Fundamentals and Applications of Supramolecular Chemistry
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Lecture 34

W7L34_Stimuli Driven Processes in Molecular Crystals

So, hello everybody, today we are going to discuss further the next topic in this course on supramolecular chemistry. And today we are going to start a discussion on stimuli-driven supramolecular processes.

This is a very important area of research, and there has been a lot of development that has happened in the past decade when different kinds of materials, particularly those that exist in the solid state, have been subjected to different kinds of stimuli. The stimuli can be of a physical nature; it can be of a chemical nature.

For example, in the case of chemical nature, we can expose the crystal to different kinds of solvents, or we can add a new chemical entity and see whether the crystal possibly undergoes a chemical reaction with it, or we can change the pH of the medium in which the crystal has been obtained. Physical stimuli mean we can actually expose it to light of a certain frequency.

For example, we can expose crystals to UV light, and it has been observed that in the presence of external stimuli, crystals also change their shape. And they also sometimes undergo different kinds of mechanical deformation because of the buildup of stress in the crystal, and this has given rise to the area of mechanically responsive molecular crystals.

We will discuss some of these as well, and stimuli can also occur through the application of stress in the crystal where you physically apply stress to the crystal. So, sometimes the mechanical strain that is developed in the crystal is a consequence of light, like, for example, UV light, and you can also apply stress physically to the crystal and see how the crystal adapts to the applied stress.

So, stimuli can be of different types. The first case today I am going to discuss with you is a very, very interesting case in which we have looked at the crystal-to-crystal transition in a chemical system in the presence of silicone oil.

This is a very interesting observation we made because most of the time we use silicone oil to mount the crystals. So, once the crystals of a particular compound have been obtained, the routine procedure is to take the crystals on silicone oil because, during the process of mounting, the crystals can actually jump, fly, or be lost.

So, to prevent that process, we use silicone oil, and most of the time, the silicone oil is an inert compound; it is non-reactive; it is something with which the crystal of interest does not interact or react.

But what was surprisingly observed is that when we looked at this particular set of molecules, we had the ethynyl-substituted amides. And in this regard, we have looked at two specific isomers, one in which R1 is fluorine and R2 is hydrogen. In the other case, when R2 is fluorine and R1 is hydrogen, when R1 is equal to fluorine, we call it the ortho isomer; when R2 is equal to fluorine, we call it the meta isomer.

What has been observed after a very systematic study is that the crystals of the compound, which is the ortho isomer, exist in two polymorphic forms, which we designate as Form 2 and Form 1. What has been observed is that in the presence of silicone oil, which is a chemical stimulus, or in the presence of heat, which is a thermal stimulus, conversion from Form 2 to Form 1 takes place.

Whereas in the meta isomer, what has been observed is that conversion from one form to another form takes place before melting. Now, when you cool the Form 1 crystal, it does not convert into Form 2; rather, it converts into a new form, which is Form 1D.

So, keeping in mind the fact that these crystals are very sensitive to external stimuli, namely chemical and thermal stimuli. We now look at this event more carefully in terms of what was actually observed under the microscope, where the crystals were kept in silicone oil. This is what was observed. This is a very interesting observation, and this is the first such observation in a molecular crystal.

So, to start with, we have the ortho compound, and we have got the plates. As you can see here, this is the initial shape and size of the crystals. We start with the initial Form 2. What we observe is that within 15 minutes, some needle-like projections were seen on the surface of the plate crystals. These are the needle-like projections that we see.

As time continued, that is within a period of 1 hour, a large amount of needle-like crystals had grown on the plate crystals. After a period of 6 hours, the conversion from Form 2 to Form 1 was complete when the plate form had converted into the needle form.

This process took place at a relatively faster rate for the ortho isomer. When we went to the meta isomer, we started with the initial set of plate-like crystals. Say on a given day, we start in the afternoon.

On the same day, after 5 hours, we saw the appearance of this needle-like crystal. Now, we see these crystals that are appearing and are needle-like. Now, please keep in mind that we have the same orientation, the same image. We are not moving the crystals on the glass plate; we are just observing on the glass plate, as a function of time, what is happening to these crystals. And then after we see that on day 2 in the morning, there has been a

conversion from Form 2 to Form 1, where you can see more and more growth of needle-like structures.

You can see these needle-like projections that are coming out, and eventually the plate form has converted into a new phase. This is also indicated by the loss of transparency in the crystal. So, these crystals are normally optically transparent, but now you see they have become opaque. So, when there is a phase transition from one form to another, these optically transparent crystals now become opaque, indicating that there is a conversion from one phase to another. So, the next thing was to actually see more carefully under the microscope on which we now apply heat.

