

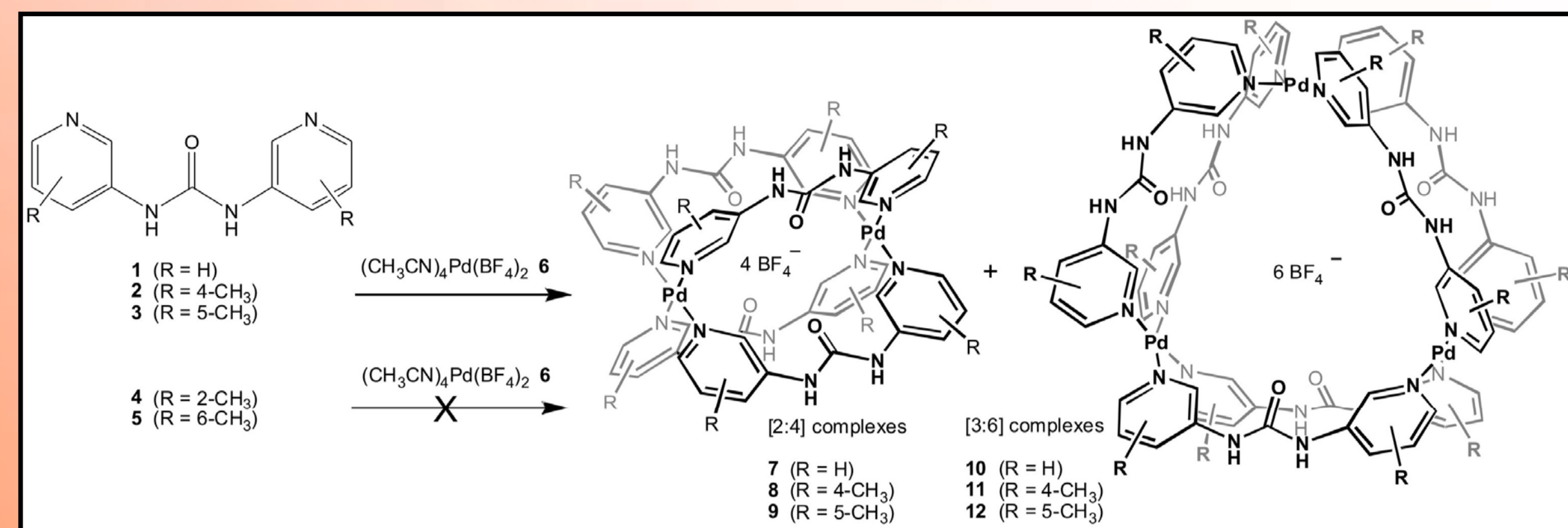
# Kinetically Controlled Self-Assembly of Metallo-Supramolecular Cages

Ralf W. Troff<sup>a</sup>, Johannes Poppenberg<sup>a</sup>, Kari Rissanen<sup>b</sup> and Christoph A. Schalley<sup>a\*</sup>

<sup>a</sup>Institut für Chemie und Biochemie der Freien Universität Berlin, Takustr. 3, D-14195 Berlin, E-Mail: schalley@chemie.fu-berlin.de

<sup>b</sup>NanoScience Center, Department of Chemistry, P.O. Box 35, 40014 University of Jyväskylä, Finland

