Thermal Physics
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Lecture-08
Topic-Experimental Determination of Mean Free Path

Hello and welcome back to another lecture of this NPTEL course on thermal physics. Now, in the last class we have discussed about actually we continued our discussion on mean free path and we have found out an expression for mean free path. By which mean free path lambda can be connected to measurable parameters like pressure and temperature of a system. Now in today's lecture, we will be discussing about the experimental determination of lambda. Then we will look into certain experimental data which is available for different systems, different gas systems. And finally, we will be discussing briefly about the vacuum, the different vacuum level which is achievable in the laboratory experiments, okay.

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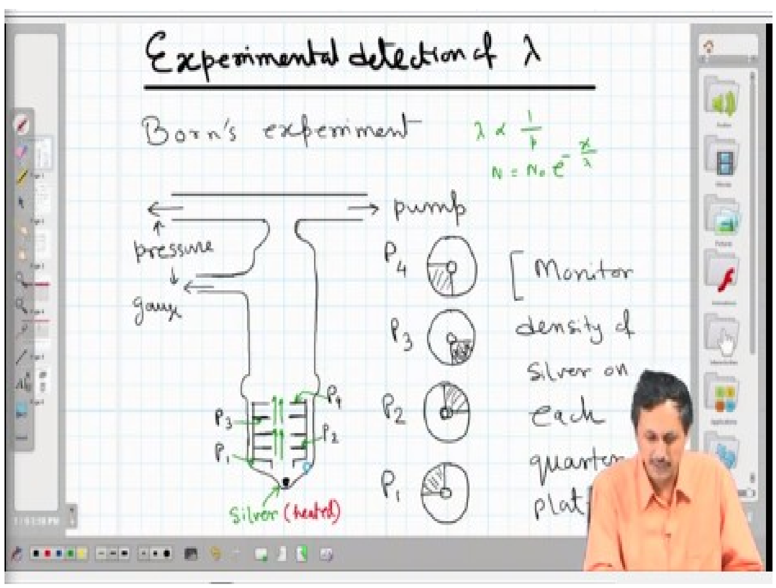

So, for the experimental data detection of lambda, the first experiment was by Born and that was back in 1933 or 36, I do not remember the exact date. So, this is the experimental arrangement, so what we have essentially is a vacuum chamber. In this everything is made of glass let us assume and inside this there are 4 slits P 1, P 2, P 3 and p 4. Now, all these plates, these are 4 plates actually, the separation between the first and the last plate that is between P 1 and P 4 is 1 centimeter, and yeah. And also these plates are quarter plate in nature, what do we mean by that?

That means, every plate if we look at the top view, every plate is essentially hollow ring except that one fourth, that means if we talk in terms of angles 90 degree of the plate is solid out of total 360 degree and rest 270 degree is hollow. Now depending on whether we are using, so basically these 4 plates are identical. And all of them has 1 identical hole in the through their center. So, these plates are identical in every respect, they have identical size, identical diameter, identical area of solid which are the shaded areas and they also have 4 identical holes through the middle.

Now for this experiment they are aligned such that the central portion remains. So, this central portion is the central hole is properly aligned. Now just below the central hole there is a small piece of silver marked by S. So, this silver is what we are going to detect, just write silver, so this is what we are going to detect. Now the rest of the tube is empty, on the top of this empty tube one end is connected to a vacuum pump which can be used to pump out reduce the pressure inside this system.

The other 2 there are 2 other openings both are connected to do 2 different types of pressure gauges in order to measure the pressure very accurately, now how does it work? The lower part actually what I have not seen here there are 2 other arrangements one part is there has to be some kind of a heating element, heating arrangement here, so that way the silver can be heated up. And secondly, there will be a cooling arrangement in this part as in the temperature of all these plates will be intact, will be unchanged throughout the measurement.

Now whenever the silver is being heated because there is very high vacuum inside this tube, the vacuum is maintained at a kind of high level. What is high level of vacuum and what are the units of that we will come back to that towards the second half of this lecture. So, what we have here is silver and the as the temperature of the silver increases heating takes place the silver molecules start to evaporate. So, basically we have heated silver at the bottom and as the evaporated silver goes up, it goes through these 4 holes the 4 aligned holes.

