Fundamentals and Applications of Supramolecular Chemistry
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Lecture 58

W12L58_Supramolecular Chirality

So, hello everybody, today we are going to discuss a new topic where we are actually going to address the issue of supramolecular chirality in nature. Now, chirality is a very interesting phenomenon. As we know, starting from an atom that can rotate in two different directions, it has two possible spin orientations: clockwise or anticlockwise.

Left-handedness and right-handedness start from the atomic level to fairly large galaxies, which also have these spiral arrangements. Chirality seems to be very intrinsic to the universe.

So, whether it is the atomic motion or the spiral motion of the galaxies, the handedness of the rotation, whether it is the left-handed or right-handed sense of rotation, decides the sense of chirality.

Thus, chirality is kind of embedded in the very fabric of the universe. It has been observed that starting from a simple aggregation of molecules that can form a chiral arrangement to form larger molecules, we can have covalent bond formation where there are stereogenic centers, with different chiral centers within the covalent framework of the molecule.

Or you can also have chirality, which is created by the different chiral arrangements of molecules, where a set of arrangements does not have mirror image symmetry of that particular arrangement. So, once you have, say, a particular helical arrangement of molecules—let's say this is one particular helical arrangement—now I put in a mirror symmetry.

This is the opposite helicity. So, for example, if I were to say this is left, this is right helicity. So, this is a chiral arrangement; this is one chiral helix, this is another chiral helix, and on this particular backbone, we can either have the covalent connectivity, or we can also have the molecules that are connected via non-covalent interactions.

This will give rise to a chiral solid, a chiral compound, and a molecule that will give rise to a chiral supramolecular unit.

So, we can have these helices, which signify chirality and are associated with covalent bond formation or with the molecules connected in a non-covalent sense, to give the supramolecular chiral building blocks.

It is also to be kept in mind that, in the case of a covalent association, you need to introduce the chiral information at some part of the molecule. Whereas, in the case of supramolecular chirality, the molecule per se need not have any chirality associated with it.

It can be an achiral molecule; M can be an achiral molecule, which I am using here. But the arrangement of this M via the non-covalent interactions creates a helical structure, which is a helical supramolecular association, and hence the resulting arrangement of molecules is chiral in nature. And it is important to look at supramolecular chirality because supramolecular chirality is very much present in all crystals and in all the molecules that associate in the solid state.

And when you have chirality, it is basically characterized by the absence of a center of inversion or the absence of mirror symmetry. So, mirror symmetry is absent. Otherwise, it will generate the enantiomer of the opposite handedness, and both enantiomers will exist simultaneously in the solid state, and the resulting solid that will be obtained is not a chiral solid.

So, it is important to keep in mind that chirality in a molecule can lead to chirality in solids, and it can also lead to non-chirality in solids. So, when you have a chiral molecule, there is a possibility of both chirality in the solid, because now you have only one particular enantiomer, which is forming a chiral arrangement via non-covalent interactions, and the arrangements can be such that you will actually have the mirror symmetry present.

In that case, it will generate the opposite handedness, and therefore, it will lead to a non-chiral solid. And if you have an achiral molecule, you can definitely have a chiral arrangement; that is, just as I mentioned here, you can have an achiral molecule, but you can have a chiral arrangement; you can have an achiral molecule and a non-chiral arrangement.

And by and large in solids, they are also characterized by the presence of a center of inversion, which we call centrosymmetric, or the absence of a center of inversion, which we call non-centrosymmetric. But overall, the mirror symmetry must be absent in the crystal packing, and this kind of helical arrangement is characterized using the screw axis in crystals, which consist of n-fold rotation plus 1/n translation.

So, in these helical arrangements, essentially, you have, for example, a two-fold axis plus a half translation of the unit cell.

So, you have, say, for example, this particular object A, and you can rotate it by 180 degrees, okay, and then you can actually translate it by half. So, say it comes here, then it comes here, then it comes here.

So, this is related to what we call a 21-screw axis, where 2 indicates the n-fold that is a 180-degree rotation, followed by half translation. So, that means this connectivity now creates the parallel arrangement. You can also have a 3-fold axis plus t/3 translation, you can have a 6-fold axis plus t/6 translation, you can have a 4- fold axis plus t/4 translation.