## I. Self-Assembly

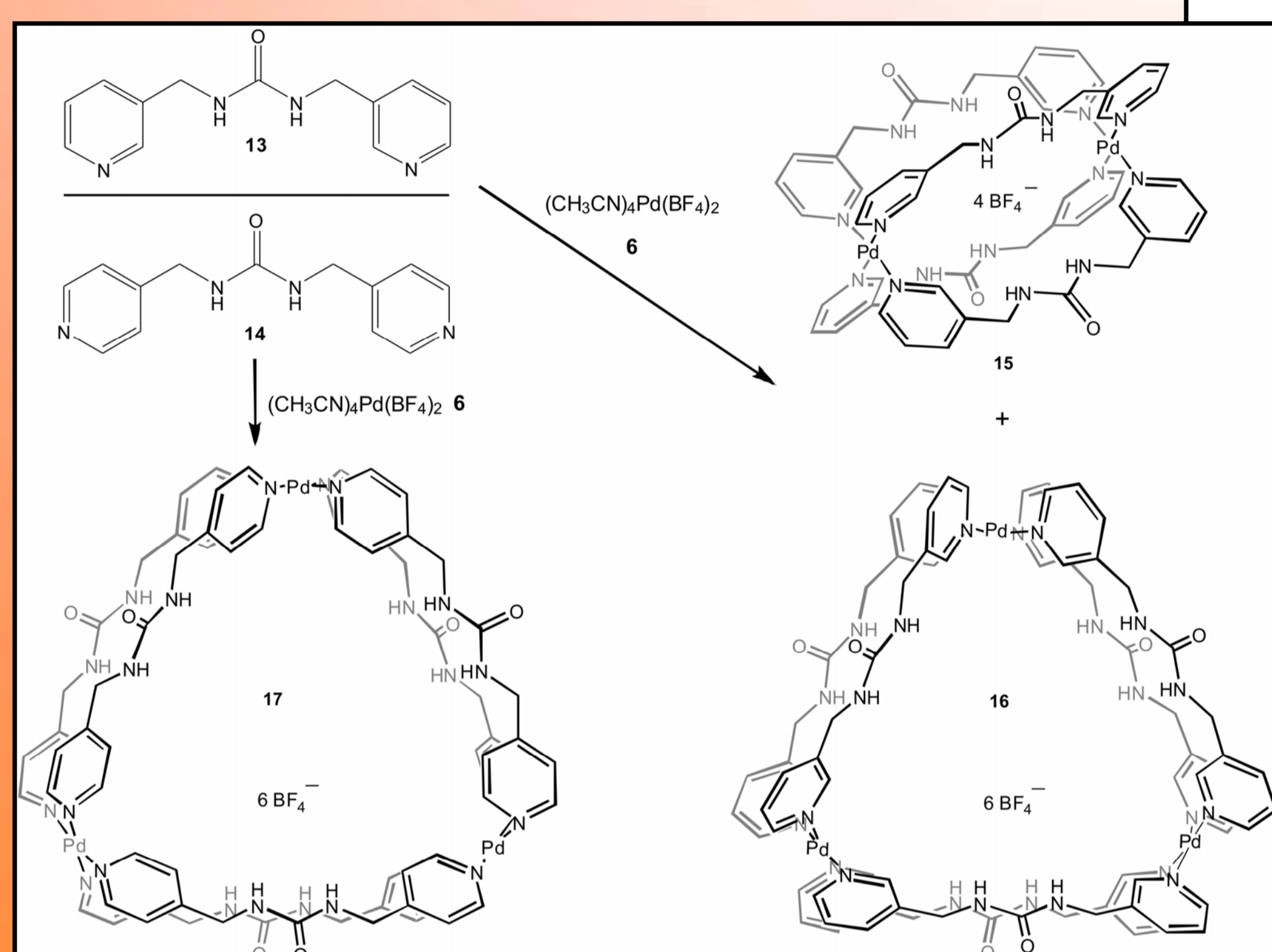


The metallo-supramolecular [2:4] and [3:6] complexes<sup>[1]</sup> **7** - **12** are achieved by the self-assembly of the rigid dipyriddyurea ligands **1** - **3** and tetrakis(acetonitrile)palladium(II) tetrafluoroborate **6**. With the ligands **4** and **5** no complexes are observed, which can be explained by the methyl groups in *ortho* position to the pyridine nitrogen.

If the more flexible dipyriddyurea ligands **13** and **14** are used, two different systems are observed.

On the one hand the self-assembly of ligand **13** with **6** leads to an equilibrium between [2:4] and [3:6] complexes.

