PROFESSOR: So last time we started talking about superfluid helium. And we said that the phase diagram of helium-4, the isotope that is a boson has the following interesting properties. First of all, helium stays a liquid all the way down to 0 temperature because of the combinations of its light mass and heat interactions.

And secondly, that [INAUDIBLE] to cool down helium through this process of evaporated cooling, one immediately observes something interesting happening at temperatures below 2 degrees Kelvin, where it becomes this superfluid that has a number of interesting properties. And in particular as pertaining to viscosity, we made two observations. First of all, you can make these capillaries-- and I'll show you been movie in more detail later on where it flows through capillaries as if there is no resistance and there is nothing that sticks to the walls of the capillaries. It flows without viscosity, whereas there was this experiment of Andronikashvili, in which you had something that was oscillating and you were calculating how much of the helium was stuck to the plates of the container.

And the result was something like this, that is there was a decrease in the amount of fluid that is stuck to the plates. But it doesn't go immediately down to 0. It has a kind of form such as this that I will draw more clearly now and explain. So what we did last time was to note that people observed that there were some similarities between this superfluid transition and Bose-Einstein condensation.

But what I would like to highlight in the beginning of this lecture is that there are also very important differences. So let's think about these distinctions between Bose-Einstein condensate add the superfluid helium. One set of things we would like to take from the picture that I have over there, which is diffraction of the fluid that is stuck to the plates and in some sense behaves like a normal fluid.

Now let me make the analogy to Bose-Einstein condensation. You know that in the Bose-Einstein condensation there was also this phenomenon that there was a separation into two parts of the total density. And be regarded as a function of temperature some part of the density as belonging to the normal state. So when you are above Tc of n, everything is essentially normal.

And then what happens is that when you hit Tc of n you can no longer put all of the particles that you have in the excited states. So the fraction that goes in the excited states goes down and eventually goes to 0 at 0 temperature. And essentially, this would be the reverse of the curve that we have in that figure over there. Basically, there's a portion that would be the normal part that would be looking like this.

Now, the way that we obtained this result was that basically there was a fraction that was in the normal state. The part that was excited was described by this simple formula that was g over lambda cubed [INAUDIBLE] of 3/2. So it went to 0 as T to the 3/2.

So basically, the proportionality here is T to the 3/2. And then basically, the curve would come down here and go to 0 linearly. Now what is shown in the experiment is that the curve actually goes to 0 in a much more sharp fashion. And actually, when people try to fit a curve through this, the curve looks something like Tc minus T to the 2/3 over.

But also it goes to 0 much more rapidly than the curve that we have for Bose-Einstein condensation. Indeed, it goes through 0 proportionately to T to the fourth. And so that's something that we need to understand and explain.

Now all of the properties of the Bose-Einstein condensate was very easy to describe once we realized that all of the things that correspond to excitation, such as the energy, heat capacity, pressure, come from this fraction that is in the excited state. And we can calculate, say, the contribution to energy heat capacity, et cetera. And in particular, if we look at the behavior of the heat capacity as a function of temperature, for this Bose-Einstein condensate, the behavior that we had was that again simply at low temperatures it was going proportionately to T to the 3/2, because this was the number of excitations that you had. So these two T to the 3/2 are very much related to each other.

And then this curve would basically go along its way until it hit Tc of n at some point. And we separately calculated the behavior coming from high temperatures. And the behavior from high temperatures would start with the classical result that the heat capacity is 3/2 per particle due to the kinetic energy that you can put in these things. And then it would rise, and it would then join this curve over here.

Now when you look at the actual heat capacity, indeed the shape up the heat capacity is the thing that gives this transition the name of a lambda transition. It kind of looks like a lambda. And at Tc there are divergences approaching from the two sides that behave like the log.

And again more importantly, what we find is that at 0 temperature, it doesn't go through 0, the heat capacity as T to the 3/2, but rather as T to the third power. So the red curve corresponds to superfluid, the green curve corresponds to Bose-Einstein condensate. And so they're clearly different from each other. So that's what we would like you to understand.

