

Shadow Mask Templates for Site-Selective Metal Exchange in Magnesium Porphyrin Nanorings

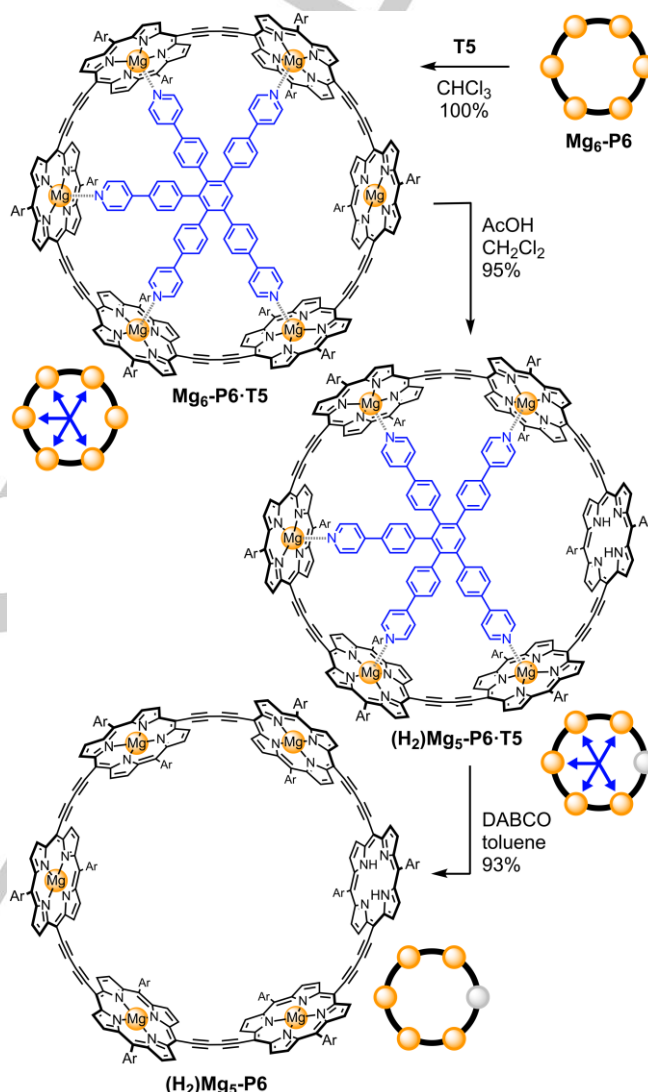
Pernille S. Bols and Harry L. Anderson*

Dedicated to Professor Jeremy Sanders on the occasion of his 70th birthday

Abstract: Molecular templates can be used in many different ways to control the outcome of chemical reactions. Here we present a new type of template-directed synthesis. We show that templates can be used as shadow masks: the shape of the template becomes imprinted on the product because reaction only occurs at sites not masked by the template. We demonstrate this effect by using oligopyridine templates to dictate the sites of demetallation when a magnesium porphyrin nanoring is treated with acid. Magnesium centers that are coordinated to the template are protected whereas uncoordinated magnesium centers are removed. After site-selective demetallation, the template can be removed and other cations, such as zinc(II) and copper(II), can be inserted into the free-base porphyrin centers. This strategy provides a simple route to a wide range of heterometallated porphyrin arrays.

Stencils and shadow masks have been used to create patterns since at about 60,000 years ago^[1] and this strategy is widely exploited in top-down nanofabrication.^[2] Here we demonstrate the same effect on a molecular scale, through the use of ‘shadow mask templates’. Busch defined a chemical template as a species that organizes an assembly of atoms, with respect to one or more geometric loci, in order to achieve a particular linking of atoms.^[3] A template provides instructions for the formation of a single product from a substrate or substrates which otherwise have the potential to assemble and react in a variety of ways.^[4] Recently, many new types of template-directed synthesis have been invented, providing routes to previously inaccessible molecular architectures.^[5–7] There are previous reports of the use of molecules as shadow masks,^[8] but to the best of our knowledge, this is the first time this principle has been used to create precisely defined molecular structures.