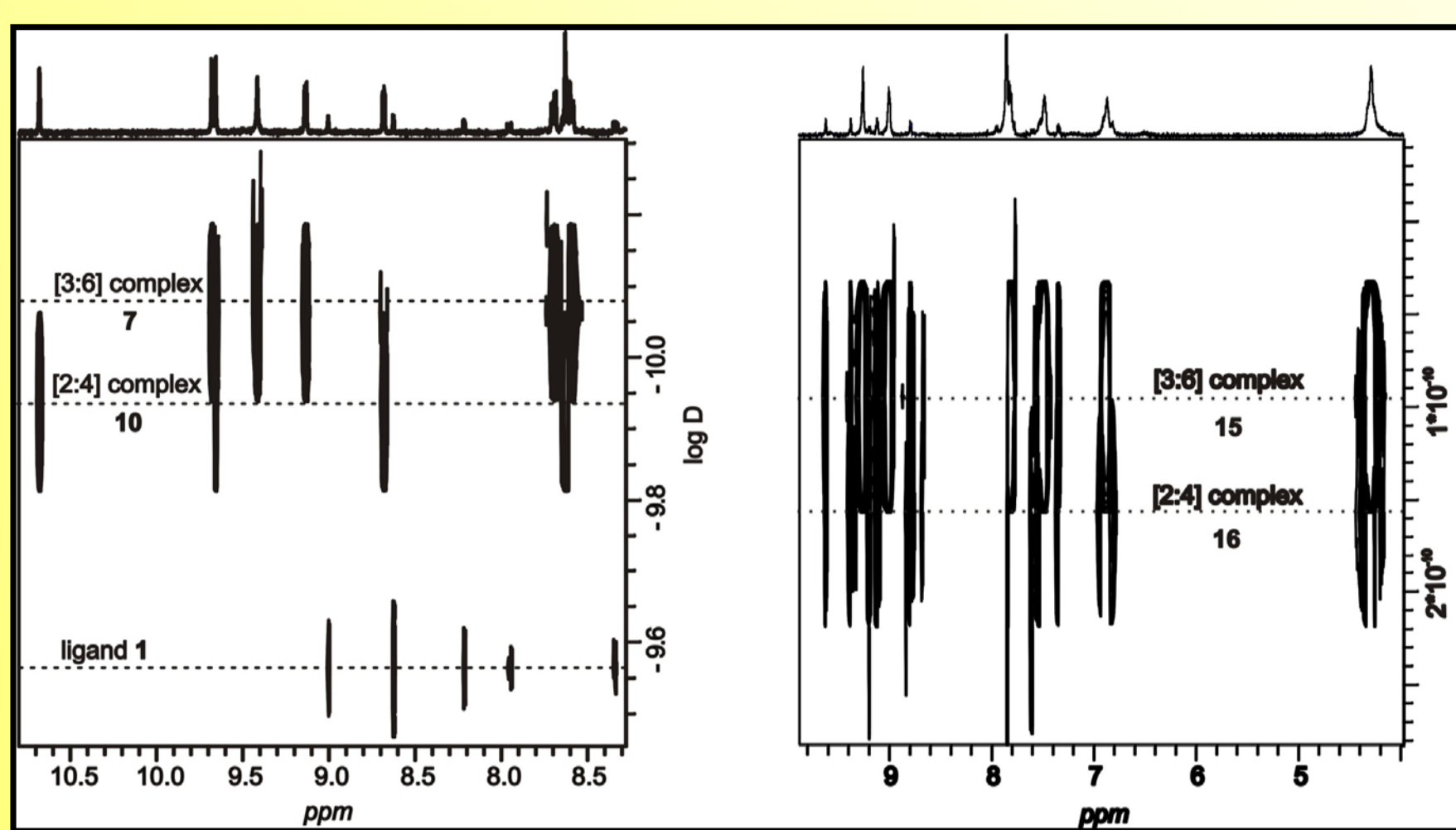
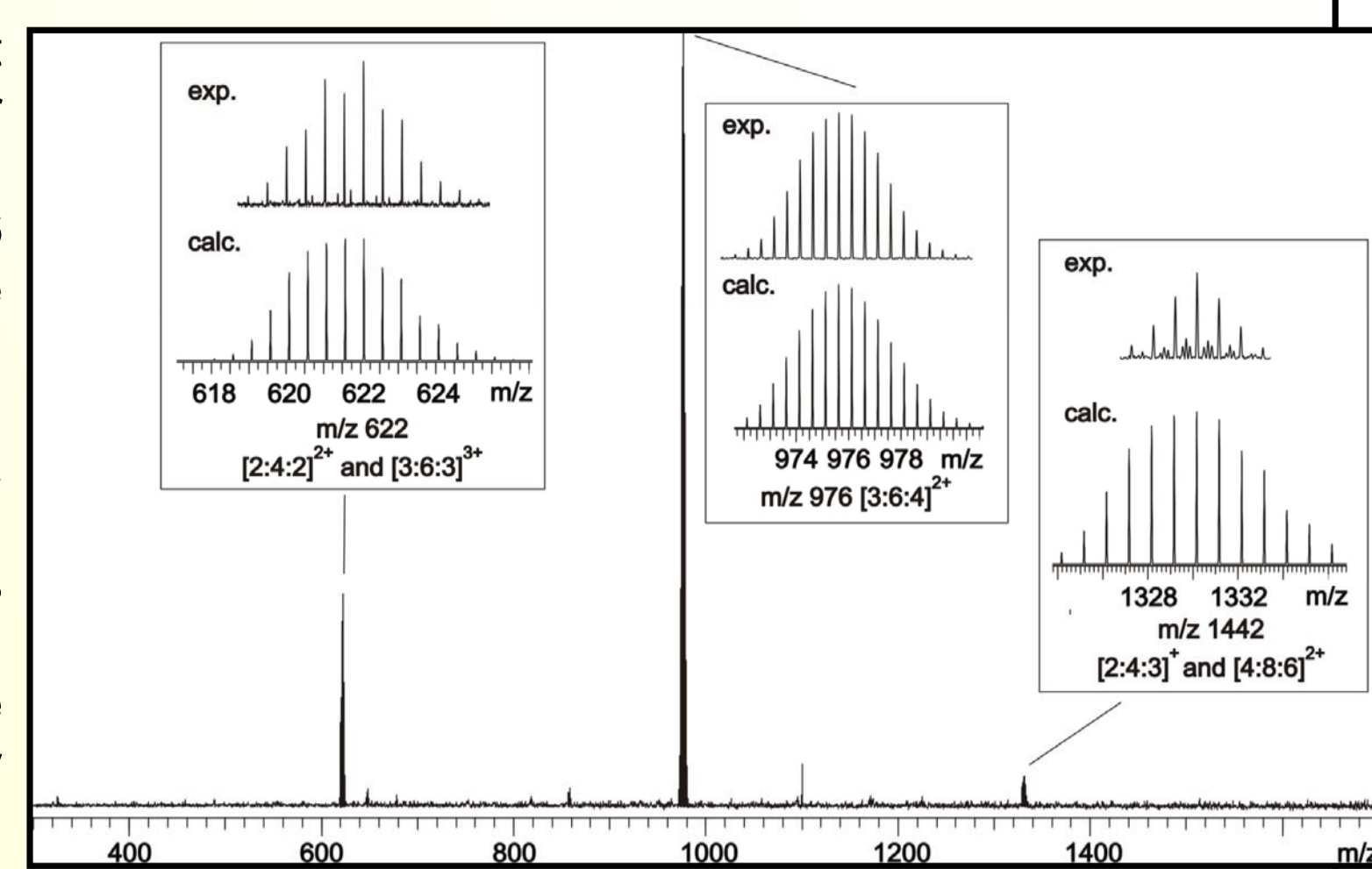
On the other hand the self-assembly of **6** with ligand **14** just result in [3:6] complexes. This can be explained by the coordination geometries of the building blocks.



