Fundamentals and Applications of Supramolecular Chemistry
Deepak Chopra
Department of Chemistry
IISER Bhopal
Week 09
Lecture 41

W9L41_Self Assembly Processes

So, hello everybody, today we are going to start a new module in the course of supramolecular chemistry, and we are first going to begin with self-assembly processes in nature.

And here we are going to first start by understanding the principles of self-assembly, which I can refer to as SA, and we are also going to look at metal complexes as model systems to understand SA processes, meaning self-assembly processes, and then we will look at some specific cases of self-assembly in biological systems.

So, this is going to be quite an extensive discussion on self-assembly processes, and we need to actually start by understanding what self-assembly is. Till now we have been focusing on events related to molecular recognition and supramolecular chemistry between different kinds of species via intermolecular interactions.

A self-assembly is also an extension of the understanding or knowledge that has been derived from supramolecular interactions, but in this particular exercise of self-assembly, the manner or mechanism in which the process proceeds is done in a very, very specific way.

And it actually follows a series of sequences or a series of instructions that are contained within the system, or that are programmed within the system, or you can say they are coded in the system, such that the species, molecules, and different atoms and ions first recognize each other in specific ways to form specific species, which then further assemble to give you the larger architecture or the larger species.

So, it is not that the self-assembly process is not a random process or a randomized process where, statistically, you have a set of species in solution, and then the molecules of the species will come close to each other or collide with each other and then form a certain set of structures.

It is more programmed; it is more of a precise recognition process, and that is why we need to understand the principles of self-assembly in a more rigorous way. So, to start with, let us look at a definition of self-assembly. So, in this particular lecture, we will be taking down a few very important points or notes related to self-assembly.

So that we are more familiar and comfortable with the language used to understand self-assembly. So, this is a process that involves the spontaneous association of two or more molecules or ions to create a larger aggregate species.

The formation of this is a very important point for the formation of reversible supramolecular interactions. The process of these supramolecular interactions or events of reversible recognition depends on this, is in accordance with the information encoded in the system, and so this is the definition of self-assembly.

So, to start with, let us first consider events related to processes of self-assembly in metal-ligand complexes, and first of all, we will look at synthetic probes or examples to understand molecular self-assembly processes.

And why we are choosing metal-ligand complexes: number 1, because they have lability associated with them, that is, the metal-ligand bonds are of a labile nature; and number 2, they are also characterized by a high degree of directionality.

Okay, and the directionality is because, given a metal ion and a specific ligand environment, we are able to predict with confidence and certainty the nature of the metal-ligand association to form a much larger aggregate or species.

For example, let us consider the following ligand. So, we have nitrogen as the donor atoms, and we consider four equivalents of these, as well as four equivalents of a palladium complex with ethylene diamine. This is the corresponding palladium species.

And now we know that palladium tends to form a square planar complex, with a coordination number of 4, and in this regard, we see that this palladium center can now form two additional Pd-N bonds from these two particular directions. So, this particular bipyridyl system can come from here.

Now you can see we have formed this larger species, and the overall charge in this complex is 8 plus, and this is referred to as a molecular box. This is referred to as a molecular box, and you can see that there is a void here in which you can have different kinds of solvent molecules that can be included.

So, we see that this kind of very specific association takes place between the palladium center and the bipyridyl ligand to give you this molecular box.This is most specifically referred to as a molecular square, and this square can now aggregate further in solution to form a molecular box kind of arrangement.

So, this molecular square is formed, and this process of self-assembly now leads to the formation of a thermodynamically stable product. It leads to the formation of a thermodynamically stable product given a set of reaction conditions.

So, there could have been the possibility of the formation of, you know, a species, say, if it could have also formed this kind of species where you have two of the nitrogen centers coming from the two bipyridyl ligands, and it could have formed half of the species.

So, it could have formed this particular species, which satisfies the valency of the palladium center, that is, the dsp^2 hybridization and the square planar geometry.

But then we also have another such species on this side, which is the square planar palladium, and now, because of these two specific nitrogens at this particular site, they can satisfy the coordination requirement of another palladium center; therefore, this particular box is now being formed.

So, you see here that when you had this particular species at this particular site, the palladium was empty. The palladium here had a valency of three, so the fourth one comes from this nitrogen. Here, too, the fourth one comes from this nitrogen. It forms a molecular box, a very specific arrangement that has greater thermodynamic stability.