Well the thing that is easiest to understand and figure out is the difference between these heat capacities. And the reason for that is that we had already seen a form that was of the heat capacity that behaved like T cubed. That was when we were looking at phonons in a solid.

So let's remind you why was it that for the Bose-Einstein condensate we were getting this T to the 3/2 behavior? The reason for that was that the various excitations, I could plot as a function of k, or p, which is h bar k. They're very much related to each other.

And for the Bose-Einstein condensate, the form was simply a parabola, which is this p squared over 2 mass of the helium. Let's say, assuming that what we are dealing with is non-interacting particles with mass of helium. And this parabolic curve essentially told us that various quantities behave as T to the 3/2.

Roughly, the idea is that at some temperature that has energy of the order of kT, you figure out how far you have excited things. And since this form is a parabola, the typical p is going to scale like T to the 1/2. You have a volume in three dimensions in p space. If the radius goes like T to the 1/2, the volume goes like T to the 3/2. That's why you have all kinds of excitations such as this.

And the reason for the Bose-Einstein condensation was that you would start to fill out all of these excitations. And when you were adding all of the mean occupation numbers, the answer was not coming up all the way to the total number of particles. So then you have to put an excess at p close to 0, which corresponds to the ground state of this system.

Now of course when you look at helium, helium molecules, helium atoms have the interactions between them that we discussed. In particular, you can't really put them on top of each other. There is a hard exclusion when you bring things close to each other.

So the ground state of the system must look very different from the ground state of the Bose-Einstein condensate in which the particles freely occupy the entire box. So there is a very difficult story associated with figuring out what the ground state of this combination of interacting particles that make up liquid helium is. What is the behavior? What's the many-body wave function at 0 temperature?

Now as we see here, in order to understand the heat capacity we really don't need to know what is happening at the ground state. What we need to know in order to find heat capacity is how to put more energy in the system above the ground state. So we need to know something about excitations.

And so that's the perspective that Landau took. Landau said, well, this is the spectrum of excitations if you had [? plain ?] particles without any interactions. Let's imagine what happens if we gradually tune in the interactions, the particles start to repel each other, et cetera. This non-interacting ground state that we had in which the particles were uniformly distributed across the system will evolve into some complicated ground state I don't know.

And then, presumably there would be a spectrum of excitations around that ground state. Now the excitations around the non-interacting ground state we can label by this momentum peak. And it kind of makes sense that we should be able to have a singular label for excitations around the ground state of these interacting particles.

And this is where you sort of needed a little bit of Landau's type of insight. He said, well, presumably what you do when you have excitations of momentum p is to distort the wave function in a manner that is consistent with having these kind of excitations of momentum p. And he said, well we typically know that if you have a fluid or a solid and we want to impart some momentum above the ground state, if will go in the form of phonons. These are distortions in which the density will vary in some sinusoidal or cosine way across the system.

So he said that maybe what is happening is that for these excitations you have to take what ever this interacting ground state is-- which we don't know and can't write that down-- but hope that excitations around it correspond to these distortions in density. And that by analogy with what happens for fluids, that the spectrum of excitations will then become a linear. You would have something like a sound wave that you would have in a liquid or a solid.

So if you do this, if you have a linear spectrum then we can see what happen. For a particular energy of the order of kT, we will go here, occupied momenta that would be of the order of kT over H bar. The number of excitations would be something like this cubed, and so you would imagine that you would get a heat capacity that is proportional to this times kB. And if you do things correctly, like really for the case of phonons or photons, you can even figure out what the numerical prefactor is here. And there's a velocity here because this curve goes like H bar vP.

So then you can compare what you have over here with the coefficient of the T cubed over here, and you could even figure out what this velocity is. And it turns out to be of the order of 240 meters per second. A typical sound wave that you would have in a fluid. So that's kind of a reasonable thing.

Now of course, when you go to higher and higher momenta, it corresponds to essentially shorter and shorter wavelengths. You expect that when you get wavelengths that is of the order of the interatomic spacing, then the interactions become less and less important. You have particles rattling in a cage that is set up by everybody else. And then you should regain this kind of spectrum at high values of momentum.