So, we see that the stimulus here was in the presence of silicone oil. In the presence of silicone oil, we were able to achieve this transformation, and the next question was what if we took other oils or other liquids.

For example, long-chain fatty acids and dicarboxylic acids, or we could take glycerol and other glycols, and when the crystals were placed in other hydrophobic liquids, no phase conversion was observed.

So, this was a very extensive screening of the crystals of this particular compound in different kinds of oils, different kinds of fatty acids, and different kinds of glycerols, as well as long-chain alcohols, but no such phenomena were observed. It was only very specific to silicone oil.

And now we also want to see this phase transition, from Form 2 to Form 1, and we put the crystals under the hot stage microscope. So, here you can see that we first start with room temperature, where we have isolated the crystals of Form 2 and Form 1 separately.

You see this is a nice transparent crystal; this is an opaque one, and now at around 90 degrees centigrade, you see that Form 1 starts growing. As we have already discussed in our chapter on phase transitions, phase transitions take place according to different models, and the most popular model is the nucleation and growth model.

So, this process of phase transition from one form to another takes place gradually and continuously over a period of time, starting from a particular region in the crystal, and it essentially propagates this crystal phase via nucleation.

This means the nucleation of the new phase starts from one particular region of the crystal, and then this propagates, eventually covering the entire mass of the crystal where it has transformed from one form to another.

And now you can see that it has converted into Form 1 at 93.5 degrees centigrade. This is Form 1, and it also becomes opaque, and once it has converted from Form 2 to Form 1, we can see that they both melt because this was also the Form 1 crystal. Both the crystals melted at 102 degrees centigrade, indicating successful conversion from Form 2 to Form 1

followed by melting of Form 1.

So, with these kinds of experiments, we can actually validate the nucleation and growth model regarding how this phase transition took place and what the physical changes are taking place. Also, it has to be kept in mind that no solvents are included in the crystal structure of either Form 2 or Form 1, for both the ortho and meta isomers, and no silicone oil is formed either.

That means silicon did play a role in initiating the transformation from one form to another, but there is no inclusion of silicone oil in the final structure. Now, the next thing was to actually look at the crystal structures of both these forms, and this is something that is very interesting: the presence of silicone oil or heat, as we mentioned. The Form 2 converts to the Form 1, and you can see the dramatic change in the crystal packing.

I again re-emphasize that you can see here that this forms a layered structure where the different colors indicate the different molecules of the asymmetric unit. That means the basic unit of crystallization is actually that you have this purple and this yellow color.

Now you can see the purple-colored molecules stack in this direction and these yellow-colored molecules also stack in the other direction. The separation is close to 3.8 angstroms, which is essentially the van der Waals gap, and for the violet molecules, this gap is slightly reduced to 3.7 angstroms.

So, you have this pi-pi stacking, which actually packs the molecules into a layered structure in Form 2. Whereas in Form 1, we now have a double sandwiched herringbone structure, where you can see that this sandwich actually has a perpendicular arrangement.

So, this gives rise to the herringbone structure, and the dotted lines indicate the different intermolecular interactions that are present in this herringbone structure. As you can see here very clearly, you have a C-H...N hydrogen bond, and you have a C-H...pi hydrogen bond. The C-H...pi is not only with the phenyl carbon but also with the acetylenic carbon. The acetylenic carbon also interacts due to the pi electron density.

So, we have these C-H...π weak interactions, which stabilize the final structure, and you can also see the dramatic change in the structure when it transforms from Form 2 to Form 1, which has been mediated by the silicone oil or the heat.

Now, this kind of dramatic change in the crystal packing without loss of crystallinity is very much unprecedented in the literature, and this turned out to be a really interesting case of silicone oil-induced phase transition in molecular crystals.

And to summarize, we also conducted further studies where we actually grew the morphology of the crystal. You can actually use software to compute the bulk morphology, and what was observed in the bulk morphology was that in the case of Form 2, it is the acetylenic bonds that are actually exposed on the surface.

So, there is a possibility of interaction between the unsaturation corresponding to a triple bond and the silicon vacant orbitals, and this interaction between a large number of these isolated or exposed triple bonds with the silicone oil present in the vicinity of this crystal can possibly trigger a process where some of these molecules dissolve in silicone oil, but it also templates the crystallization of a new phase.

Again, this is only the initial process that we have speculated. The dynamics are extremely fast, and it has been difficult to capture these and understand how they are triggered and what the pathway is to go from the initial phase to the final phase.

