characterised both spectroscopically and crystallographically from the reaction of 5-bromo-10,15,20-triphenylporphyrinatonicel(II) with hydrazine under palladium catalysis.

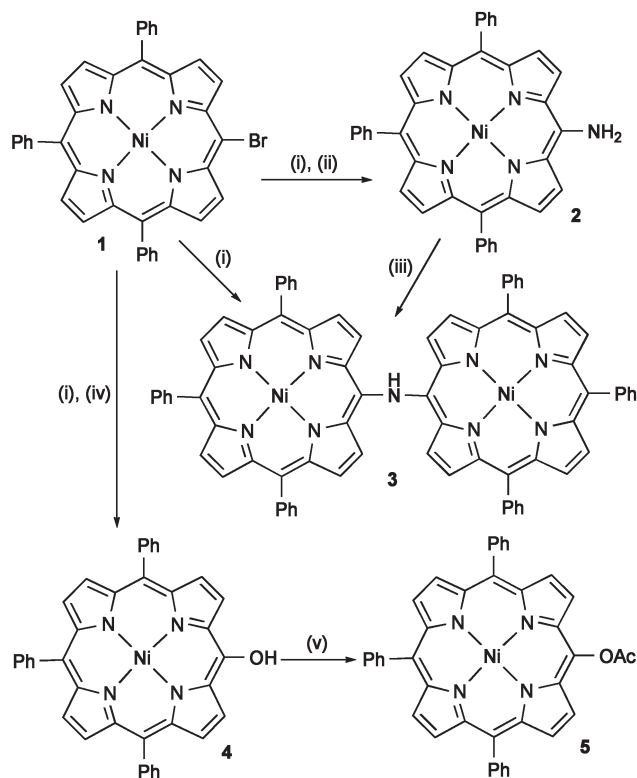
Palladium catalysed coupling reactions on haloporphyrins have revolutionised the functionalisation of the porphyrin periphery.¹ There are now many and varied examples of successful C–C and C–X couplings, especially on the *meso* positions(s) of 5,15-diaryl- or 5,10,15-triarylporphyrins, to produce a range of functionalised mononuclear derivatives, as well as di- and oligonuclear arrays with alkynyl, alkenyl and aromatic linkers. Recently, there have been examples of porphyrin–heteroatom couplings with nucleophiles such as amines,^{2,3} amides,^{2,4} alcohols and phenols⁵ thiols,⁶ and phosphine sources.⁷

In seeking to extend the amination/amidation reactions, we reacted bromoporphyrins with *tert*-butyl and ethyl carbazates, and uncovered a strong tendency for the bis(carbazate) porphyrins to oxidize to azocarboxylates or to de-aromatise to form novel diiminoporphodimethenes.⁸ As an extension of this work, we tried the same conditions (first reported for amidation by Takunami *et al.*²) with *unsubstituted* hydrazine as nucleophile, using palladium(II) acetate and *rac*-BINAP as catalyst precursors, caesium carbonate as base, and THF as solvent. The porphyrin precursor, 5-bromo-10,15,20-triphenylporphyrinatonicel(II) (NiTriPPBr, **1**), with just one available *meso* position, was chosen to avoid complications of the type seen in our work with the carbazates.⁸

The results of this experiment (Scheme 1) at a molar ratio of 2(**1**) : 1(N₂H₄·H₂SO₄) were surprising and remarkable. From the one reaction mixture, we isolated and obtained X-ray crystal structures for three novel nickel(II) complexes, namely the primary amine NiTriPPNH₂ **2**, the secondary amine (NiTriPP)₂NH **3** and the hydroxyporphyrin NiTriPPOH **4**.[†] Logically, the secondary amine **3**, the first bis(porphyrinyl)amine to be isolated, results from amination of **1** by **2**. However, formation of the primary amine by the apparent Pd-induced cleavage of hydrazine or a porphyrinyl-hydrazine and the formation of a phenol analogue in an amination

reaction mixture deserved closer scrutiny. We therefore investigated the effects of changing the ratios of the various components and have discovered conditions that favour the formation of **2** or **4** from **1**, and also obtained **3** by independent reaction of **2** with **1**.