And so what Landau did was he basically joined these things together and posed that there is a spectrum such as this that has what is called a phonon part, which is this linear part where energy goes like H bar, like the velocity times the momentum. And it has a part that in the vicinity of this point, you can expand parabolically. And it's called rotons. There is a gap delta, and then H bar squared over 2, some effective mass, k minus k0 squared.

This k0 turns out to be roughly of the order of the inverse [INAUDIBLE], two Angstrom inverse, between particles. This mu is of the order of mass of [INAUDIBLE]. So about 10 years or so after Landau, people are able to get to this whole spectrum of excitation through neutron scattering and other scattering types of experiments. And so this picture was confirmed. So, yes?

AUDIENCE: What is a roton? [INAUDIBLE]

PROFESSOR: Over here what you are seeing is essentially particles rattling in the cage. It is believed that what is happening here are collections of three or four atoms that are kind of rotating in a bigger cage. So something, the picture that people draw is three or four particles rotating around. Yes?

AUDIENCE: Is there some [INAUDIBLE] curve where energy's decreasing [INAUDIBLE]? Does the transition between photon and roton [INAUDIBLE]?

PROFESSOR: There is no thermodynamic or other rule that says that the energy should be one of [INAUDIBLE] momentum that I know. Yes?

AUDIENCE: Is there an expression for that k0 in terms of temperature and other properties of the system?

PROFESSOR: This curve of excitations is supposed to be property of the ground state. That is, you take this system in its ground state, and then you create an excitation that has some particular momentum and calculate what the energy of that is. Actually, this whole curve is phenomenological, because in order to get the excitations you better have an expression for what the ground state is.

And so writing a kind of wave function that describes the ground state of this interacting system is a very difficult task. I think Feynman has some variational type of wave function that we can start and work with, and then calculate things approximately in terms of that. Yes?

AUDIENCE: What inspired Landau to propose that there was a [INAUDIBLE]?

PROFESSOR: Actually, it was not so much I think looking at this curve, but which I think if you want to match that and that, you have to have something like this. But this was really that the whole experimental version of the heat capacity, it didn't seem like this expression was sufficient. And then there was some amount of excitation and energy at the temperatures that were experimentally accessible that heated at the presence of the rotons in the spectrum. Yes?

AUDIENCE: So continuing [INAUDIBLE], if you raise the thermal energy kBT, [INAUDIBLE] level where you have multiple roots of this curve.

PROFESSOR: Yes.

AUDIENCE: So you will be able to excite some states and have some kind of gap, like a gap of momenta which are not.

PROFESSOR: OK, so at any finite temperatures-- and I'll do the calculation for you shortly-- there is a finite probability for exciting all of these states. What you are saying is that when there is more occupation at this momentum compared to that, but much less compared to this. So that again does not violate any condition.

So it is like, again, trying to shake this system of particles. Let's imagine that you have grains, and you are trying to shake them. And it may be that at some shaking frequencies, then there are things that are taking place at short distances in addition to some waves that you're generating. Yeah?

AUDIENCE: I have a question about the methodology of getting this spectrum, because if we have a experimental result of the [INAUDIBLE] capacity, then if we assume there's a spectrum, there has to be this one, because it gives a one to one correspondence. So we can get the spectrum directly from the c. So--

PROFESSOR: I'm not sure, because in reality this is going to be spectrum in three-dimensional space. And there is certainly an expression that relates the heat capacity to the excitation spectrum. What I'm not sure is whether mathematically that expression uniquely invertible. It is given an epsilon-- c, you have a unique epsilon of p. Certainly, given an epsilon of p, you have a unique c. Yes?

AUDIENCE: But if the excitation spectrum only depends on, let's say, k squared, not on the three-dimensional components of k, then maybe it's much easier to draw a one to one correspondence?

PROFESSOR: I don't know, because you have a function of temperature and you want to convert it to a function of momentum that after some integrations will give you that function of temperature. I don't know the difficulty of mathematically doing that. I know that I can't off my head think of an inversion formula. It's not like the function that you're inversing.