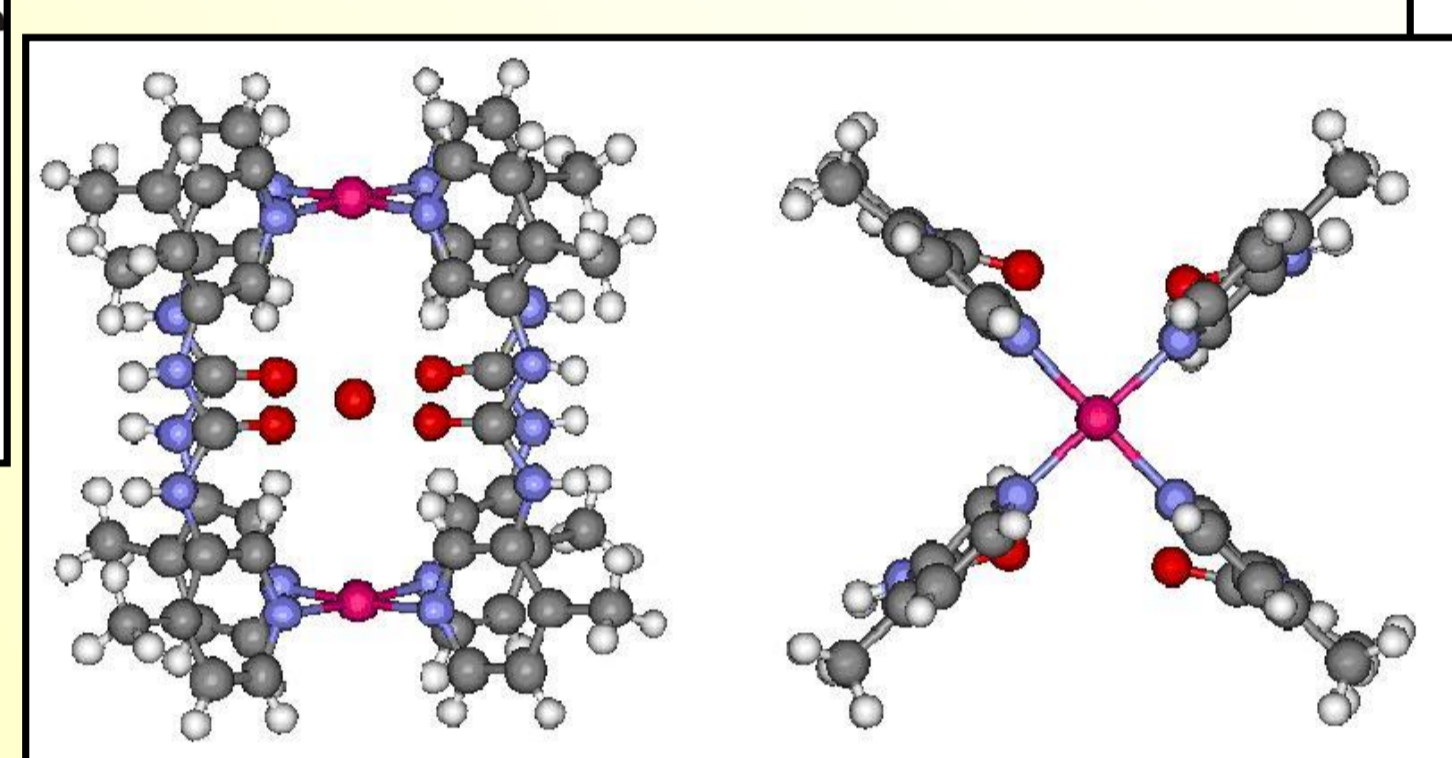
## II. The Equilibria between [2:4] and [3:6] Complexes

The systems were analyzed by a combination of several different analytical methods. <sup>1</sup>H NMR and mass spectrometry (shown for system **7/10**) show that [2:4] and [3:6] complexes **7** - **12** and **15/16** exist in these systems. In the self-assembled system of **6** and **14** just a [3:6] complex **17** is observed, which is due to the coordination geometry of the ligand **14**.

Due to the complexity of the systems, 2D-DOSY NMR spectroscopy is used to identify the different species in solution (the DOSY NMR spectra of **7/10** and **15/16** are shown as representative examples). On the base of the experimental diffusion coefficients, the radii of the different complexes are calculated<sup>[2]</sup>. A comparison of these radii with calculated ones (by molecular modelling) allows us to identify the species as [2:4] and [3:6] complexes.



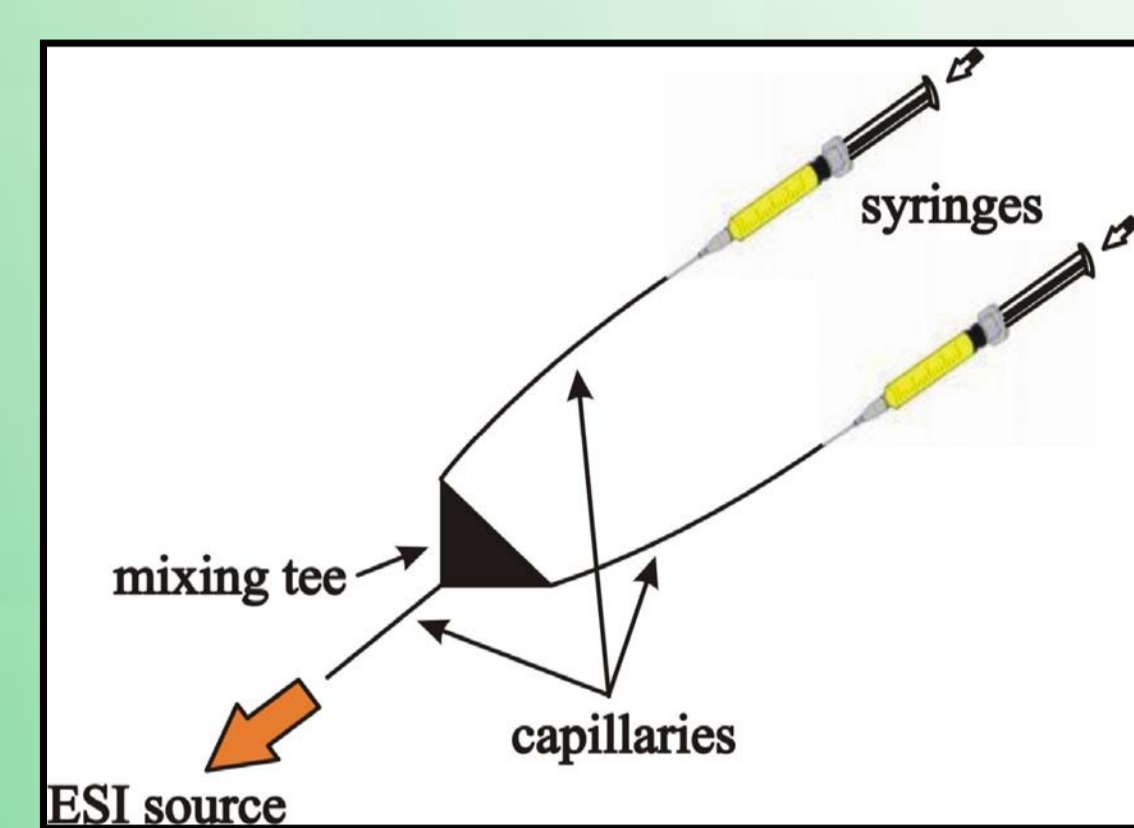
In the case of the complexes with the rigid ligands, NOESY and ROESY NMR spectroscopy tell us that the carbonyl groups of the urea ligands are pointing inwards the cavity of the complexes **7** - **12**. For the other complexes **15/16** and **17** no information of the ligand conformation in these complexes could be achieved up to now.