The aminoporphyrin **2** can be isolated in high yield by increasing the relative amount of hydrazine. Even at 1 : 1 molar ratio, the primary amine becomes the major product and formation of **3** and **4** is suppressed. The NMR spectrum of **2** is typical for a *meso*-amino porphyrin, the NH₂ signal appearing at 5.77 ppm.¹⁰ Similar primary aminoporphyrins have previously been prepared by the NaBH₄/Pd/C reduction of the metallonitroporphyrin, itself obtained under mild conditions from the free base unsubstituted porphyrin substrate using I₂/AgNO₂, followed



Scheme 1 Palladium catalysed amination and hydroxylation. *Reagents and conditions:* (i) hydrazine sulfate (0.5 eq.), Pd cat., THF, 68 °C, 15 h; (ii) hydrazine sulfate (1 eq.), Pd cat., THF, 68 °C, 16 h, 51%; (iii) **1**, Pd cat., dioxane, 100 °C, 3 d, 25%; (iv) Pd cat., THF, 68 °C, 4.5 d, 79% [Pd cat. = Pd(OAc)₂ (7 mol%), *rac*-BINAP (20 mol%), Cs₂CO₃ (7 eq.)]; (v) Ac₂O, py, 75 °C, 10 min, 77%.

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by metallation.¹⁰ This new method from the nickel(II) bromoporphyrin and hydrazine is competitive in terms of crude yield and reaction time, but the nitration/reduction route can be scaled up more readily. A control experiment in the absence of palladium salt led only to small amounts of debromination of **1** after 3 days.

The amination of **1** with **2** is a sluggish reaction in THF, but using 1,4-dioxane at 100 °C, the yield of purified **3** after recrystallisation has been increased to 25%. The two amines can be readily separated from each other by column chromatography. Further optimisation experiments are in progress. While there are a few examples of diporphyrins linked by just one carbon atom,¹¹ there are no other *meso,meso*-linked diporphyrins with a single *heteroatom* bridge. The unique NH proton appears significantly downfield at 9.86 ppm, and the effects of close proximity of the porphyrin rings are apparent in the chemical shifts of the ring protons on the 10,20-phenyl groups, which are more widely dispersed than those of **2**. As expected, the UV-visible spectrum of **3** differs considerably from that of **2** (Fig. 1), the split Soret band indicating the expected excitonic coupling between the transition dipoles of the two rings. The Q bands are also significantly shifted to lower energy.

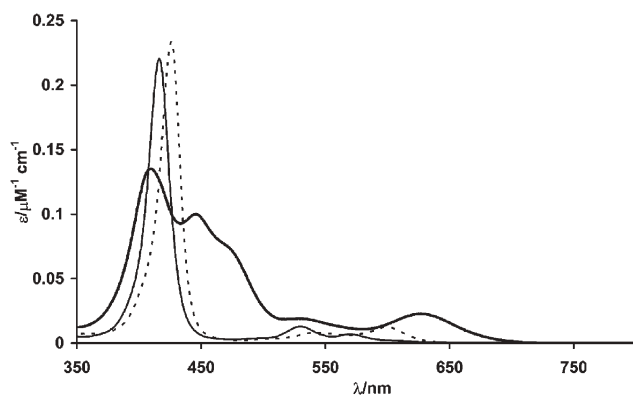


Fig. 1 UV-visible spectra of **2** (dashed), **3** (bold), and **4** (solid) in CH_2Cl_2 .

Lastly, the hydroxyporphyrin **4** can be readily prepared selectively in 79% yield, by the simple expedient of omitting the hydrazine in the reaction with **1** and extending the reaction time. This implies that the caesium carbonate is actually providing the nucleophile for reaction on the palladium. Although we conducted experiments with rigorous drying of the base, we cannot yet rule out the possibility that water is required. To our knowledge, Pd-catalysed formation of hydroxyarenes by such a method is unreported. The normal Pd promoted route to phenols from halobenzenes uses *tert*-butoxide or *tert*-butyldimethylsiloxide as protected hydroxide source.¹² Hydroxyporphyrin metal complexes (the free bases of which exist as the keto “oxophlorin” tautomer) have been investigated in detail because of their significance (as Fe complexes) in the natural heme degradation pathways.¹³ They are usually prepared by oxidative routes,¹⁴ but for the triarylporphyrin Ni(II) complexes, this new method is very convenient and high-yielding.