So, that tells you that starting with a particular molecule M, you are going to first rotate by a certain angle, say 90 degrees, then you are going to translate by T/4, then from there you again rotate by 90 degrees and then translate T/4. So, you have come to T/2.

So, in this way, you will be able to have arrangements of molecules at all these points, and that connectivity will now create the chiral helices. So, these chiral helices, which we have drawn here, can actually be present in the sense that they are connecting the molecules via any of these four given combinations. Therefore, the resulting arrangement of molecules is called a chiral arrangement, and that is the origin of supramolecular chirality in solids.

So, let us compare molecular and supramolecular structures. For example, in the case of a molecule, the actual composition is based on the atom, but here it is the molecule or the building block that is connected by non-covalent bonds. Here, the bonding is covalent.

The chiral geometry, in this case, is a tetrahedron, an axis, or a plane; here, this is helical, spiral, a chiral sheet, or different chiral domains. So, the 1, 2, 3 manifestations of chirality are with respect to a point, axis, or a plane.

Here it is with respect to the conformation, secondary and tertiary structures, and helicity as we observed. Then we have different kinds of chirality. For example, we have induced chirality. To achieve induced chirality, you must have a chiral molecule. For an achiral molecule to have a strong association or interaction with a chiral host through non-covalent bonds, it will actually create the necessary chirality in the resulting structure.

Then we can also look at helical chirality, which we have discussed. That is, you have an axis about which the substituents are spatially arranged, so that these are non-superimposable on their mirror image.

And how do we actually study these chiral domains? There are different techniques by which we can actually understand the association of molecules to form a chiral arrangement, not only in the solid, but it can also manifest in terms of the external appearance of molecules that have crystallized out.

So, the process of crystallization itself can result in the formation of helical kinds of fabric aggregates, helical kinds of morphologies, fibrous networks, fibrillar networks, helical arrangements, and helical networks. You can also sometimes have gel-like structures, which are formed and are called the helical fibrous arrangements internally present.

So, you can have internal arrangements, and you can have the external morphology, which is the physical appearance that you see when a compound of interest has been crystallized from a saturated solution. And these can actually now be imaged or viewed using different microscopic techniques. For example, we can use AFM, we can use STM, we can use SEM, and we can use TEM.

So, with different imaging techniques, we have the AFM technique, which is atomic force microscopy, the scanning tunneling microscopy, the SEM, and the TEM techniques as well. These are the other microscopy techniques, and the measurement here involves the force between a cantilever and the sample of interest, and what you are imaging is a 3D surface, with the coating done on a mica or silicon flat surface.

In the case of STM, we are using electron tunneling of the tip and the surface. It is again a 3D surface imaging technique. The surface is called HOPG, which is highly oriented pyrolytic graphite. Then, in the case of SEM, we have the scattered electrons; this is the basis of the measurement. We get a 2D photo, and it is a grid that is coated with gold or carbon.

TEM involves the absorption and diffraction of electrons. Again, it is a 2D photo, and it is placed on a copper grid or a grid made of carbon. In addition to this, if you would like to understand the bulk arrangement in crystals, then single crystal X-ray diffraction is a technique of choice that will clearly give you the arrangement of the molecules in a chiral manner, so that the resulting solid is a supramolecular chiral solid.

You can also look at the conformation and the network of interactions that create these helical arrangements inside the crystal, which is the internal supramolecular chirality, using XRD. Additionally, there are other techniques; for example, circular dichroism, vibrational circular dichroism (VCD), and Raman spectroscopy for analysis.

So, there are different techniques, and in this regard, circular dichroism is a very useful technique that is used to understand the presence of chiral structures of a particular handedness. And it has been observed that depending on the chirality, the magnitude of the Cotton effect is going to be the same, but the sign is going to be reversed, depending upon the chirality or the handedness of the chiral solid that has been formed, or the chiral association that has occurred.

So, with this background in mind, we would like to take up some important examples of helical aggregates that have been probed using different imaging techniques. So, first of all, let us consider this particular molecule here, which is a fairly large molecule, and you can see that with respect to the benzene ring, it has these tetra-thiafulvalene units, and it has C3 symmetry. This is the C3 symmetrical molecule, but at this position, you can see that you have the chirality, which is present because of the R prime groups.