Complex **8** can be crystallized by diffusion of diethyl ether into a solution of **2** and **6** in DMF. The crystal data of **8** supports the results of the NOESY and ROESY NMR experiments. The carbonyl groups of the urea ligands point inwards the cavity of the complex.

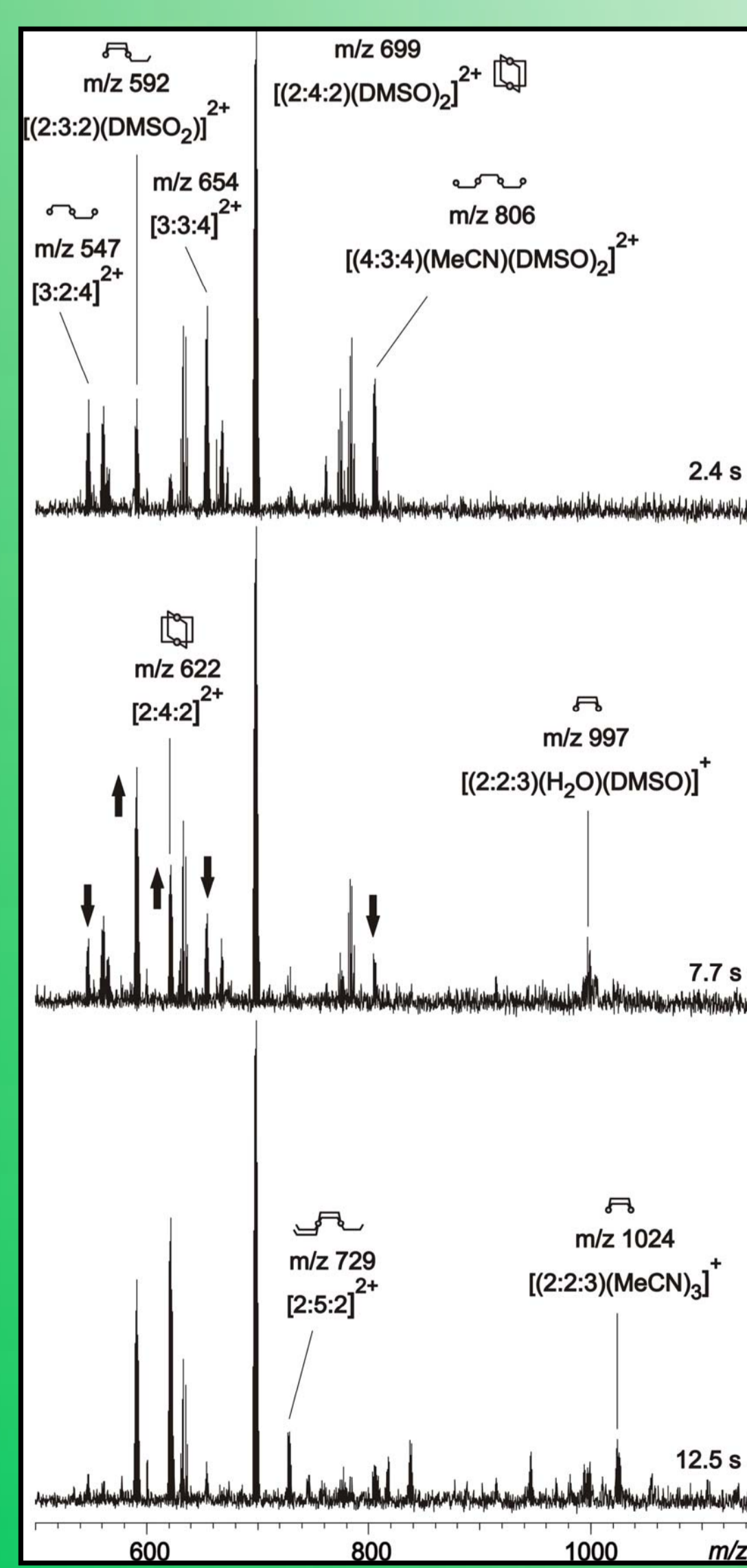
Furthermore, a water molecule was observed as a guest inside the cavity of the complex. The water molecule forms some hydrogen bonds with the carbonyl groups of the ligands. This can as well be an explanation for the non symmetrical orientation of the urea-carbonyl groups in the crystal structure.