Hydroxyporphyrin complexes readily oxidise and deprotonate to give oxygen-centred free radicals, which in several cases have been characterised crystallographically.¹³ This phenomenon is evident for **4**, as the proton NMR spectrum is broad and

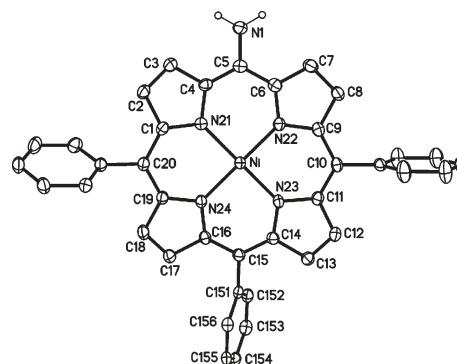


Fig. 2 View of the molecular structure of **2** in the crystal. Thermal ellipsoids are drawn for 50% occupancy; selected hydrogen atoms have been omitted for clarity.

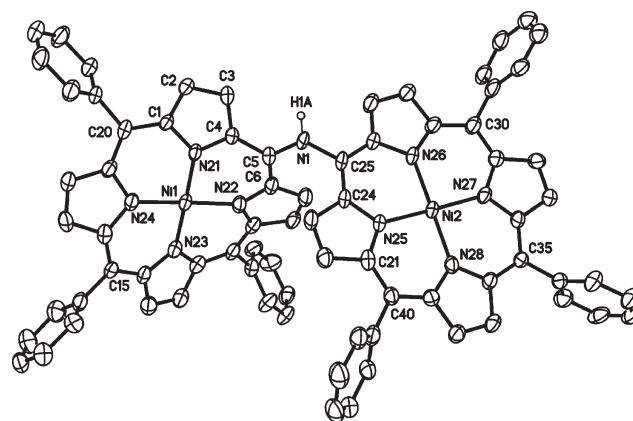


Fig. 3 View of the molecular structure of **3** in the crystal. Thermal ellipsoids are drawn for 50% occupancy; selected hydrogen atoms have been omitted for clarity.

uninterpretable, however upon addition of excess hydrazine hydrate to the CDCl_3 solution, the lines sharpen and appear as expected for a mono-*meso*-substituted nickel(II) triarylporphyrin. The UV-visible spectrum of **4** also implies the presence of small and variable amounts of the oxyl radical, with a very weak band at 803 nm appearing in some samples.¹⁵ Compound **4** was further characterised by its simple conversion into the corresponding acetate **5** by reaction with acetic anhydride and pyridine.

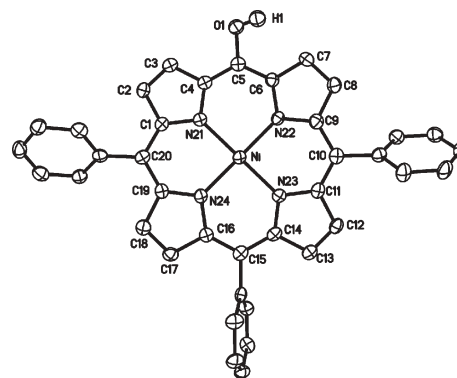


Fig. 4 View of the molecular structure of **4** in the crystal. Thermal ellipsoids are drawn for 50% occupancy; selected hydrogen atoms have been omitted for clarity.