So the Landau spectrum can explain this part. It turns out that the Landau spectrum cannot explain this logarithmic divergence. Yes?

AUDIENCE: Sorry, one more question about this. The allowed values of k, do they get modified, or are they thought to be the same?

PROFESSOR: No. So basically at some point, I have to change perspective from a sum over k to an integral over k or an integral over p. The density of states in momentum is something that is kind of invariant. It is a very slight function of shape. So the periodic boundary conditions and the open boundary conditions, et cetera, give you something slightly different over here. But by the time you go to the continuum, it's a property of dimension only. It doesn't really depend on the underlying shape.

AUDIENCE: So we still change sums for integrals with the same rules?

PROFESSOR: Yes. It's a sort of general density of state property. So there's some nice formula that tells you what the density of state is for an arbitrary shape, and the leading term is always proportional to volume or area [INAUDIBLE] the density of state that you have been calculating. And then there are some leading terms that are proportional to if it is volume to area, or number of edges, et cetera. But those are kind of subleading the thermodynamic sense.

So I guess Feynman did a lot of work on formalizing these ideas of Landau getting some idea of what the ground state does, is, and excitations that you can have about the spectrum. And so he was very happy at being able to explain this, including the nature of rotons, et cetera. And he was worried that somehow he couldn't get this logarithmic divergence.

And that bothered him a little bit, but Onsager told him that that's really a much more fundamental property that depends on critical phenomena, and for resolving that issue, you have to come to 8.334. So we will not discuss that, nor will we discuss why this is Tc minus T to the 2/3 power and not a linear dependence. It again is one of these critical properties.

But we should be able to explain this T to the fourth. And clearly, this T to the fourth is not as simple as saying this exponent changed from 3/2 to 3, this 3/2 should also change the 3. No, it went to T to the fourth, so what's going on over here?

So last time at the end of the lecture I wrote a statement that the BEC is not superfluid. And what that really means is that it has too many excitations, low energy excitations. So imagine the following, that maybe we have a container-- I don't know, maybe we have a tube-- and we have our superfluid going through this with velocity v sub s. We want it to maintain that velocity without experiencing friction, which it seems to do in going through these capillaries. You don't have to push it, it seems to be going by itself.

And so the question is, can any of these pictures that we drew for excitations be consistent with this? Now, why am I talking about excitations and consistency with superfluid? Because what can happen in principle is that within your system, you can spontaneously generate some excitation. This excitation will have some momentum p and some energy epsilon of p.

And if you spontaneously can create these excitations that would take away energy from this kinetic energy of the flowing superfluid, gradually the superfluid will slow down. Its energy will be dissipated and the superfluid itself will heat up because you generated these excitations with it. So let's see what happens. If I were to create such an excitation, actually I have to worry about momentum conservation because I created something that carried momentum p.

Now initially, let's say that this whole entity, all of the fluid that are superflowing with velocity Vs have mass M. So the initial momentum would be MVs. Now, I created some excitation that is carrying away some momentum p.

So the only thing that can ensure this happens is that I have to slightly change the velocity of the fluid. Now this change in velocity is infinitesimal. It is Vs minus p divided by M. M is huge, so why bother thinking about this?

Well, let's see what the change in energy is. Delta E. Let's say, well, you created this excitation so you have energy epsilon of p. But I say, in addition to that there is a change in the kinetic energy of the superfluid. I'm now moving at Vs prime squared, whereas initially when this excitation was not present, I was moving at Vs.

And so what do you have here? We have epsilon of p, M over 2 Vs minus p over M, this infinitesimal change in velocity squared minus M over 2 Vs squared. We can see that the leading order of the kinetic energy goes away, but that there is a cross term here in which the M contribution-- the contribution of the mass-- goes away.

And so the change in energy is actually something like this. So if I had a system that when stationary, the energy to create an excitation of momentum p was epsilon of p, when I put that in a frame that is moving with some velocity Vs, you have the ability to borrow some of that kinetic energy and the excitation energy goes down by this amount.