Now these holes are aligned, so that silver can essentially pass through and it will on the process as the silver molecules go up through this hole, right. They will put coating on these plates, this is a standard technique for vacuum deposition and nowadays in our labs we routinely use such technique to create electrodes. So, basically we have a vacuum one part we have a heated filament in which we have either silver or gold or aluminum, even copper or tungsten and then the rest of the chamber is evacuated.

So, when we start hitting this element the what you call, the metal molecules go up and they put coating on whatever they can find. So, of course they will put coating on the silver plates, no surprise here they will put some coating on the silver plates. Now as they go up and as they coating on the silver plates I should probably use another colour for this, right. As this one depending on which what is the height of the plate from this silver source, the density of silver coating will be changing.

Because close to the surface of the silver itself the coating will be thick, if we go far the coating will be thin. So, end to end the separation is 1 centimeter, so whatever is happening; whatever variation is happening is happening inside 1 centimeter of length. Now, so basically in this experiment what was measured? It was the density of this silver coating was monitored, that was the measurement parameter.

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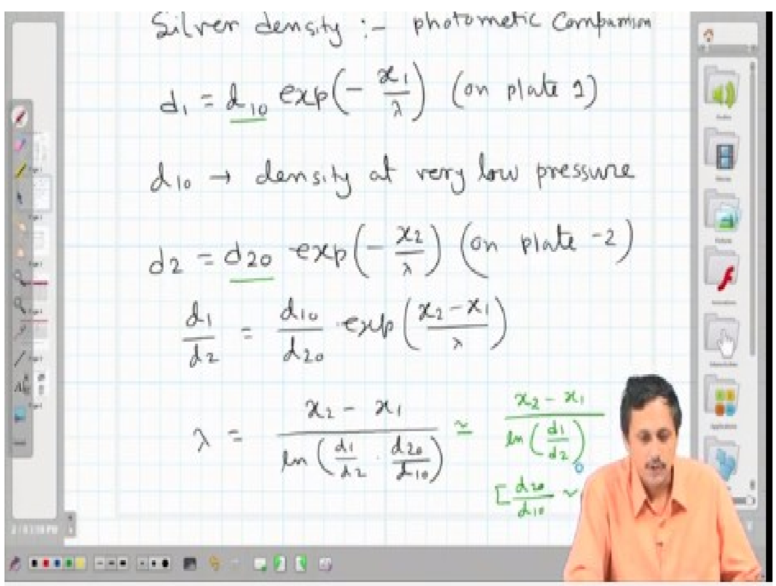

Now that was measured using some photometric compensation technology by which the density can be very accurately measured. Now let us assume the first plate or we just choose 2 random plates, it could be P 1 P 4, P 2 P 3, P 1 P 2 or P 2 P 4 whatever. We just take 2 random plates and call them 1 and 2 just randomly. So, at the beginning the entire arrangement is pumped at a very low vacuum. Once again what is very low vacuum and what is very high vacuum? What are the necessary numbers? We will discuss that in a moment.

So, let us assume at the beginning they have been pumped at very high vacuum that is the pressure becomes extremely low. Now as you remember that lambda is inversely proportional to 1 over p. So, when the pressure becomes very low lambda goes up really high. So, that is the mean free path, we will see that in a moment that mean free path can be as long as few meters or sometimes even kilometers.

So, the mean free path are without any loss the silver molecule that will start from here, the exact same silver molecule will end this portion or to the end of this tube without any loss of kinetic energy, let us assume without any collision that is to say. So, at very low pressure whatever deposition rate we get on this whole plate, we can call this as d 10 and d 20. Ideally d 10 and d 20 should be identical to each other ideally but there could be some variation.

Now the pressure is being increased not by much but to some extent now it is being increased. As the pressure increases, the mean free path decreases. So, according to the survival equation which is again N is equal to N 0 e to the power minus x by lambda, number of molecules which will suffer collision over or rather which will not suffer collision over a length of x is decreasing. As the pressure increases lambda decreases and this factor becomes more and more dominant.