So, keeping in mind these features associated with metal-ligand complexes, let us look at the other characteristics of self-assembling systems: the final product. The final product formation takes place in a series of steps.

First, we have the smaller aggregates; then they self-assemble to give the larger aggregates, which lead to the formation of the stable product. So, first is the formation of the metallic complex, and then further supramolecular processes can happen before the species can assemble further with each other.

And the next thing that is important is that there exist multiple equilibria between the differently formed species, and this can be influenced by the concentration and temperature of the experiment.

So, for example, we know that when we have a metal, it combines with the ligand. It forms ML first, then ML combines further with the ligand to give ML2.

In this way, we finally get the ML6, and eventually, we know that the beta is actually the product of the equilibrium constant for each of these particular steps. So, each step here having the constants k1, k2 like that influences the magnitude of the equilibria and influences the product formation.

So, the overall equilibrium constant is a product of the constants for the individual reactions where the individual equilibria exist, and this can be influenced by the concentration and temperature of the experiment.

So, overall, the driving force is the formation of the thermodynamically more stable product. The next thing is that when you have self-assembly processes, more than one type of interaction will participate.

For example, you can have a combination of metal-ligand interactions and also hydrogen bonding between the atoms in the complex. Again, the process is to form the thermodynamically most stable products. And finally, this is a very important feature of self-assembly: we are utilizing interactions with different strengths.

For example, the metal-ligand bond is the strongest, followed by the strong hydrogen bonds, then the medium-strength hydrogen bonds, and finally the weakest interactions.

So, the spectrum of the interaction strengths operates, and then by utilizing these interactions with different strengths, we can design large supramolecular arrays such that this specific information or memory is encoded in the system of interest.

This results in the formation of an ordered assembly in a particular manner to create the thermodynamically stable product. So, all the points are actually directed towards understanding the formation of the thermodynamically most stable product via the process of self-assembly, highlighting the role of concentration, temperature, and the different types of interactions based on interaction strengths; this will actually guide the process of self-assembly, which is also referred to as the process of hierarchical self-assembly.

Hierarchical means it is taking place in a specific manner, in a specific fashion, and this particular information about the specificity of the interaction strength is actually encoded in the system of interest, which overall now results in the formation of a highly ordered supramolecular array, resulting in the formation of a thermodynamically very stable product.

So, self-assembly means there is a set of specific instructions given to the system that is contained in the memory of the system, and then the system operates utilizing this well-defined set of instructions. It is just like a computer that operates given a set of instructions.

So, here also the process of self-assembly is very specific, and if there is any mistake that happens during the process of recognition or self-assembly. Because of the reversibility of the process, the system can then dissociate and correct the process of recognition again so that the self-assembly takes place in a proper fashion. So, this type of memory in the system, in order to erase any wrong associations or wrong atomic contacts and then recreate the relevant atomic content, is what makes self-assembly processes very unique, and they have implications in nature.

So, self-assemby is important, and that is why the process of reversibility is very important. That means if, by mistake, we have formed a particular contact or interaction through either thermal processes or statistically random processes, the system gets an opportunity to repair or correct itself.

So that it can now again form the relevant contact of interest and the process of self-assembly continues to give you the highly ordered structure which is the thermodynamically more stable product.

And in this regard, what is important is, as I told you, hierarchical self-assembly, where there are several levels of complexity that operate over several self-assembly processes. One level cannot exist without the existence of the preceding one.

The process and the directions that are to be given to the system to be followed during the process of self-assembly have already been programmed into the system and take the system in a linear fashion, serially stepwise from the high energy state to a lower energy state.

So I hope you have been able to appreciate the principles that govern self-assembly processes. Now there are classifications of self-assembled systems. So first is the single-interaction self-assembly. In the case of single interaction self-assembly, we also call this the single code self-assembly; it refers to the existence of only one specific interaction.

For example, you can have a system where the species interact via only O-H...O hydrogen bonds, O-H...N hydrogen bonds, N-H...O hydrogen bonds, and so on and so forth. Or you can have a palladium-nitrogen interaction of a given specific type.

So, all these are examples of single interaction self-assembly. Then we can have multiple interaction self-assembly, the process in which more than one interaction of a given type is present. It is referred to as multiple interaction self-assembly.

So, a given type of interaction is there, say palladium-nitrogen or O-H...O, and the number of such interactions that are present is more than one; that is why it is called multiple interaction self-assembly.