So, this is the SEM image that has been recorded, and in this same image, you can very clearly see the formation of the helical aggregates. So, when this particular compound is crystallizing, it forms this kind of helical aggregate, and it has been ascribed to the formation of this kind of intertwined helices, which form this kind of helical arrangement.

Then, we can take another interesting example here of this particular compound. As you can see, it has chirality here, and this is an achiral molecule; this is a chiral molecule. Normally, if you were to crystallize the achiral molecule, it would form these kinds of planar sheets.

But now, when you are actually doing the crystallization of 5 mole percent of 99, these are the bisamides, with 95 mole percent of 98. So, we have this compound: 5 mole percent of this, with 95 mole percent of that, and we have this achiral unit, and this is the chiral unit. And when these two have been mixed in this particular ratio, what has been observed, by looking at the SEM images, is that you now have twisted ribbons of very high aspect ratio.

That means one of the dimensions, say, the length, is very, very long compared to the thickness of these fibers or ribbons. What actually prompted this chiral association? In order to understand the chiral association for this particular composition, which actually has almost 95 percent of the achiral component and just 5 percent of the chiral component, we must also understand the origin of chirality and how this mixing promoted the chiral association.

Because you now have the achiral solid, but you also have a chiral solid, the presence of the chiral centers actually templates the formation of these helical arrangements when this mixture is being crystallized together.

So, what was proposed is that the presence of stereogenic centers in the co-assembly provoked the chiral propagation of the hydrogen bonding of the amide functionality, thereby reinforcing the formation of twisted ribbons. This approach is referred to as the Sergeant and Soldier approach.

So, the sergeant here, which is the chiral solid, the minor component, with extremely low concentration, directs the large army of soldiers and gives them the necessary instructions, or provides the necessary information, by which they can actually now self-aggregate or self-assemble to form these kinds of helical structures and these kinds of twisted ribbons.

And this is a very popular approach to understanding the origin of supramolecular chirality in the crystallization of compounds, where we add another component, which is actually chiral, present in a minor concentration, but which can now favorably trigger the formation of bulk structures of bulk units that resemble twisted ribbons.

And if you look at figure A, it has been obtained in this ratio: 95 to 5 percent mole ratio. In the case of A and B, the images have been taken. In the case of C, it is 90 : 10, and in the case of D, it is 85 : 15.

So, as you increase the concentration of the chiral component, it leads to an increased concentration of these chiral units or these twisted ribbons, which will further crystallize in larger quantities. So, there is an increase in the population of these chiral aggregates as you increase the concentration of the chiral component, which is the chiral bisamide in the crystallizing chamber.

So, this way you can induce or bring about supramolecular chirality. We can take another example of this particular molecule here, and this is actually a disc-shaped molecule. It has these long alkyl chains OC10H21, and it has an imidazole unit.

And this imidazole unit gives some kind of asymmetry to the molecule; it creates a certain kind of asymmetric environment in this particular molecule, and when we actually try to crystallize this compound in 2-methoxy ethanol, it leads to the formation of gels. So, you see, these are the fibers that are obtained, and in this, you can also see the helical structures that are formed, and this crystallization was done at 20 degrees centigrade.

And this is the TEM image of this, and this is the corresponding AFM image of this twisted nanofiber. You can see both the left-handed and the right-handed fiber, which has been crystallized during the process of gel formation.

So, the fact that you have both the left-handed and the right-handed fibers was characterized using circular dichroism spectroscopy, where you can clearly see that you have both the positive cotton effect and the negative cotton effect, corresponding to the different chirality of the left-handed and right-handed fibers, which is present as you can see here from the CD studies.

So, what does the imidazole group do? It basically increases the asymmetrical characteristics of the building block and promotes hydrogen bonding as well. Hence, you are able to achieve chiral symmetry breaking via the steric effect of this unit during gelation.

So, the process of gelation favors the formation of chiral twisted nano ribbons of both handedness; therefore, we are able to achieve chiral symmetry breaking via the steric effect of this imidazole group.

So, these are some of the interesting examples we have, and I hope this impresses upon you that supramolecular chirality is very much intrinsic. In the literature, there are a large number of examples that actually demonstrate supramolecular chirality in different kinds of chemical as well as biological systems. So, with this, we come to the end of this lecture on supramolecular chirality.

Thank you.