So, rather this factor becomes progressively become smaller, so more and more molecules suffer collision. So, as a result the number of molecules that will reach the plate will definitely decrease. Now let us assume in a given pressure p the deposition the on the same 2 plates let it be plate 1 and plate 3 let us assume. On the same 2 plates the density which used to be d 10 and d 20 at very low pressure, now it becomes d 1 and d 2.

So, we can write d 1 is equal to d 10 exp to the power minus x 1 by lambda. Because density is nothing but which is density is directly proportional to the number of particles that is reaching that plate. So, it will be exactly following the survival equation. So, d 1 is equal to d 10 exponential to power 4 minus x 1 by lambda and similarly d 2 is equal to d 20 exponential minus x 2 by lambda. So, by dividing we can write d 1 by d 2 is equal to d 10 by d 20 exponential x 2 minus x 1 by lambda. So, just by simple manipulation we get lambda is equal to x 2 minus x 1 lon d 1 by d 2 d 20 by d 10.

Now as I already mentioned that d 10 and d 20 in an ideal condition or rather even in an experimental condition they are almost identical to each other. So, we can might as well write this and x 2 minus x 1 if we just look at the 2 extreme plates P 1. So**,** this is P 1, P 2, P 3 here and P 4 here. So, if I look at the P 1 and P 4 then the separation is 1 centimeter but anyway let us not worry about that. So, for all practical purposes we can write this as x 2 minus x 1 divided by lon d 1 by d 2. So, because assuming that d 20 by d 10 is approximately equal to 1. So, this is the working formula we have in hand.

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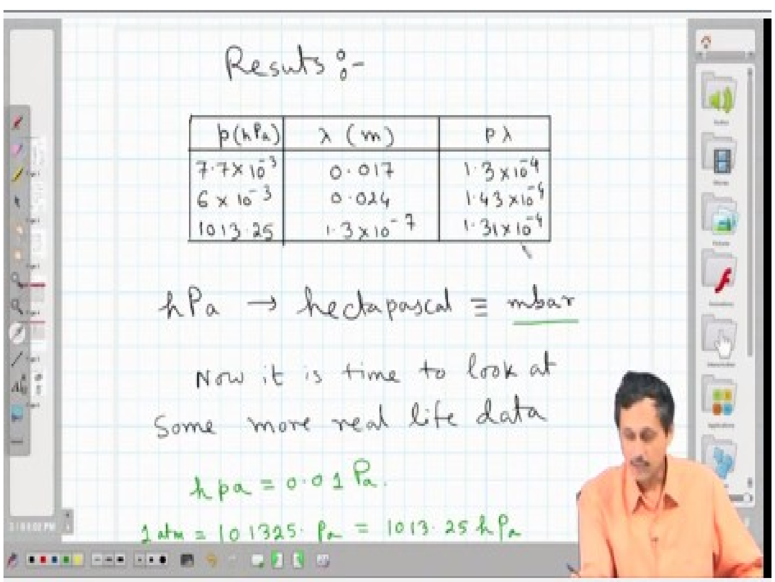

And by using this relation Born determined the following parameters. So, pressure is given some units called hectopascal, what is an hectopascal? Hectopascal is nothing but millibar and which is 0.01 Pascal's, this unit millibar is the most widely used unit of low pressure at the laboratory level. So, please remember this unit, this is nothing but hectopascal, hectopascal is hPa is equal to 0.01 Pascal.

Now what is atmospheric pressure? Once again atmospheric pressure if you remember is 1 atmosphere is equal to 101325 point something I do not remember roughly this much Pascal, so it will be 1013.25 hectopascal. So, this hectopascal in this unit at 7.7 into 10 to the power minus 3 millibar or 3 hectopascal pressure, the mean free path what was 0.017 meters.

So, original results were I think in centimeters but I just converted everything in meters. And then also it is important to note that the product P into lambda, P into lambda is 1.3 into 10 to power minus 4 the unit will be hPa meter. Similarly at 6 into 10 to the power minus 3 hectopascal pressure, the value of lambda is 0.024 and the product is 1.43 into 10 to the power -4 which is kind of similar to the previous number.