So, this was a very interesting example of silicone-induced transformation in crystals. And now we go to the next set of stimuli that are of interest. So, we now see that stimuli in molecular crystals can actually come in different forms.

We just now looked at a case of, you know, thermal events that can trigger phase transitions in molecular crystals. We can have optical stimuli; that is, the presence of light, which can lead to changes in the crystals. We can have mechanical stimuli; we can have the role of humidity and also the role of pH, which can be a stimulus in molecular crystals.

Now, what is the response of molecular crystals? It has been observed that molecular crystals are subjected to different kinds of stimuli. In this particular discussion, we will be focusing mostly on mechanical stimuli.

It has been observed that the crystals can bend, undergo twisting motion, or undergo coiling motion. Now, this is very, very interesting. It was perceived until now that crystals are actually kind of inert objects; the molecules present in the crystal are kind of inert, and it is very difficult for them to respond to any kind of external stimuli.

But now, with the research in the last two decades, it has indeed been observed that crystals are very sensitive to external stimuli, and they can undergo macroscopic changes in shape, size, and different kinds of motion, where there is conversion of the applied mechanical energy to different kinds of kinetic energy, as we observed. So, we can have changes in kinetic energy.

For example, in ballistic motion, we can have the splitting of crystals. Thus, the crystals can break into different pieces, parts, or sizes. We can have an explosion of crystals, we can have shape-shifting in the crystal, and then, when you apply mechanical stress, when you apply shape-shifting, and when you withdraw mechanical stress, then it comes back to the initial shape. We can have the self-healing of crystals.

For example, if the crystal has cracked and then you bring it close to each other again, the surfaces can heal, and the crystal will return to its initial arrangement where the cracks completely disappear.

And these applications of dynamic crystals are of interest in the fields of sensors, the design

of dielectric materials, optical waveguides, and drugs because, after they are prepared, drugs are also subjected to mechanical stress, particularly in the process of tableting or the application of pressure to achieve compaction.

So, it would be interesting to see what the response of drug molecules is, particularly the crystals, to the external stress, flexible semiconductors, and actuators. And what is very important to keep in mind is that when you apply mechanical stress to the crystal.

You can actually have different kinds of events, and what is important is to keep in mind the stress-strain relationship. So, there are different regimes, and under the application of a small amount of stress, there is a strain, and this is what constitutes Hooke's law: that stress is proportional to strain within a narrow limit.

So, within the narrow limit, until permanent deformation takes place, if you withdraw the stress, then it will return to the initial configuration. And these kinds of systems are called elastic crystals, where if you continue to apply stress, then they go into a non-elastic regime, from which they do not return to the initial configuration.

Those kinds of crystals are called plastic crystals. So, all plastic crystals definitely go through the elastic regime, but plastic crystals, by and large, do not return to the initial configuration when you withdraw the stress.

So, the restoration of the shape does not take place, and what has been done is that people have now applied different stimuli for a plastic crystal so that it restores back to the initial configuration.

However, in the case of elastic crystals, they do get back their initial shape. So, with this in mind, it is relevant that we look at the elastic-to-plastic regime, which we sometimes call the elasto-plastic spectrum.

It is also important to modulate the crystal in a way that allows for either an elastic response or a plastic response. And what has been proposed is different structural models to achieve elastic deformation as well as plastic deformation. And so, we start with an initial arrangement of molecules in the crystal.

When we subjected it to a stress, what happens is that the molecules in the outer arc are present in this fashion where the separation between the molecules is gradually increasing.

Here you see that there is a compressive stress; here the molecules get compressed, and here the molecules get elongated. So, you actually have expansion in the outer arc and compression in the inner arc during bending.

What happens is that when you withdraw the stress, shape recovery takes place, and it comes back to the initial configuration. So, you essentially have reversible deformation, and you have interlocked crystal packing for shape restoration.

So, what happens is that you have crystal, and now you have different intermolecular interactions. These intermolecular interactions actually allow the molecules to move only in a limited way.

So, beyond a certain strain, they actually lock the structure, preventing the movement of molecules. So, elastic crystals essentially lock the molecules into a certain arrangement via initial displacement, such that when you release the stress, they again come back to the initial configuration. And this requires a structural buffer that essentially consists of a large number of weak interactions because the weak interactions can be easily broken.

So, they can allow the movement of molecules to a certain extent, but then beyond a certain stage, there is a locking of the structure because now there is no free space available for the molecules to move further.