## III. Intermediates in Self-Assembly



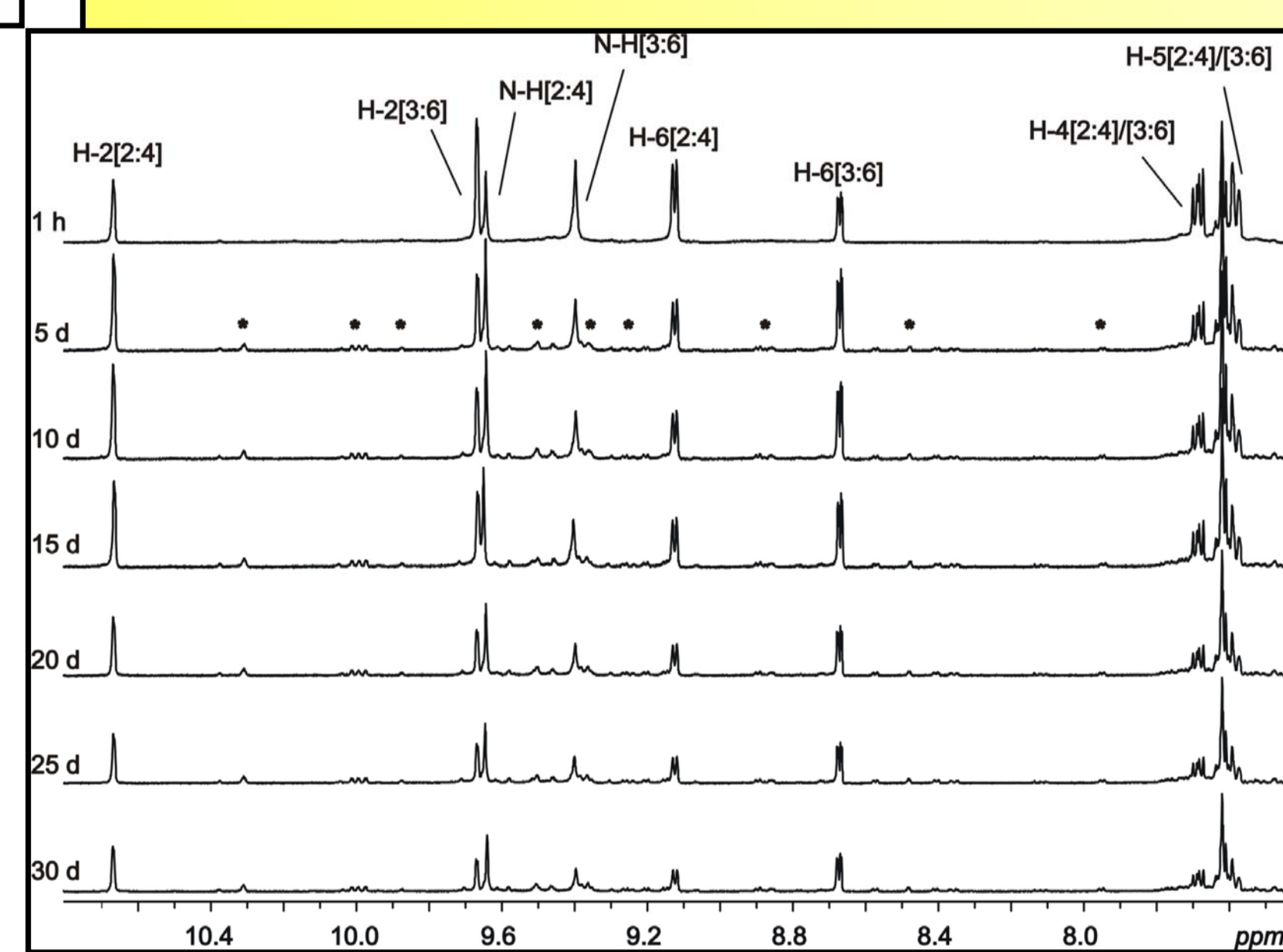
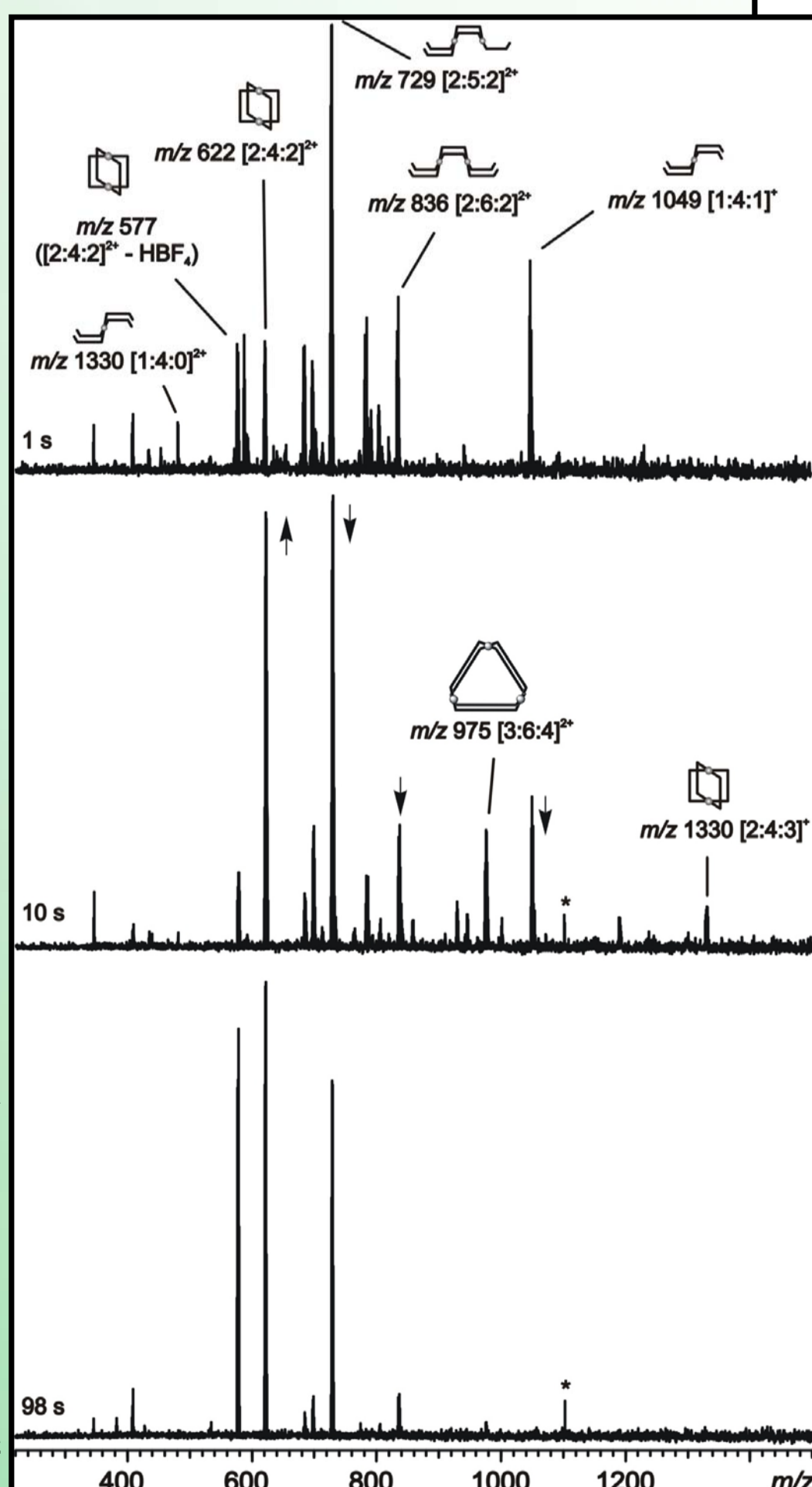
Intermediates of self-assembly processes of at least two different building blocks can be observed with mass spectrometry by using a fast mixed-flow technique. Solutions of the building blocks are separated in different syringes and pressed into capillaries and mixed in a microreactor (mixing tee). The mixture of the building blocks is transported by another capillary to the ESI source of an ESI FT-ICR mass spectrometer to measure the mixed sample solution after a defined time.