And that atmospheric pressure which is 1013.25 hectopascal, the mean free path reduces to 1.3 to 10 to the power minus 7 meters and but the product still remains almost constant as 1.3 into 10 to the power minus 4 meters. There are 2 very important aspects to this result, first one is that this one the mean free path at low pressure is of the order of 1 centimeter this is basically 1.7 centimeters and 2.4 centimeters which becomes very, very, very small at high pressure. And the second is the product p lambda remains almost constant.

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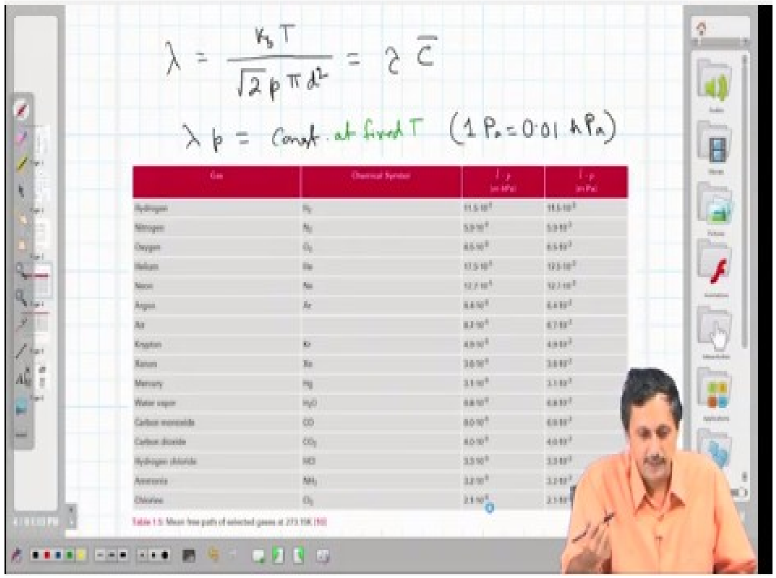

Now let us look at and this is expected because if you look at this relation, then you see lambda p is equal to constant at fixed temperature. If the temperature is fixed then the product lambda p should be constant because every other thing except temperature is a constant quantity. Now these are some data, these are measured at atmospheric pressure, unfortunately I cannot find these values of I mean we can always convert anyway.

So, I cannot find the values in pure length unit but it is given us l into p units. And you see for hydrogen and nitrogen and oxygen, helium, neon all even water vapour everything is given in this particular unit. So, these are some real time data also how this mean free path changes with pressure in order to get an idea?

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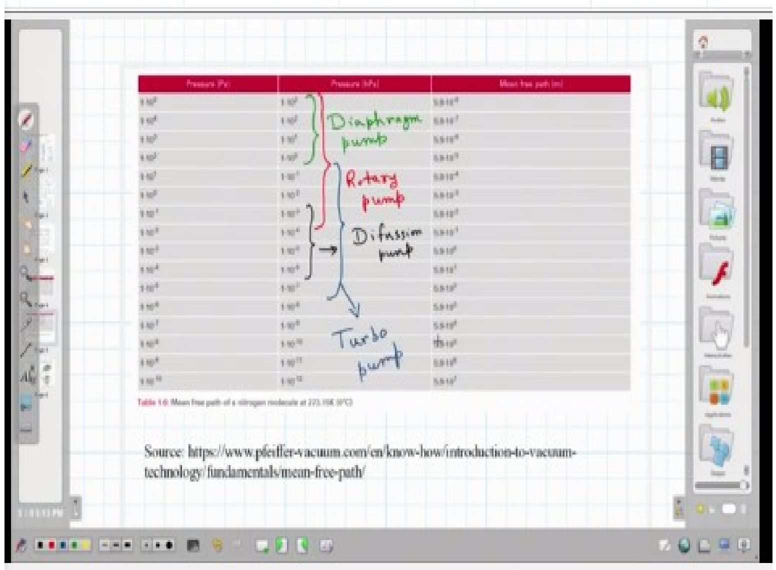

I have included another data set in here which is for nitrogen at 0 degrees centigrades. The previous dataset was also at 0 degrees centigrades and this is also at 0 degrees centigrades but here the mean free path is reported as a function of pressure. So, pressure is given either in Pascals in the first column or in hectopascals in the second column and you see there is a factor of 2 between them. So, the one is 1 into 10 to the power 5 is 1 into 10 to the power 3 actually hectopascal will be 0.01 Pascal, yes that is right.