The crystal structures of **2**, **3** and **4** (Fig. 2–4) reveal several interesting features. All compounds show various degrees of *ruf* (ruffled) distortion induced by the small Ni(II) ion.¹⁶ Compound **4** exhibits only a small degree of distortion [average Ni–N bond length 1.963(3) Å]. Secondary amine **3** has both a relatively planar macrocycle [Ni–N = 1.952(4) Å] and a severely ruffled one [Ni–N = 1.905(4) Å], while primary amine **2** shows an intermediate degree of distortion [Ni–N = 1.939(2) Å]. All compounds exhibit very close intermolecular packing arrangements. Compound **2** forms π -stacked polymers in which the amino nitrogen atom is located on top of a neighboring Ni(II) center [Ni–N1 = 3.109 Å, Ni–H1B = 2.866 Å]. The other side of the macrocycle exhibits a short phenyl hydrogen–nickel contact [Ni–H15B = 2.819 Å]. Compound **3** forms polymeric zig-zag chains in which a pyrrole β -hydrogen atom and a phenyl hydrogen atom are located close to a neighboring Ni(II) center [Ni1–H37 = 3.037 Å, Ni1–H103 = 2.945 Å, Ni2–H3A = 2.776 Å]. The hydroxyporphyrin **4** forms very closely packed π -stacked dimers,^{14,17} where an aryl hydrogen atom is coordinated to a Ni(II) center and a pyrrole nitrogen atom [Ni–H156 = 3.037 Å, N21–H156 = 2.488 Å]. In the absence of any real acceptor groups, the donor –OH or –NH₂ hydrogen atoms are not involved in any other binding in either structure.

In summary, the novel reactions we have uncovered suggest several new avenues of study, in both porphyrin chemistry and more generally in palladium catalysis of unsuspected processes. While there are many cases of reductive cleavage of hydrazine(s) by transition metal species,¹⁸ the use of hydrazine as an ammonia surrogate in Pd catalysed aminations of aryl bromides is unprecedented and invites further investigation. Primary amine synthesis by Pd catalysed amination is normally achieved in two steps using (di)allylamines, *tert*-butyl carbamate, imines, or sulfoximines as intermediates.¹² Likewise, the formation of the hydroxyporphyrin from a carbonate base suggests that the direct substitution of haloarenes to form phenol analogues may be viable. Our own interests lie in the new porphyrin chemistry and especially in the further study of the secondary amines such as **3**. We are currently pursuing the coupling reactions and redox chemistry of **3**, as bis(diarylamines) linked by conjugated bridges are currently of significant interest due to the delocalised electronic structures of their mixed-valence radical cations. Porphyrin analogues of such species may offer favourable electronic delocalisation and stability of relevance to molecular electronics applications.¹⁹

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Notes and references

‡ Crystal data (all grown from CH₂Cl₂/MeOH using standard techniques⁹): **2**: C₃₈H₂₅N₅Ni, *M* = 610.34, orthorhombic, *a* = 6.4778(2), *b* = 19.0155(6), *c* = 22.2824(7) Å, *U* = 2744.72(15) Å³, *T* = 90 K, space group *P*2₁2₁2₁, *Z* = 4, $\mu(\text{Mo-K}\alpha)$ = 0.746 mm⁻¹, 31404 reflections measured, 6313 unique (*R*_{int} = 0.0612) which were used in all calculations. The final *wR*(*F*₂) was 0.08 (all data). **3**: C₇₆H₄₇N₉Ni₂, *M* = 1203.65, triclinic, *a* = 12.4790(9), *b* = 14.1516(9), *c* = 16.1406(11) Å, α = 101.5380(10), β = 99.8540(10), γ = 95.8160(10)°, *U* = 2724.3(3) Å³, *T* = 90 K, space group *P* $\bar{1}$, *Z* = 2, $\mu(\text{Mo-K}\alpha)$ = 0.75 mm⁻¹, 27815 reflections measured, 10802 unique (*R*_{int} = 0.079) which were used in all calculations. The final *wR*(*F*₂) was 0.1354 (all data). **4**: C₃₈H₂₄N₃NiO, *M* = 611.32, triclinic, *a* = 9.6815(19), *b* = 12.028(2), *c* = 12.986(3) Å, α = 69.02(3), β = 77.92(3), γ = 85.14(3)°, *U* = 1380.6(6) Å³, *T* = 90 K, space group *P* $\bar{1}$, *Z* = 2, $\mu(\text{Mo-K}\alpha)$ = 0.744 mm⁻¹, 15377 reflections measured, 5050 unique (*R*_{int} = 0.0624) which were used in all calculations. The final *wR*(*F*₂) was 0.169 (all data). CCDC 610310 (**2**); 610308 (**3**); 610309 (**4**). For crystallographic data in CIF or other electronic format see DOI: 10.1039/b608365j