So what happens if I take the Bose-Einstein type of excitation spectrum that is p squared over 2M and then subtract a v dot p from it? Essentially there is a linear subtraction going on, and I would get a curve such as this. So I probably exaggerated this by a lot. I shouldn't have subtracted so much. Let me actually not subject so much, because we don't want to go all the way in that range.

But you can see that there is a range of momenta where you would spontaneously gain energy by creating excitations. If the spectrum was initially p squared over 2M, basically you just have too many low energy excitations. As soon as you start moving it, you will spontaneously excite these things. Even if you were initially at 0 temperature, these phonon excitations would be created spontaneously in your system.

They would move all over the place. They would heat up your system. There is no way that you can pass the Bose-Einstein condensate-- actually, there's no way that you can even move it without losing energy.

But you can see that this red curve does not have that difficulty. If I were to shift this curve by an amount that is linear, what do I get? I will get something like this.

So the Landau spectrum is perfectly fine as far as excitations is concerned. At zero temperature, even if the whole fluid is moving then it cannot spontaneously create excitations, because you would increase energy of the system. So there's this difference.

Ultimately, you would say that the first time you would get excitation is if you move it fast enough so that some portion of this curve goes to 0. And indeed, if you were to try to stir or move a superfluid fast enough, there's a velocity at which it breaks down, it stops being a superfluid. But it turns out that that velocity is much, much smaller than you would predict based on this roton spectrum going down. There are some other many body excitations that come before and cause the superfluid to lose energy and break down. But the genetic idea as to why a linear spectrum for k close to 0 is consist with superfluidity but the quadratic one is not remains correct.

Now suppose I am in this situation. I have a moving super fluid, such as the one that I have described over here. The spectrum is going to be somewhat like this, but I'm not at 0 temperature. I want to try to describe this T to the fourth behavior, so I want to be at some finite temperature.

So if I'm at some finite temperature, there is some probability to excite these different states, and the number that would correspond to some momentum p would be given by this general formula you have, 1 over Z inverse e to the beta epsilon of p minus 1. Furthermore, if I think that I am in the regime where the number of excitations is not important because of the same reason that I had for Bose-Einstein condensate, I would have this formula except that I would use epsilon of p that is appropriate to this system. Actually, what is it appropriate to this system is that my epsilon of p was velocity times p.

But then I started to move with this superfluid velocity. Actually, maybe I'll call this c so that I a distinction between c, which is the linear spectrum here, and the superfluid velocity dot p. No, this is actually a vectorial product. And because of that, I only drew one part of this curve that corresponds to positive momentum. If I had gone to negative momentum, actually, this curve would have continued and whereas one branch the energy is reduced, if I go to minus p, the energy goes up.

So whereas if the superfluid was not moving, I can generate as many excitations with momentum p as momentum minus p. Once the superfluid is moving, there is a difference. One of them has a v dot p. The other has minus v dot p.

So because of that, there is a net momentum that is carried by these excitations. This net momentum is obtained by summing over all of these things, multiplying with appropriate momentum. So I have beta is CP minus v dot p minus 1. This is the momentum of the excitation. This is the net momentum of the system for one excitation.

But then I have to sum over all possible P's. Sum over P's, as we've discussed, I can replace with an integral. And sum over k be replaced with V. Integral over K, K and P are simply related by a factor of h bar. So whereas before for k I had 2 pi cubed for v cubed, I have 2 pi h bar cubed. So this is what I have to calculate.

Now what happens for small v? I can make an expansion in vs. The 0 order term in the expansion is what we would have for non-moving fluid. Momenta in the two directions are the same, so that contribution goes away. The first contribution that I'm going to get is going to come from expanding this to lowest order in P.

So there is a P that is sitting out front. When I make the expansion, I will get a vs dot P times the derivative of the exponential function gives me a factor of beta e to the beta CP. And down here I will have e to the beta CP minus 1 squared.

Now, in the problem set you have to actually evaluate this integral. It's not that difficult. It's related to Zeta functions. But what I'm really only interested in what is the temperature dependence?

You can see that I can rescale this combination, call it x. Essentially what it says is that whenever I see a factor of p, replace it by Kt over Cx. And how many P's do I have? I have three, four, five.