So, note the other way around actually say if 0.01 Pascal, sorry I think it should be 0.01 Pascal. So, it will be a factor of 0.01, if I multiply this with 010 this is ok fine, sorry. So, we see, we will focus on the second column versus the third column because the first column is given in Pascals and in laboratory level we always try to use hPa hector Pascal. So, it is 1 into 10 to the power 3, 10 to the power 3, 10 to the power 210, 1 10 power minus 1, minus 2, minus 3 like this. And you see the mean free path is actually increasing as the pressure going down. So, at 10 to the power 3 the mean free path is 5.9, so 6 into 10 to the power minus 8 meters.

Whereas at 10 to the power minus 3 the mean free path is 5.9 into 10 to the power minus 2 meters. And that itself tells you that there is a change in factor of 6 here, there is a change in factor of 6 here, that the product lambda times p is essentially constant. So, it is the real time data on nitrogen at 0 degrees centigrades up to very, very, very low pressure. And the source I have also mentioned the source you can always go and look at the dataset and they also have supplementary dataset for different types of experiments, you can have a look.

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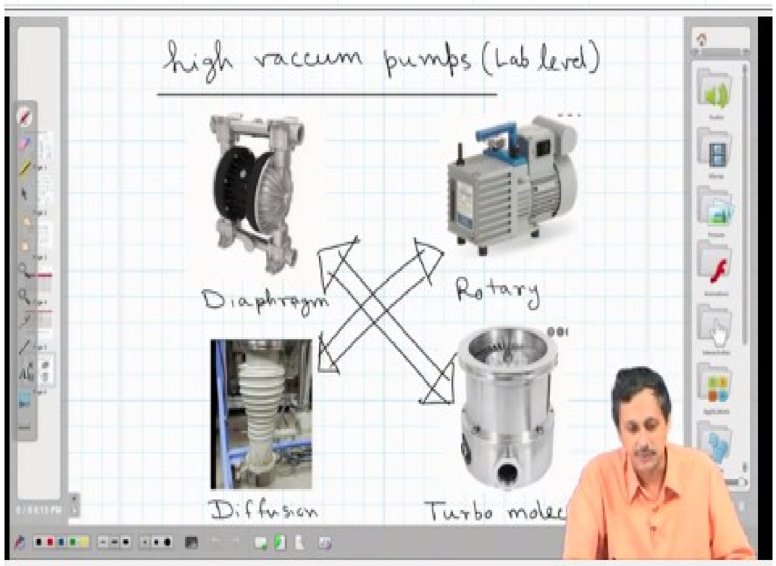

Now for the last part we already have talked about low pressure and as I have said that low pressure is essential for increasing the mean free path in the gas assembly. It has many applications, for example in vacuum deposition system we always use low pressure in order to increase the mean free path. So, that we have a even dispersion of molecules on a given surface. Ultra high vacuum systems like molecular beam epitaxy also explored the same fact.

So, that the epitaxial growth layer by layer molecular growth is possible up to 1 or few mono layers is possible on selected substrate. And at the end of this lecture let me give you a brief overview on how to get to this the pressure for example. So, in this table we have listed different range I mean different ranges of pressure. So, let me tell you there are different pumps which can take you to different ranges of pressure.

First of all there is the diaphragm pump, now up to which diaphragm pump is basically a dry pump, I am not going to discuss the detail mechanism of each and every pump, I will just give you the name. But let me tell you very briefly the diaphragm pump is a dry pump for which there is no lubricating oil is used and it will just suck in the air and it will create a mild vacuum. What do I mean by mild vacuum? By mild vacuum I mean maybe up to this level or slightly less maybe but typically this is the range of a diaphragm pump.

Now for the rotary pump it actually is a bigger pump, diaphragm pumps typically small could be like this small could be slightly bigger but not more than that. There is something called a rotary pump which is a lot bigger, bigger than a diaphragm pump definitely a lot heavier, makes a lot of noise. It has oil in it, there are advantages of having oil and disadvantages also we will come to that but it can take you to slightly higher vacuum.