Equimolar amounts of ligand **1** and metal center **6** were dissolved in DMSO, respectively. This solutions were diluted with acetonitrile to a concentration of 100 μmol/L, which were used for the mass spectrometric experiments. In here, the reaction time was controlled in two different ways. At first the flow rate of the solvents was varied (see on the right side). In another experiment the reaction time was controlled by using mixing-capillaries with different lengths (see below).

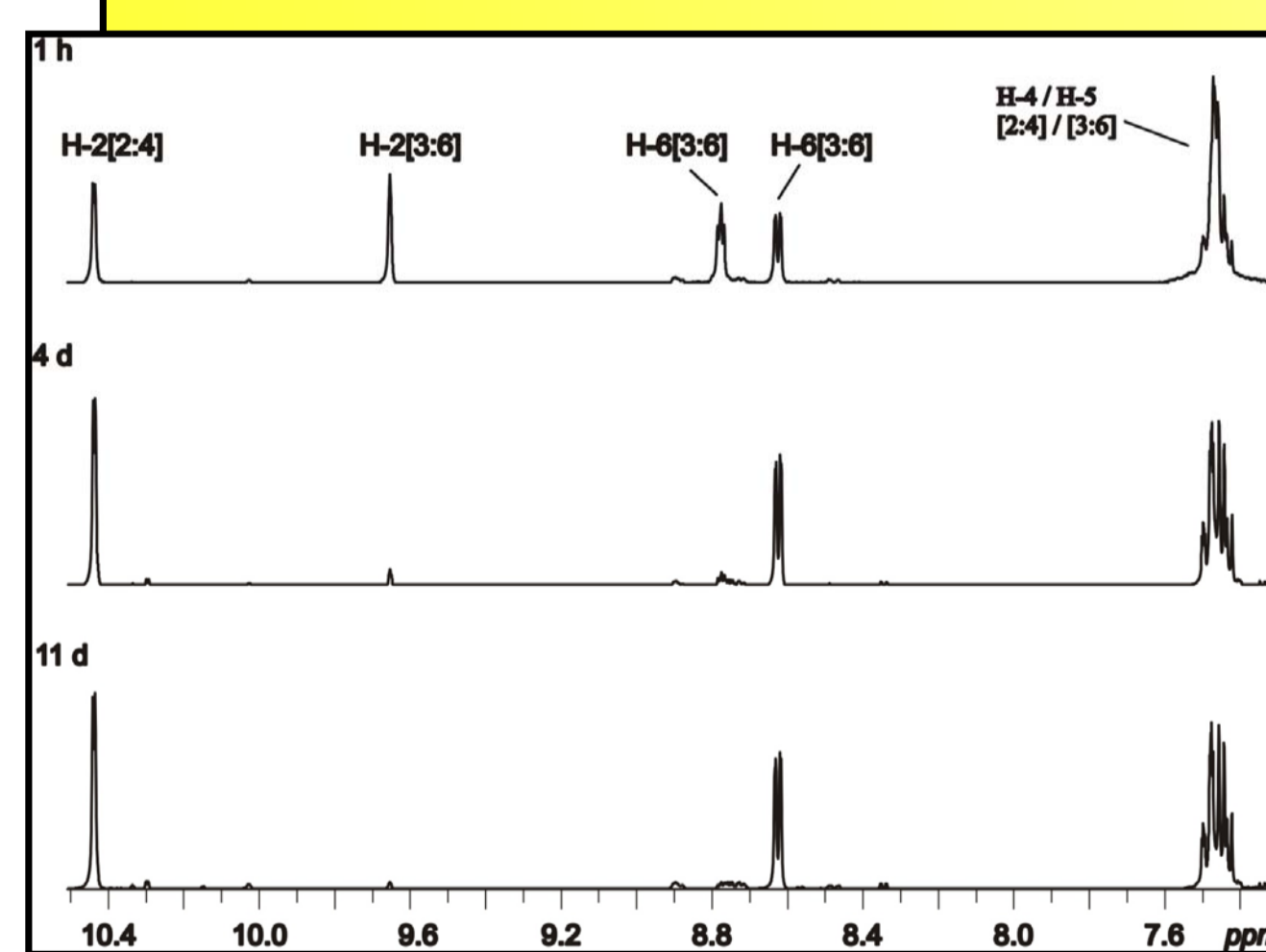


In both cases, a fast self-assembly process was observed. Even at short reaction times, the [2:4] complex was observed. The [3:6] complex was just observed irregularly, which could be explained by the influence of concentration.

Some intermediates were observed as well. On the one hand, several species occur, which have to be open chained and somehow linear complexes ([1:4], [2:5], [2:6] and [4:3]). On the other hand, some complexes are observed, which could have open chained or closed structures ([2:2], [2:3] and [3:3]). With increasing reaction times the signal intensities of the intermediates decrease and those of the [2:4] complexes increase. Additionally to this, solvent molecules also play a certain role in the self-assembly process. This can be explained by coordination of the solvent molecules to the metal centers and/or interaction with the urea ligands.



In the system of **8/11** the [3:6] complex is converted into the [2:4] complex and after 40 hours no **11** is observed with NMR spectroscopy (see on the right side). This result was verified by ESI-FT-ICR mass spectrometry, wherein a complete conversion was observed after 15 days. This can be interpreted by involving a bite-angle change comparing the ligands **1** and **2**, which is caused by the ligand's methyl groups.



The equilibria between the [2:4] and the [3:6] complexes can be influenced by changing the solvent.

The addition of water to a solution **7/10** in DMSO leads to a conversion of the [3:6] (**10**) into the [2:4] complex **7**. In a mixture of DMSO/water in the ratio 3:7 **10** is almost converted into **7** within 4 days (see on the left).

In a mixture of DMSO and THF the bigger [3:6] complex **10** is promoted in the beginning (see table). With increasing time, a conversion of **10** into **7** is observed here as well.

solvent mixture (ratio)	ratio (1h) [2:4] : [3:6]
DMSO/THF (9:1)	1.00 : 0.88
DMSO/THF (7:3)	1.00 : 0.79
DMSO/THF (1:1)	1.00 : 1.39
DMSO/THF (3:7)	1.00 : 1.85

Temperature depending <sup>1</sup>H NMR experiments did not give clear results. This can be explained with a relatively slow exchange between [2:4] and [3:6] complexes compared to other self-assembled metallo-supramolecular systems.

For the example of **7/10**, concentration depending <sup>1</sup>H NMR experiments clearly show that the [2:4] complex **7** is preferred at lower concentration, whereas the [3:6] complex **10** is promoted at higher concentrations.

## IV. Conclusion

The [2:4] and [3:6] complexes have two shells with different polarity which is caused by the directed dipyriddyurea ligands. This feature can be used for molecular recognition and host-guest chemistry.

The equilibria between [2:4] and [3:6] complexes is influenced by the bite angle of the ligands as shown for **8/11**. The self-assembly of [3:6] complexes is affected by the solvent. In the case of solvent mixtures with water, the inclusion of water molecules in the [2:4] complex may promote the conversion of [3:6] into [2:4] complexes as well. This is indicated by the crystallographic data. The [2:4] complex is thermodynamically more stable than the [3:6] complex which is converted to the [2:4] complex under kinetic control.

The building process of [3:6] complexes is depending on the concentration of the starting materials which is observed in the mass spectrometric mixed-flow experiments.

Due to the big variation of different intermediates in the self-assembly process, we assume that in the beginning many different species are formed, which convert into the preferred complexes (here: [2:4] and [3:6]) with increasing time.

### Acknowledgement

We thank the Deutsche Forschungsgemeinschaft and the Fond der Chemischen Industrie and the Deutscher Akademischer Austausch Dienst for financial support. C.A.S. thanks the Dozentenstipendium (VCI) for financial support.

[1] The nomenclature of the complexes: a) in the text: [metal:ligand]; b) in the mass spectra: [metal:ligand:counter ion]<sup>charge</sup>.