So I have five factors of P. So I will have five factors of Kt. One of them gets killed by the beta, so this whole thing is proportional to T to the fourth power.

So what have we found? We have found that as this fluid is moving at some finite temperature T, it will generate these excitations. And these excitations are preferably along the direction of the momentum.

And they correspond to an additional momentum of the fluid that is proportional to the volume. It's proportional to temperature to the fourth and something. And of course, proportional to the velocity.

Now, we are used to thinking of the proportionality of momentum and velocity to be some kind of a mass. If I divide that mass by the volume, I have a density of these excitations. And what we have established is that the density of those excitations is proportional to t to the fourth.

And what is happening in this Andronikashvili experiment is that as these plates are moving, by this mechanism the superfluid that is in contact with them will create excitations. And the momentum of those excitations would correspond to some kind of a density that vanishes as T to the fourth, again in agreement with what we've seen here. OK? Yes?

AUDIENCE: So in an integral expression you have vs as part of a dot product.

PROFESSOR: Yes.

AUDIENCE: And then in the next line [INAUDIBLE]. So it's in that direction.

PROFESSOR: So let's give these indices p in direction alpha. This is p in direction alpha. This is p in direction alpha. This is v in direction beta, p in direction beta, sum over beta.

Now, I have to do an angular integration that is spherically symmetric. And then somewhere inside there it has a p alpha p beta. That angular integration will give me a p squared over three delta alpha beta, which then converts this v beta to a b alpha, which is in the direction of the momentum. Yes?

AUDIENCE: Will you say once again what happened to the integral dimension?

PROFESSOR: OK. So when we are in the Bose-Einstein condensate, as far as the excitations of concerned we have zero chemical potential. Whatever number of particle that we have in excess of what can be accommodated through the excitations we put together in the ground state. So if you like the ground state, the kp equals to 0 or k equals to 0, is a reservoir. You can add as many particles there or bring as many particles out of it as you like. So effectively, you have no conservation number and no need for a [? z. ?]

Of course, that we only know for the case of the true Bose-Einstein condensate. We are kind of jumping and giving that concept relevance for the interacting superfluid. OK? Any other questions?

So this is actually the last item I wanted to cover for going on the board. The rest of the hour, we have this movie that I had promised you. I will let that movie run.

I also have all the connection of problem sets, and exams, and test that you have not picked up. So while the movie runs, you are welcome to sit and enjoy it. It's very nice. Or you can go and take your stuff and go your own way or do whatever you like. So let's go back.

[VIDEO PLAYBACK]

PROFESSOR: There will be more action.

-We just made a transfer from liquid helium out of the storage tank into our own experimental equipment. It is a remarkable [INAUDIBLE]. It has two different and easily distinguishable liquid phases-- a warmer and a colder one. The warmer phase is called liquid helium I and the colder phase liquid helium II. The two stages are separated by a transition temperature, known as the lambda point.

When liquid helium is pulled down through the lambda point, a transition from helium I to helium II is clearly visible. We will show it to you later in this film. The two liquids behave nothing like any other known liquid, although it could be said that helium I, the warmer phase, approximates the behavior of common liquids.

But it is helium II, the colder phase, which is truly different. Because of this, it is called a superfluid. The temperatures involved when working with liquid helium are quite low.

Helium boils at 4.2 degrees Kelvin under conditions of atmospheric pressure. And the lambda point lies at roughly 2.2 degrees. Note that this corresponds to minus

269 and minus 271 degrees centigrade.

The properties of liquid helium that I have just been telling you about are characteristic of the heavy isotope if helium, helium-4. The element occurs in the form of two stable isotopes. [INAUDIBLE] The second and lighter one, helium-3, is very rare. Its abundance is only about 1 part of 10 million. Pure liquid helium-3 is the subject of intensive study at the present time, but so far no second superfluid liquid phase has been found to exist for helium-3.