What do we mean by slightly higher vacuum? Slightly higher vacuum I mean this one, this range, so it can start from atmospheric pressure and it can take you to 10 to the power minus 3 or maybe 10 to the power minus 4. This is the domain of rotary pump, right. Next up is a diffusion pump, diffusion pump once again is a oil based pump, working principle it will actually dissolve the gas molecules in oil and bring it down.

So, basically there is a jet of oil that goes up inside the vacuum chamber and then it dissolves the remaining gas molecules and bring it down in a dissolved manner and then it is sucked out by the rotary pump. Now the diffusion pump cannot work alone, it needs the support of a rotary pump, it can only start pumping when the pressure goes below let us say 10 to the power minus 3 millibar. So, that means the operating range starts from here operating ranges rather narrow but it starts from here and it can go to 10 to the power minus 6, this is the range of diffusion pump.

And please remember the diffusion pump and rotary pump they are what? They are always cobbled together, a diffusion pump need to have a rotary pump as it is back. So, we typically we call this the backing pump and then this is called the high vacuum pump in a system, so rotary and diffusion that make a good pair. Similarly, there is a turbo molecular pump which actually has a simplest possible principal, it has fans inside you can see some of the fan blades are visible over here.

So, it has fans inside arrangement of blades, they rotate at a very high speed, typical rpm is typical speed is 1500 rpm for the smaller ones and sometimes 30,000, 35,000 rpm for the big ones. They rotate at very high speed and they just simply suck out any molecule that they can any gas molecule they can basically they just suck out simply by moving the fans. Now these ones they are little more powerful than the diffusion pump and also one advantage is they are dry pump, there is no oil. Now what happens is if you have oil in the system, for example diffusion pump works with oil, rotary pump works with oil.

If you have oil in the system, they have a chance to contaminate the chamber they are pumping. Of course not that huge load of oil goes in into the vacuum chamber not like that. But typically there are tiny bits sometimes not even visible by your naked eye but they are sufficient to contaminate a sophisticated surface. So, let us say you have plasma clean the surface and you want to deposit an electrode on that for some measurement under vacuum, few molecules of oil is sufficient to contaminate the surface.

So, that is why although diffusion and rotary they are actually altogether the cost less, they are big assembly but the cost less, they are a bit noisy but they work in a very efficient manner. They sometimes are avoided and they are replaced by a combination of a diaphragm and a turbo which is a lot expensive combination. So, diaphragm starts the pumping initially because once again turbo molecular pump they are sophisticated pump.

If they work under very high pressure the blades might get damaged, so it needs to have a low pressure at least down to 10 to the power minus 1 or of the order of 10 millibar by help of diaphragm pump and then the turbo molecular pump can take over and it has an active range of all the way up to 10 to the power 7, so, this is the range of turbo pump. So, these are the 4 different pumps and as I have already mentioned many times that rotary and diffusion they work as a couple, diaphragm and turbo they work in a coupled manner.

For example, if I want to couple a turbo and a rotary, I have a good chance of damaging the turbo pump by oil contamination, right, so we do not do that. We always couple a dry pump with a dry pump and a wet pump with a wet pump. So, this is how these vacuum systems work and please remember we are talking about lab level detection, lab level pumping only. Because at industrial level the pumping volume becomes huge, the technology is totally different.

We are talking about lab level where the highest volume we evacuate is probably a chamber of the order of few cubic meters sometimes maybe 10 cubic meters or so. But that is also very high, we generally do not do that or most of the time we use those to pump the cryostats the vacuum jacket of a cryostat or sometimes we use diaphragm pump to maintain our samples in vacuum. So, these are kind of daily usage pump in a normal research lab. Also in some teaching labs the rotary and diaphragm pumps are in use.

So, probably if you are lucky enough then you will come across one of these pumps and you will know why, what are the usefulness? From this lecture you will have an idea of what are the usefulness of these pumps and what are the typical working range for this pumps, vacuum range for this. So, that is where we will stop today and in the next lecture we will start solving some problems. And also we will start discussing the fundamentals of transport phenomena, thank you.