The work presented here grew from a simple observation: treatment of the magnesium complex of a butadiyne-linked six-porphyrin nanoring, **Mg₆-P6**, with acetic acid in dichloromethane results in rapid removal of the magnesium cations from all six porphyrin centers, whereas the complex of this nanoring with a hexapyridyl template, **Mg₆-P6·T6**, is not demetallated under these conditions. We concluded that the template masks the magnesium ions from acid. To test this hypothesis, we inserted a five-legged template **T5**^[7] into a magnesium porphyrin nanoring and submitted it to demetallation conditions. As expected, the uncoordinated magnesium porphyrin is cleanly demetallated, whereas the template-coordinated magnesium cations remain in place (Scheme 1). Analysis of crude reaction mixtures by ¹H NMR spectroscopy and MALDI-ToF mass spectrometry shows that site-selective demetallation of **Mg₆-P6·T5** to **(H₂)Mg₅-P6·T5** is a quantitative reaction with no detectable trace of over-demetallated by-products. The template is displaced from **(H₂)Mg₅-P6·T5** by treatment with a large excess of DABCO, and **(H₂)Mg₅-P6** is isolated in 88% yield from **Mg₆-P6**.^[6,7,9]



Scheme 1. The template masking method applied to synthesize **(H₂)Mg₅-P6** using the template **T5**. Ar = 3,5-bis(triethylsilyl)phenyl.

To test the scope of this template effect, we investigated whether it could be applied to four-legged templates, by comparing three ligands with pyridine coordination sites in different positions (**T4a**, **T4b** and **T4c**, Figure 1).^[10,11] In each case, the complex of the template with magnesium nanoring **Mg₆-P6** was treated with 10% acetic acid in dichloromethane. All three reactions give clean site-selective demetallation, and the products are obtained in high yield without need for chromatographic purification (Scheme 2). The identities of the final compounds were confirmed by ¹H NMR and MALDI-ToF MS analysis. The NH protons in the free-base porphyrins give distinctive proton resonances at chemical shifts of –1.0 to –1.3 ppm, and the exact chemical shift is characteristic of each isomer.

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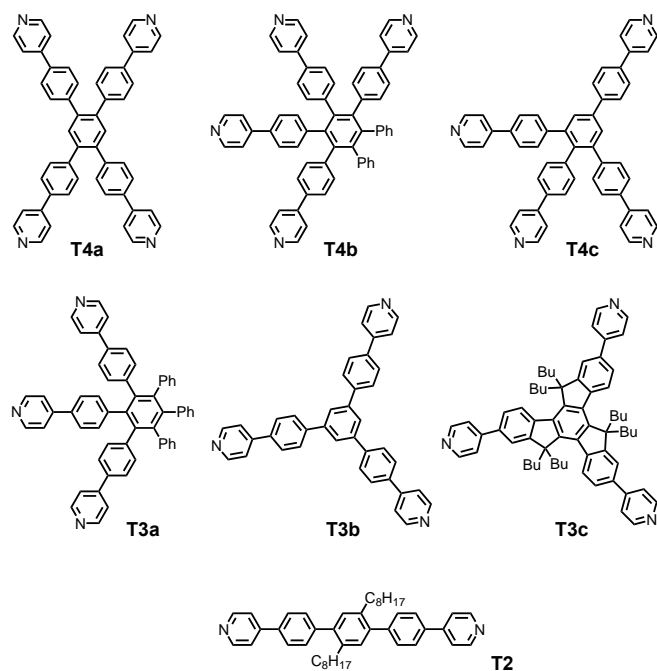
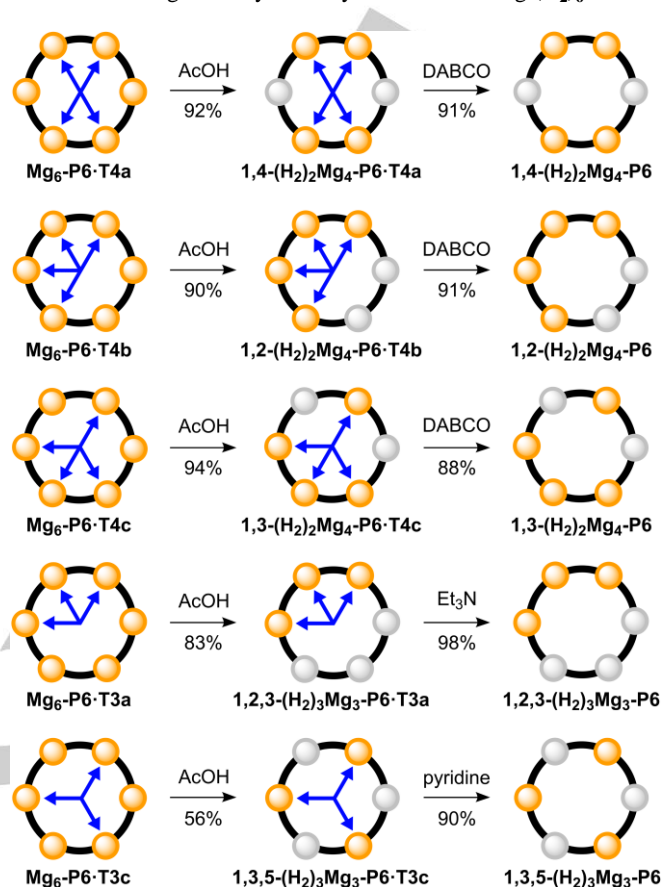


