

# Synthesis of Platinum(II) Metallocycles Using Microwave-Assisted Heating

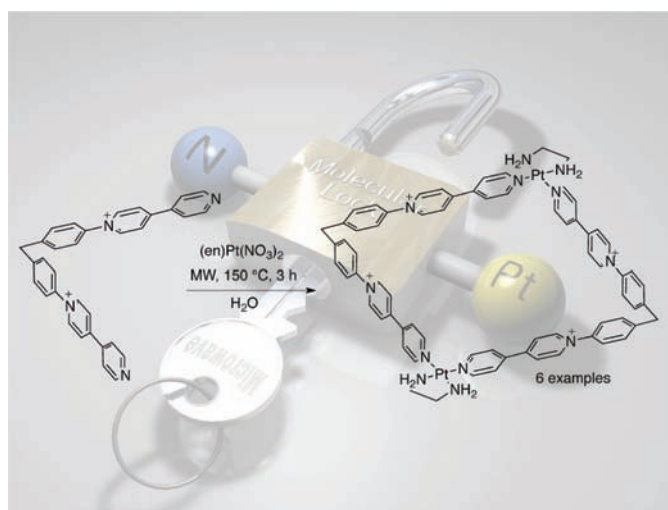
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## ABSTRACT



An efficient microwave-assisted self-assembly of dinuclear platinum metallocycles is reported. The reactions proceed to afford the products with high purity and yields within 3–4 h. We have used this methodology to synthesize a new 14.75 Å × 14.75 Å molecular square. The solid-state structure showed a perfect alignment of the squares along the *c* axis.

Coordination-driven self-assembly strategies have provided a wide variety of well-defined two- and three-dimensional suprastructures.<sup>1</sup> In short, a combination of square-planar Pd(II) or Pt(II) metals with nitrogen ligands has proven to be especially powerful.<sup>2</sup>

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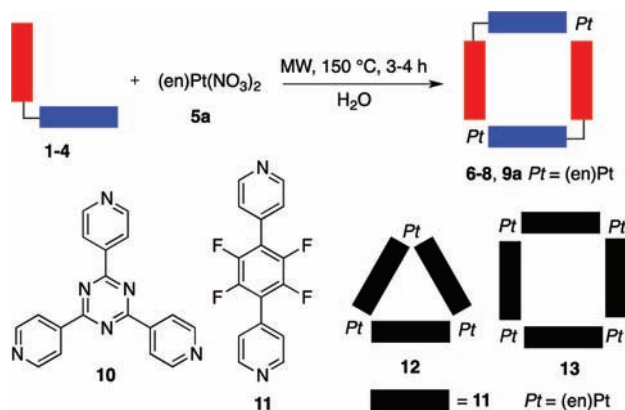
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These metal-directed self-assembly processes take advantage of kinetically labile coordinative bonds, which ensure the thermodynamic control of the system, eliminating potential defects that might lead to product heterogeneity. Under proper reaction conditions, the assembly can undergo self-sorting and self-correcting processes until all the components converge into a well-defined final product that is the most stable thermodynamically.

It is well known that some Pt–N bonds are kinetically inert at room temperature, but under certain reaction conditions this inertness can be overcome to reach thermodynamic control. This dual behavior is the foundation of the molecular lock strategy and has been thoroughly used in

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**Scheme 1.** Synthesis of Metallo-cycles **6–8** and **9a**<sup>a</sup>



<sup>a</sup> See Table 1 for structural representation.

the synthesis of structures based on platinum.<sup>3</sup> In contrast to palladium structures that show concentration dependence and characterization problems, the molecular lock strategy allows the isolation and a more reliable characterization of platinum species. In his seminal work, Fujita described that the inert nature of the Pt–N bond becomes labile in the presence of a salt.<sup>4</sup> However, high temperatures and long reaction times are required, and subsequent purification is usually needed. More recently, other procedures based on irradiation,<sup>5</sup> temporary labilization of Pt(II)–pyridine bonds in 2,2,2-trifluoroethanol,<sup>6</sup> and solvent-free conditions<sup>7</sup> have proven effective in molecular lock strategies. However, photochemically driven self-assembly is not general, and when the coordinating pyridine is conjugated, UV irradiation does not produce clear and discrete products.<sup>8</sup> On the other hand, our attempts to apply the solvent-free procedure to the synthesis of our previously reported metallo-cycles were unsuccessful. Therefore, an efficient

and straightforward synthesis of platinum metallo-cycles becomes highly desirable.

Alternately, use of microwave radiation has been known to decrease reaction times for reactions carried out under thermal conditions.<sup>9</sup> During the course of our ongoing study on the development of new metallo-cyclic receptors,<sup>10</sup> we found that platinum metallo-cycles could be efficiently prepared under microwave irradiation conditions.