So, a given type of interaction, but the number of such interactions is multiple, and therefore it is called multiple interaction self-assembly. This can be further divided into uni-mediated or multi-mediated self-assembly processes.

And this is, if you have only one type of interaction, it is uni-mediated, but if you have multiple types of interactions, then it is multi-mediated. For example, you can have both palladium-nitrogen interaction and O-H...O hydrogen bond; then it becomes a multi-mediated self-assembly process.

So, if there are now different categories of interactions, this is one category of interaction and this is another category of interactions. And also, if the numbers are more than 1, then this is referred to as a multi-mediated multiple interaction process, so it is a multi-mediated multiple interaction self-assembly.

And if you have these interactions, which are of different types and are present, but there are multiple interactions of a given type, we can call this uni-mediated multiple interaction.

So, in this case, you will see that if you have a given type of interaction, say either palladium-nitrogen or O-H...O, but they are present multiple times—say they are present 2 times or they are present 3 times—then they are of a given type, but they are present a multiple number where they are called uni-mediated multiple interactions.

Here there are different types, and multiple numbers of each type are present; they are called multi-mediated multiple interaction self-assembly. And there is a tendency to actually use multi-mediated and multiple-interaction self-assembly interchangeably. But now we should keep in mind that they are actually different terms, and they should not be used interchangeably or confused. That is, multiple interaction assembly is different from multi-mediated assembly.

So, let us look at some representations of these. For example, we can have a metal here and a metal here, and they are interacting in a particular coordination environment. So, you have metal-ligand interactions, and therefore this is a single interaction assembly. This is a single interaction assembly. We have the same type of metal-ligand interaction in all the regions.

But now we change. So now we see. We put a metal here; we put a metal here; we put a metal here. So, we are now going to have a different environment. We have two different metal-ligand interactions, but the type is the same.

So, although we have two different metal-ligand environments, they are still referred to as uni-mediated assembly because, although they are distinct interactions, they all belong to the same type. So, because the type is the same, that is, there is only one type of metal-ligand interaction, but they exist in different coordination environments, we call it uni-mediated multiple interaction assembly.

And now, in the third case, what we can have is, say for example, an O-H...O hydrogen bond; here we have metal, and here we again have metal. So, here we can see that now you have got two different types of interaction.

We call this multi-mediated multiple interaction assembly. So, these are the different types of interactions that we can have now, given these kinds of self-assembly processes. Now we can look at the formation of different kinds of large-size discrete species, and in this regard, we have a classification based on the formation of metal-ligand complexes, wherein we can now look at the formation of ladders, polygons, and helices.

So, as we told you, in this regard we need to have the metal and the ligand in a certain coordination environment so that they can form discrete species, and different kinds of building blocks have been proposed. In this regard, let us look at a couple of such design elements to create larger discrete species.

For example, we can have a metal, a metal we know is divergent in nature, and we can now have a ligand that has convergent sites; therefore, we can have a process of self-assembly, where we can have the metal, which can come here and now form a discrete species.

And in this case, we have two such equivalents of the metal and two equivalents of the ligand. So, we see that the numbers actually now add up statistically in the form of much larger-sized species.

To start with entropically, this is not very favored because it reduces the number of units; however, what is important is the number of enthalpically driven metal-ligand interactions that drive this process. Similarly, we can have a different kind of design where we have a metal and a protected ligand.

And now this is a convergent metal because there are only two distinct binding sites, and they must come and approach the metal in a converging manner, and now the ligand is actually open.

So, the ligand has divergent sites, and we have a protected convergent metal. So, this can now lead to the formation of a very specific discrete species. So, this is the ligand here, and this is the ligand here. This is something we looked at in the case of the molecular box, where we had palladium, which had two nitrogens coordinated, and then four nitrogens can come and coordinate and stabilize the species.

Obviously, it led to a larger box, but we can have this discrete species that are formed, and the overall charge depends on the oxidation state of the metal ion and also that of the ligands. And we can have a third one, where we have a divergent metal and a divergent ligand that can actually give rise to a polymer.

So, these are the different kinds of design principles that can be followed in the construction of large discrete pieces involving supramolecular assembly. So, in the next lecture, we will take up examples where we will look at more realistic examples of such chemical entities that form these supramolecular self-assembled building units.

Thank you.