So, that kind of limits the extent to which the movement of molecules can take place and also limits the extent of deformation. Therefore, the structural buffer is very important. This can lead to either 1D or 2D elastic deformation. Thus, elastic deformation is a very interesting phenomenon.

On the contrary, in the case of a plastic model, what we have is that the interactions are weak and they actually do not prevent the slippage of molecules. There are certain planes along which you will have irreversible movement of the molecules, and this will lead to permanent deformation in your crystal.

And this mostly happens in an anisotropically packed crystal, where you have strong interactions in, say, a sheet, a layered structure, but perpendicular to the sheet you have very weak interactions.

So, when you apply stress, you can have molecular migration, migration of the molecules over long distances, but because the interactions between these layers are weak, within the layer the interactions are very strong, and that can be the basis of plastic deformation.

So, let us look at these cases. The first case I would like to present here is in this particular organic system where these molecules have been synthesized and where the researchers have looked at four different compounds, where the scaffold is fixed and then we have different substituents: we have the chloro one, then the chlorobromo, then the dibromo one, and then two chlorine atoms in the same phenyl group.

Now, what has been observed is that these are the crystal morphologies; the crystal morphologies are given here for these particular compounds. Then, we do something called a 3-point bending experiment, where we actually apply stress in this region.

So, we apply stress to this region, and we fix this region, and this is done using a pair of forceps; we call this a three-point bending experiment. So, you have a crystal; we bring in the forceps here, hold this particular point, and then apply stress like this on the other two

parts, and then you see that the crystal can now deform.

This is mostly done along the major phases. So, if you apply the stress on the major phase, then either, if the crystal is brittle, it will crack immediately and break into pieces; but if it is not brittle and can adjust or adapt to the applied stress, it will deform, and this deformation can be either elastic. If you have applied relatively less stress, applying more stress can make it plastic in nature as well.

So, the idea is to do this three-point bending experiment, and this can be done on different phases, different major phases of the crystal. And as you can see here, this is the plastic crystal in the sense that it has deformed under the application of stress. and this is irreversible deformation such that when you release the stress it continues to maintain the final shape.

The same thing happens for the chloro and bromo compounds, dibromo compound, and in the case of the dichloro in this particular molecule, the extent of deformation is quite reduced. It deforms within a limited range, beyond which the crystal breaks into pieces.

And the careful analysis of the crystal structures reveals the following. So, here you can see that in the chloroisomer, the chlorine atoms are close to each other. In this case, we can see that these are again the chlorine atoms that are close to each other.

We also have these layers, which are held by these C-H...O hydrogen bonds. So, they form a nice arrangement of molecules along the a-axis. But what is interesting is that now, when you apply the stress on the 001 phase, the 001 phase is when you apply it; then you will see that there is a sliding of these molecular layers in this particular direction.

And this is referred to as the slip plane along which molecular migration takes place. So, when you apply stress to this particular phase, which is the 001 phase, you will see that molecular migration takes place, and the molecules can move in a facile way.

So, because there exist very weak halogen-bonded contacts here, this facilitates migration or the movement of the layers in an irreversible way, leading to plastic deformation. The separation is actually longer compared to the case of bromo or chloro compounds. So, here you see, these are the two chlorine atoms, and on this side, you have got the two bromine atoms.

The separation is around 2.1 angstroms here. It is around 2 angstroms, and when we go to the corresponding dibromo case, again we can see the separation here is similar to what it was in the previous case. Here it is around 2 angstroms, and this is interesting irrespective of whether you have fluorine.

The separation between the layers is similar; thus, these again facilitate the migration of molecules over long distances, leading to plastic deformation. However, in the case of the

dichloro compound, as you can see here, the dichloro molecules and the dichloro atoms in this molecule are present between these two molecules in the gap that is created.

So, this does not really facilitate long-range migration because, after a certain displacement, these molecules tend to get locked.

These molecules tend to get locked, and because they tend to get locked, they do undergo some minimum amount of deformation, which is seen here; but beyond that, the crystals simply crack because of the brittle nature that sets in when you actually apply a greater amount of stress.

So, these features, which are the supramolecular chemistry of these compounds, and looking at the packing, the layers, and then the migration of the molecules in between the layers across the slip planes, allow us to rationalize the observed plastic response, which occurs upon the application of mechanical stimuli to these crystals.

So, with this, I think we have discussed many interesting cases of stimuli-responsive crystals. And now in the next lecture, we will go to more supramolecular entities, which react to the presence of light, and we will look at some processes related to supramolecular photochemistry and so on.

Thank you.