

## CHAPTER VI

### CONCLUSION AND COMMENTS

In this final chapter, we make conclusions on various themes and on what has been done and observed. Some comments could be also made, on the basis of an existing data.

#### 6.1 On the basis set

The STO-3G basis set, without applying the Boys-Bernardi counterpoise correction, is found to be suitable one for this system. The obtained stabilization energies are nearly the same as those computed using DZP basis set with BSSE corrections, while the optimal distance is 0.30 Å shorter. However, this discrepancy is within the KT limit. In addition, the selected basis set gives the best value of the dipole moment of water and ammonia molecules, in comparison with an experimental data and with the results obtained using the 3-21G, 6-21G, 6-31G, DZV, DZ and DZP basis set.

#### 6.2 On the solvent structure

One seems conflict is that the cyclen molecule was found to influence solvent structure up to 8.00 Å - 9.00 Å from its molecule centre, while structural properties, *e.g.* radial distribution functions, were not significantly altered from their ideal bulk values. A clear picture of this finding is that it is not possible for a solvent molecule to be induced to form a solvation shell, since cyclen-solvent interactions are quite weak. What is observed as ligand's solvation shell is an usual arrangement of solvent molecules. The difference is in the structure of solvent molecules lying in the border near the ligand, which is similar to that at the liquid surface and is the end of the hydrogen bond network. The other difference, specific form this study, is one or two water molecule (W1, W2) could not orientate freely.

### 6.3 On the entire solvation shell of cyclen

The entire picture for the solvation shell of cyclen in 18.45 mol% aqueous ammonia solution can be summarized as the following;

- The *nearest neighbor* of cyclen consists dynamically of either one or two water molecules, located close to its cavity (W1 and W2 in Figure 5.21 and 5.28). The ratio having one or two water molecules is 1:2.3.

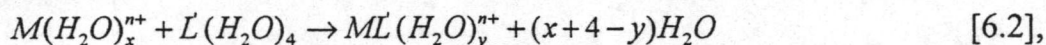
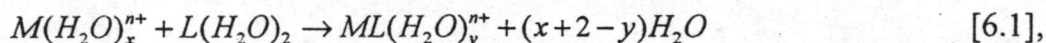
- The *inner solvation shell* contains 6 water molecules. Excluding the two nearest neighbors, they are in the region around NH functional groups of cyclen, without forming hydrogen bonds (W3-W6 in Figure 5.21 and 5.28). Rotation of W1 and W2 about an axis perpendicular to the ligand's plane, leads to a transition between the two favoured configurations of W3-W6.

- The *outer solvation shell* accommodates both water and ammonia molecules. An inner part of this shell contains about 3 ammonia molecules, coordinated to the W3-W6 via hydrogen bonds (Figure 5.28). The outer part shows "ideal" characteristics of bulk water-ammonia solvent.

- The *overall picture* for the solvation shell of cyclen is like the *sandwich* lying in the hydrogen-bond network of water. This water network is then again linked to the other ideal bulk network of water-ammonia mixture.

### 6.4 On the macrocyclic effect

Only two water molecules, W1 and W2, were found to attach to the ligand cavity. The ratio of having one or two water molecules is 1:2.3, leading to an average value of 1.7 water molecules. Suppose that its open-chain analog was solvated by four waters and both complexes of cyclic and open-chain ligands were solvated by the same amount of water (which is less than 4), as suggested by other authors (3). The exchange reactions are:



where  $x$  is the coordination numbers of the  $n$  fold charges cation (M) and  $y$  is the hydration numbers of the cyclic (L) and open chain (L') ligands, which is expected to lower than 4.

It is obviously seen that more energy would be needed for the open-chain ligand than the cyclic one for removing more water molecules ( $x+y-4$ ) from its hydration shell during the complexation process. It is not certain whether the energy required for breaking some hydrogen bonds could lead to the difference between the stability of L and L' complexes on the order of a million times. However, there is no doubt in suggestion, according to our results, that *solvation effect* partially supports the existing of the *macrocyclic effect*. The reason behind this conclusion is that the stabilization energy of about -3 kcal/mol in the binding of water molecules to the NH functional groups of cyclen is too weak, in comparison to those between solvent molecules. This reason is different from those reported originally by Paoletti and Handcock (4,5), but leads to the same conclusion, that the space around the cyclic ligand is not large enough to accommodate more water. We believe that their reasons may be valid for very big solvent molecules, but not for water ammonia, methanol, and other similarly sized solvents.

## 6.5 Prediction for other systems

On the basis of the available data, prediction of the contribution of solvation effect to the macrocyclic effect could be made, *i. e.*, such a contribution is expected to be controlled by the relative solute-solvent and solvent-solvent interactions. If the solute-solvent interaction is stronger than the solvent-solvent one, even by some kilocalories per mole, coordination of solvent molecules to the NH groups should be easily possible. It has been found from the Monte Carlo simulations of a cyclen molecule in water, using the HR cyclen-water potential (63) that W3-W6 were also bonded to NH groups by hydrogen bonds. In those

simulations, the local minimum for water approaching the cyclen molecule along a N-H bond is -9 kcal/mol and there was no defect on this direction. Therefore, the solvation of the cyclic ligand should not be limited by the space around them, at least for small-sized solvents.

A consequence of forming hydrogen bond to the NH group is an increase of the solvation energy of cyclic ligands, which leads, finally, to an opposite conclusion, *i.e.*, that macrocyclic effect is caused primarily by the different solvation of cyclic and open-chain ligands.

## 6.6 On the further study

It is interesting to pursue the further study on the influence of macrocyclic ligands on the solvation structure of the solvent. In this regards, the following systems are proposed with supporting reasons:

- A system where the ligand-solvent interaction is stronger than the solvent-solvent one. If it is a mixed solvent, interactions between ligand and each of both solvents in the mixture should not differ much. It was mentioned in section (6.5) page 79 that if solute-solvent interaction is stronger than that of solvent-solvent even by a few kilocalories per mole, the solvation number may be higher than the case of more or less equal in magnitude of interaction as it is in this work. In addition, the competition of both solvents to approach the first shell of the ligand may also lead to more interesting outcome. A change of solvent molecules to a larger size is also recommended since this may provide an opportunity to look into the effect of the availability space around ligand on the extent of the solvation.

- Since the interaction between macrocyclic ligands and solvents is usually quite weak while the size of the system under consideration is quite big, the STO-3G basis set is still thought as a suitable one. To improve the quality of the results, scaling the related pair potentials to the same basis or recalculating them using the same basis set is recommended. The use of a bigger basis set or including the Boys-Bernardi correction is not expected to lead to a significant alteration of the simulation results. However, it is interesting to employ a bigger basis set in the future, when a high performance computer is commonly available.