A simple method to synthesize these metallo-cycles in water was designed (Scheme 1). Reaction temperature was set to 150 °C, higher than the conventional heating one and below decomposition temperature. Concentration is a crucial factor in these self-assembly processes and can prevent the obtention of the desired products on a multigram scale. It is well known that for entropic reasons small metallo-cycles are favored over larger ones as dilution increases. Consequently, the reactions were carried out at 5 and 20 mM (with respect to the ligand) to test the limitations of the methodology. We chose a series of previously reported di- and tetranuclear metallo-cycles in order to verify the effect of microwave irradiation. In addition, a new platinum metallo-cycle (**9a**·8NO<sub>3</sub>) has been synthesized following this procedure.

In all examples tested, excellent yields could be achieved in less than 4 h. This indicates a dramatic reduction in reaction time as compared with the conventional thermal process (Table 1). Moreover, metallo-cycles **6–8** and **9a** were obtained with a high purity, and no further purification was necessary.

We have also self-assembled successfully the nanocage derived from 2,4,6-tris(4-pyridyl)-1,3,5-triazine (**10**) (Scheme 1) and (en)Pt(NO<sub>3</sub>)<sub>2</sub>.<sup>11</sup> Remarkably, the M<sub>6</sub>L<sub>4</sub> structure was formed in 3 h following our procedure and isolated in quantitative yield without the requirement of guest-template effect.<sup>4b</sup>

In a similar manner, a mixture of the square and the triangle derived from ligand **11** was synthesized. The size of the metallo-cycles was confirmed by ESI-MS. The resulting mass spectrum, measured from an acetonitrile solution, displays multiply charged molecular ions that correspond to the square **13** at  $m/z = 1556.6$  [M – 2PF<sub>6</sub>]<sup>2+</sup>, 987.4 [M – 3PF<sub>6</sub>]<sup>3+</sup>, 704.1 [M – 4PF<sub>6</sub>]<sup>4+</sup>, 534.5 [M – 5PF<sub>6</sub>]<sup>5+</sup>, and 421.1 [M – 6PF<sub>6</sub>]<sup>6+</sup>. Analogously, the peaks appearing at  $m/z = 1128.6$  [M – 2PF<sub>6</sub>]<sup>2+</sup>, 704.1 [M – 3PF<sub>6</sub>]<sup>3+</sup>, 491.8 [M – 4PF<sub>6</sub>]<sup>4+</sup>, and 364.6 [M – 5PF<sub>6</sub>]<sup>5+</sup> correspond to the molecular triangle **12** (see Supporting Information). It is worth noting that this system was not self-assembled in solution using conventional heating, though many attempts were made using forcing reaction conditions (long reaction times, high temperatures, addition of different salts, etc.).<sup>12</sup>

As mentioned above, the new metallo-cycle **9a** was synthesized and, in addition, its palladium analogue **9b** was

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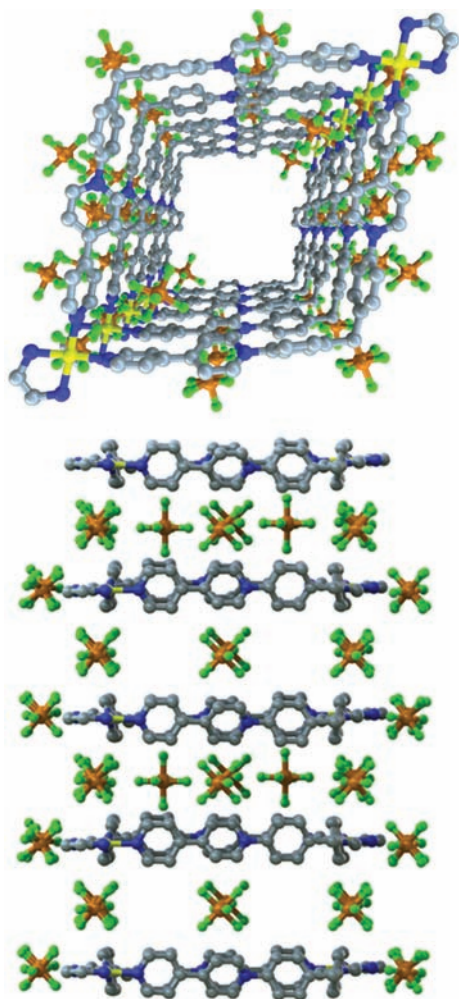
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(12) Alternately, the square **13** was successfully obtained by grinding a powdered 1:1 mixture of **11** and (en)Pt(NO<sub>3</sub>)<sub>2</sub> in the absence of solvent: Ferrer, M.; Gutiérrez, A.; Mounir, M.; Rossell, O.; Riuz, E.; Rang, A.; Engesser, M. *Inorg. Chem.* **2007**, *46*, 3395.