Figure 1. Structures of the oligopyridine ligands tested as masking templates. (T3b and T2 were found not to be effective as masking templates.)

Next, we tested three-legged templates, starting with the 1,2,3-isomer **T3a** (Figure 1).^[11] Treatment of **Mg₆-P6** with one equivalent of **T3a** followed by acetic acid results in site-selective demetallation to form **1,2,3-(H₂)Mg₃-P6·T3a**, together with about 7% of the fully demetallated ring (**(H₂)₆-P6**). This fully demetallated nanoring is easily separated from **1,2,3-(H₂)Mg₃-P6·T3a** by chromatography on silica. The formation of (**H₂**)₆-P6 as a byproduct during the reaction of **Mg₆-P6·T3a** with acetic acid reflects the weaker association constant of this tridentate template compared with **T6**, **T5** and **T4a-c**.^[11]

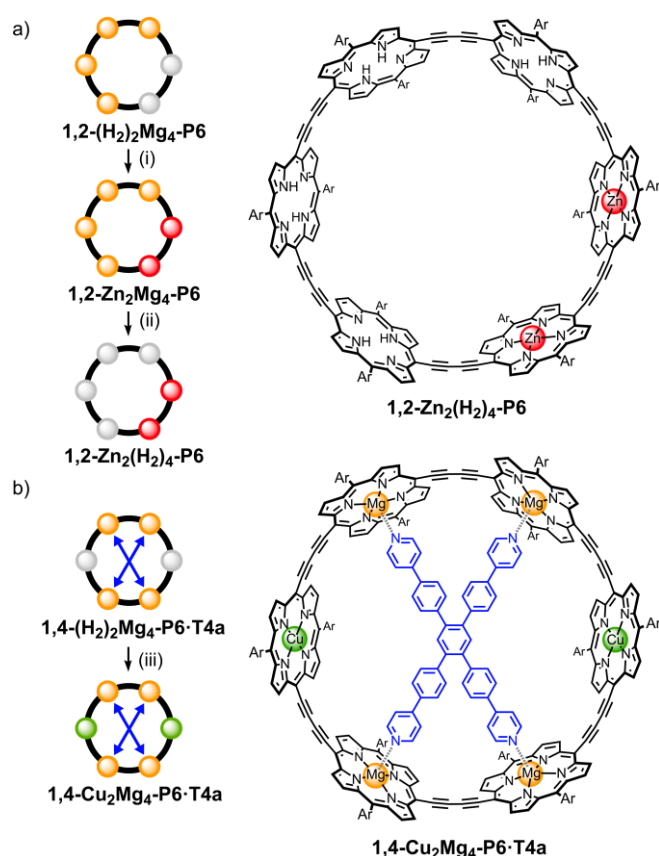
Disappointingly, treatment of **Mg₆-P6** with the symmetric three-legged template **T3b**^[12] (1:1 mole ratio) followed by acetic acid does not result in site-selective demetallation. The main products are unreacted starting material and fully demetallated ring (**(H₂)₆-P6**). ¹H NMR titrations revealed the reason for this result: when one equivalent of **T3b** is added to **Mg₆-P6**, the main product is the 1:2 complex **Mg₆-P6·(T3b)₂**, together with a small amount of the 1:1 complex **Mg₆-P6·T3b**, and some uncomplexed **Mg₆-P6** nanoring. It appears that formation of the 1:2 complex with **T3b** is too favorable, making this ligand ineffective as a masking template. In order to solve this problem, we designed a three-legged template with bulky groups to prevent the stacking, **T3c**, based on a truxene core.^[13] Template **T3c** has a similar coordination geometry to **T3b**, but the bulky *n*-butyl chains in the truxene are expected to hinder stacking. ¹H NMR spectroscopy shows that addition of **T3c** to the nanoring only leads to formation of a 1:1 complex, **Mg₆-P6·T3c**. Addition of acetic acid to this complex results in site-selective demetallation, together with formation of the fully demetallated nanoring (**(H₂)₆-P6**). ¹H NMR analysis of the crude reaction mixture (Figure S2) shows that it consists of 83% **1,3,5-(H₂)₃Mg₃-P6·T3c** and 17% (**H₂**)₆-P6. These two products are readily separated by chromatography on silica. The weaker binding resulting from the presence of only three pyridine coordination sites makes **T3c** less effective than **T4a-c** as a masking template, but the bulk of the truxene effectively blocks formation of the 1:2 complex. The two-legged template **T2** (Figure 1) binds too weakly to control the