The low temperature at which we'll be working calls for well-insulated containers. The dewar meets our requirements. The word "dewar" is a scientific name given to a double-walled vessel with the space between the walls evacuated. When these dewars are made of glass, the surface of this inner space is usually filtered to cut down heat transfer by radiation. However, our dewars will have to be transparent so that we can look at what's going on inside.

Now, liquid helium is commonly stored in double dewars. The design is quite simple, just put one inside the other like this. In the inner dewar, we put the liquid helium, and in the space between the inner and outer dewar, we maintain a supply of liquid air.

Here is a double dewar exactly like the one we will be using in our demonstration experiment. The inner dewar is filled with liquid helium. The outer dewar contains liquid air.

The normal boiling temperature of liquid air is about 80 degrees Kelvin, 75 or more degrees hotter than liquid helium. The purpose of the liquid air is twofold. First, we put the liquid air in the outer dewar well ahead of putting liquid helium in the inner dewar. In this way, the inner dewar is pre-cooled.

Secondly, we maintain a supply of liquid air in the outer dewar because it provides an additional [INAUDIBLE] of insulation now that the liquid helium is in the inner dewar. The [INAUDIBLE] liquid air attests to the fact that it is absorbing some of the heat which enters the double dewar. Even with the boiling of the liquid air, the liquid helium is clearly visible. Later, we will use liquid air cooled below its boiling temperature to reduce or eliminate the air bubbles for better visibility. Now the liquid air is cooled down and we have eliminated boiling.

The smaller bubbles of the boiling liquid helium are clearly visible. The cover over the inner dewar has a port, at present open. The liquid helium is at atmospheric pressure, so its temperature is 4.2 degrees Kelvin.

In other words, what we have in here now is liquid helium one, the warmer of the two phases. Before we cool it down to take a look at the superfluid phase, I want to dwell greatly on the properties of helium I. I've told you before that even helium I is different from the normal liquids.

The distance between neighboring atoms and this liquid is quite large. The atoms are not as closely packed as in the classical liquids. The reason for this is quantum mechanics. The zero point energy is relatively more important here than in any other liquid.

As a consequence, liquid helium has a very low mass density, only about 13% the density of water, and a very low optical density. The index of refraction is quite close to 1. This makes its surface hard to see with the naked eye under ordinary lighting conditions.

You are no doubt familiar with the fact that the helium atom has closed shell atomic structure. This explains why helium is a chemically inert element. It also accounts for the fact that the force of attraction between neighboring helium atoms, the so-called van der Waals force, is small.

It takes little energy to pull two helium atoms apart, as for example in evaporation. This gives liquid helium a better small latent heat of vaporization. Only five calories are needed to evaporate one gram. Compare this with water, where evaporation requires between 500 and 600 calories per gram.

The low van der Waals force combined with a large zero point energy also accounts for the fact that liquid helium does not freeze, cannot be solidified at ordinary pressure, no matter how far we cool it. However, liquid helium has been solidified at high pressure. The liquid helium in the dewar is at 4,2 degrees. We now want to cool it down to the lambda point and show you the transition to the [INAUDIBLE]. Our method will be cooling by evaporation using a vacuum pump.

Now, the lambda point lies at 2.2 degrees, only 2 degrees colder than the [INAUDIBLE] temperature of the liquid. What's more, not very much heat has been removed from the liquid helium now in the dewar to bring it to the lambda point. It amounts to only about 250 calories. Nevertheless, don't get the idea that this cooling process is easy. On the contrary, it's quite difficult.

More than 1/3 of the liquid helium now in the dewar has to be knocked away in vapor form before we can get what remains behind to the lambda point. That requires an awful lot of pumping and explains why we use this large and powerful vacuum pump over here. Even with this pump, the cooling process takes a considerable amount of time.

Let me explain why it is so difficult to cool liquid helium to the lambda point. I have already mentioned that liquid helium has a remarkably small [INAUDIBLE] vaporization, only five calories per gram. At the same time, liquid helium at 4.2 degrees has a high specific heat, almost calorie per gram. Therefore, 1 gram of the vapor pumped away carries with it an amount of heat which can cool only 5 or 6 grams of liquid helium by 1 degree. That's not very much cooling. It is less by a factor of almost 100 than when we cool water by evaporation.