**Table 1.** Reaction Conditions for the Preparation of Metalloacycles **6–8** and **9a**

comp	[Red Box]	[Blue Box]	microwave irradiation				conventional heating			
			time (h)	temp (°C)	c (mM) <sup>a</sup>	yield (%)	time (d)	temp (°C) <sup>b</sup>	c (mM) <sup>a</sup>	yield (%) <sup>ref</sup>
<b>1, 6</b>			3	150	5	-	7	100	10	68 <sup>10d</sup>
			3	150	20	88				
<b>2, 7</b>			3	150	5	-	4	100	0.2	50 <sup>10e</sup>
			4	150	20	96				
<b>3, 8</b>			3	150	5	95	8	100	4.6	95 <sup>10f</sup>
			3	150	20	c				
<b>4, 9a</b>			3	150	5	99	10	100	5	92
			3	150	20	c				

<sup>a</sup> Concentrations are expressed as the initial concentration of the ligand. <sup>b</sup> Heating in a sealed tube at 150 °C for 3 h does not produce clear and discrete products. <sup>c</sup> MW irradiation does not produce clear and discrete products.



**Figure 1.** Crystal structure of metalloacycle **9a**·8PF<sub>6</sub>. A projection view along the *c* axis (top) and a lateral view (bottom). Solvent molecules and hydrogen atoms have been omitted for clarity. The color labeling scheme is as follow: Pt (yellow), P (orange), F (green), N (blue), C (gray).

prepared following a conventional procedure. For the preparation of the precursor **4**·2NO<sub>3</sub> we used the Zincke reaction. The exchange of the 2,4-dinitroaniline moiety of 1-(2,4-dinitrophenyl)-[4,4'-bipyridin]-1-ium by 4,4'-methylenedianiline gave, presumably via an ANRORC mechanism and after anion exchange, the ligand **4**·2NO<sub>3</sub>.

Addition of 1 equiv of (en)Pd(NO<sub>3</sub>)<sub>2</sub> (**5b**) to a solution of the bipyridinium ligand **4**·2NO<sub>3</sub> (5 mM) at room temperature resulted in the expected formation of the square metalloacycle **9b**·8NO<sub>3</sub>, as can be seen from inspection of the 1D and 2D NMR data in either D<sub>2</sub>O (**9b**·8NO<sub>3</sub>) or CD<sub>3</sub>NO<sub>2</sub> (**9b**·8PF<sub>6</sub>, after counterion exchange) solutions. The <sup>1</sup>H NMR spectrum in D<sub>2</sub>O shows the characteristic downfield shifts expected for coordination of the pyridyl nitrogen atoms to the Pd atom (Figure S19). The composition of the mixture changed in the 0.5–10 mM (D<sub>2</sub>O) and 2–10 mM (CD<sub>3</sub>NO<sub>2</sub>) range (Figures S20 and S26). Below the 0.5 mM limit in D<sub>2</sub>O appreciable amounts of free ligand **4**·2PF<sub>6</sub> are detected, at 2.0 mM **9b**·8NO<sub>3</sub> is clearly the major species, and above 5.0 mM secondary species are present.

The platinum analogue **9a**·8NO<sub>3</sub> was prepared following the microwave procedure or conventional heating method (Table 1). In contrast to the palladium metalloacycle, **9a**·8NO<sub>3</sub> and **9a**·8PF<sub>6</sub> remained stable in the studied concentration range, as could be expected from the less labile N–Pt coordinative bond. To support the binding of the ligand **4** to the platinum atom, a DOSY (diffusion ordered spectroscopy) experiment was carried out. The results showed that the metalloacycle has a smaller diffusion coefficient than that of the ligand (Figure S37). The ESI-HRMS supported the proposed structure, showing *m/z* values and isotopic pattern distributions in agreement with the theoretical ones (Figure S38).

Single crystals of metalloacycle **9a**·8PF<sub>6</sub> were obtained from an acetonitrile solution. The crystal structure of **9a**·8PF<sub>6</sub> is shown in Figure 1. The length of the side of the quadrangular metalloacycle is 14.75 Å (distance between the platinum atom and the carbon atom of the methylene groups), the angle at the CH<sub>2</sub> corner is 110°,

and the N(Py)PtN(Py) is 89°. The two pyridine central rings are twisted with a torsion angle of 70° and 29°. The PF<sub>6</sub> anions mediate between two metallocyclic units through hydrogen bonding [N–H···F] and electrostatic interactions. The crystal packing resulted in an alternate layer arrangement of metallocycles and anions along the *c* axis with interplanar separation of 4.07 Å. Interestingly, the metallocycles are perfectly aligned, forming channels that run parallel to *c* axis direction.

In summary, we show here that the kinetic inertness of N(py)–Pt bond at room temperature can be surpassed by microwave irradiation. Under these conditions the N–Pt bond is labile, allowing the autocorrection process and the self-assembly of platinum metallocycles. Employing this procedure a new dinuclear metallocycle was prepared.

The solid-state structure shows a molecular square of 14.75 Å × 14.75 Å and a perfect alignment of the squares along the *c* axis.

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**Supporting Information Available.** Synthetic procedures, NMR data, and X-ray crystallographic files (CIF) for **9a**·8PF<sub>6</sub>. This material is available free of charge via the Internet at <http://pubs.acs.org>.