demetallation process; treatment of the complex of **Mg₆-P6** and **T2** with acetic acid gives only the fully demetallated ring (**(H₂)₆-P6**).



Scheme 2. The template masking method applied to synthesize five heterometallated rings from **Mg₆-P6**.

Magnesium porphyrins are readily demetallated by acid, but they do not easily undergo transmetalation when treated with other metal salts,^[14] which makes it possible to use shadow mask templates to achieve site-selective transmetalation. For example, treatment of **1,2-(H₂)₂Mg₄-P6** with zinc(II) acetate results in clean insertion of zinc(II) at the two free-base positions to give **1,2-Zn₂Mg₄-P6**; the remaining magnesium centers can then be demetallated selectively with acetic acid to yield **1,2-Zn₂(H₂)₄-P6** (Scheme 3a).^[15] This compound is useful for testing the cooperativity of ligand binding inside nanorings.^[11] We have also prepared a heterometallated nanoring containing two paramagnetic copper(II) ions opposite each other (**1,4-Cu₂Mg₄-P6·T4a** Scheme 3b). In this reaction, the **T4a** template was left in place during insertion of copper(II) into the two free-base centers of **1,4-(H₂)Mg₄-P6·T4a**. We removed **T4a** and inserted **T6** to obtain **1,4-Cu₂Mg₄-P6·T6** (see Supporting Information), which is a valuable compound for investigating quantum interference through long-range exchange coupling.^[16] Many metal cations can be inserted into porphyrins under mild conditions,^[17] so the magnesium/free-base nanorings reported here should be useful intermediates for preparing diverse heterometallated systems.



Scheme 3. Synthesis of heterometallated rings. a) Synthesis of a di-zinc(II) porphyrin ring. (i) Zn(OAc)₂, 2 h, 20 °C, 75% yield. (ii) 50% AcOH in CH₂Cl₂, 30 min, 20 °C, 69% yield. b) Synthesis of a di-copper(II) porphyrin ring. (iii) CuOAc, air, 1 h, 60 °C, 87% yield. Ar = 3,5-bis(trihexylsilyl)phenyl.

In summary, we have demonstrated that oligopyridine ligands can be used as shadow mask templates to achieve site-selective demetallation of magnesium porphyrin nanorings. Selective demetallation is quantitative with five- and four-legged templates, and it provides useful selectivity with three-legged templates if the binding of more than one template unit can be prevented, however it does not work with two-legged templates. This new template effect provides a simple synthetic route to functional heterometallated porphyrin arrays.

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Keywords: template • macrocycles • porphyrin oligomers • masking • magnesium

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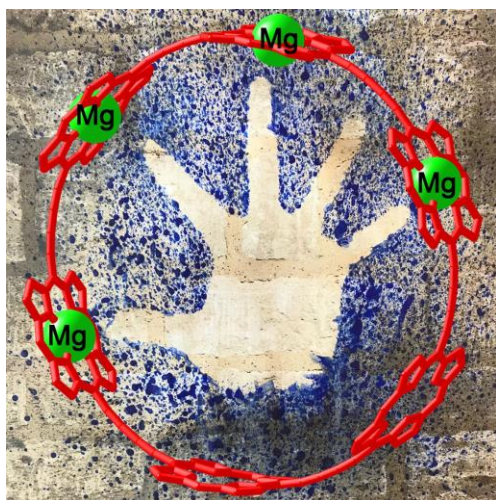
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Hidden behind a mask: Magnesium atoms that are coordinated to a template are resistant to acid, so oligopyridine templates can be used as shadow masks. The shape of the template becomes imprinted on the molecular structure of the product because reaction only occurs at sites not masked by the template.