- For reviews on Pd catalysed couplings on tetrapyrroles, see: W. M. Sharman and J. E. van Lier, *J. Porphyrins Phthalocyanines*, 2000, **4**, 441; J. Setsune, *J. Porphyrins Phthalocyanines*, 2004, **8**, 93; for general porphyrin functionalisation, including nucleophilic substitutions, see: M. O. Senge and J. Richter, *J. Porphyrins Phthalocyanines*, 2004, **8**, 934; M. O. Senge, *Acc. Chem. Res.*, 2005, **38**, 733.
- T. Takanami, M. Hayashi, F. Hino and K. Suda, *Tetrahedron Lett.*, 2003, **44**, 7353.
- Y. Chen and X. P. Zhang, *J. Org. Chem.*, 2003, **68**, 4432.
- G. Y. Gao, Y. Chen and X. P. Zhang, *Org. Lett.*, 2004, **6**, 1837.
- G. Y. Gao, A. J. Colvin, Y. Chen and X. P. Zhang, *Org. Lett.*, 2003, **5**, 3261.
- G. Y. Gao, A. J. Colvin, Y. Chen and X. P. Zhang, *J. Org. Chem.*, 2004, **69**, 8886.
- F. Atefi, J. C. McMurtrie, P. Turner, M. Duriska and D. P. Arnold, *Inorg. Chem.*, 2006, **45**, 6479.
- L. J. Esdaile, J. C. McMurtrie, P. Turner and D. P. Arnold, *Tetrahedron Lett.*, 2005, **46**, 6931.
- H. Hope, *Prog. Inorg. Chem.*, 1994, **41**, 1; M. O. Senge and K. M. Smith, *Acta Crystallogr., Sect. C*, 2005, **61**, o537.
- D. P. Arnold, R. C. Bott, H. Eldridge, F. Elms, G. Smith and M. Zojaji, *Aust. J. Chem.*, 1997, **50**, 495.
- M. O. Senge, M. G. H. Vicente, K. R. Gerzevske, T. P. Forsyth and K. M. Smith, *Inorg. Chem.*, 1994, **33**, 5625.
- D. Prim, J.-M. Campagne, D. Joseph and B. Andrioletti, *Tetrahedron*, 2002, **58**, 2041.
- A. L. Balch, *Coord. Chem. Rev.*, 2000, **200–202**, 349 and refs. therein.
- J. Wojaczyński, M. Stępień and L. Latos-Grażyński, *Eur. J. Inorg. Chem.*, 2002, 1806.
- A. L. Balch, M. Mazzanti and M. M. Olmstead, *Inorg. Chem.*, 1993, **32**, 4737.
- M. O. Senge, *Chem. Commun.*, 2006, 243.
- M. O. Senge and K. M. Smith, *J. Chem. Soc., Chem. Commun.*, 1992, 1108; M. O. Senge, C. W. Eigenbrot, T. D. Brennan, W. R. Scheidt and K. M. Smith, *Inorg. Chem.*, 1993, **32**, 313.
- For example: I. Takei, K. Dohki, K. Kobayashi, T. Suzuki and M. Hidai, *Inorg. Chem.*, 2005, **44**, 3768; M. P. Shaver and M. D. Fryzuk, *J. Am. Chem. Soc.*, 2005, **127**, 500.
- For a porphyrin example, see: J.-C. Chang, C.-J. Ma, G.-H. Lee, S.-M. Peng and C.-Y. Yeh, *Dalton Trans.*, 2005, 1504.