The situation gets even worse as cooling progresses below 4.2 degrees because the specific heat of liquid helium rises astonishingly. As we approach 2,17 degrees, the lambda point. The heat of vaporization, on the other hand, remains roughly the same. So a given amount of vapor carried off produces less and less cooling as we approach 2.17 degrees,

Our thermometer here is a low pressure gauge connected to the space above the liquid helium. The needle registers the pressure there. It is the saturated vapor pressure of liquid helium. The gauge is calibrated for the corresponding temperature. We call it a vapor pressure thermometer.

As we approach 2.17 degrees, boiling becomes increasingly violent. Suddenly it stops. This was the transition.

The liquid you now see is helium II. Even though evaporation does continue, there is no boiling. The normal liquids, such as the water in this basin, boil because of their relatively low heat conductivity. Before heat, [INAUDIBLE] at one point can be carried away to a cooler place in the liquid bubbles of the vapor form. Helium I behaves like a normal liquid in this respect.

The absence of boiling in helium II reveals that this phase acts as if it had a large heat conductivity. As a matter of fact, as the liquid helium passed through the lambda point transition you just saw, its heat conductivity increased by the fantastic factor of one million. The heat conductivity of helium II is many times greater than in the metals silver and copper, which are among the best solid heat conductors. And yet here we deal with a liquid.

For this alone, helium II deserves the name of superfluid. Actually, the way in which helium II transports such large quantities of heat so rapidly is totally different from the classical concept for heat conduction. I'll come back to the subject later in connection with an experiment demonstrating the phenomenon of second sound in helium II.

Remember that this great change in heat conductivity occurred at a single and fixed transition temperature, the lambda point. We do indeed deal with a change in phase, only here it is a change from one liquid to another liquid. As we told you before, the specific heat of liquid helium is very large as a lambda point. In fact, it behaves abnormally even below the lambda point and falls again very rapidly with the temperature. This discontinuity in specific heat is another reflection of the fact that we are dealing with a change in the phase of the substance.

By the way, the curve resembles the Greek letter lambda. The transition temperature got its name from the shape of this curve. [INAUDIBLE]

The next one has to do with the viscosity of liquid helium. When a normal liquid flows through a tube, it will resist the flow. In this experiment, we shall cause some glycerin to flow to a tube under its own weight. The top layer is colored glycerin.

The liquid layer closest to the tube wall adheres to it. The layer next in from the one touching the wall flows by it and is retarded as it flows due to the interatomic, the van der Waals force of attraction. The second layer in turn drags on the third, and so on inward from the wall, producing fluid friction, or viscosity.

The narrower the tube, the slower the liquid rate of flow through it under a given head of pressure. Here I have a beaker with an unglazed ceramic bottom of ultra-fine [INAUDIBLE]. Many capillary channels run through this ceramic disk. The diameter is quite small, about one micron which is 1/10,000 of a centimeter.

There is liquid helium in the beaker. It is 4.2 degrees Kelvin, helium I, the normal phase. The capillaries in the disk are fine enough to prevent the liquid now in the beaker from flowing through under its on weight.

Clearly, helium I is viscous. To be sure, its viscosity is very small. That's why we had to choose extremely fine capillaries to demonstrate it. Here you see the lambda point transition.

The helium II all poured out. The rate of pouring would not be noticeably slower if the [INAUDIBLE] were made yet finer. We call this kind of flow a superflow.

The temperature is now at 1.6 degrees. The superflow is even faster. The viscosity of helium II in this experiment is so small that it has not been possible to find a value for it. It is less than the experimental uncertainty incurred in attempts to measure it.

We now believe that helium II, the superfluid, has zero viscosity, although we should be more precise here. We believe its viscosity is zero when observing capillary flow. Bear this statement in mind, for we will come up with a contradiction to it in the next experiment, where we will look for viscosity by a different method. There is a copper cylinder in the liquid helium, so mounted as we can turn it about a vertical axis.

In order to turn it smoothly and with as little vibration as possible, we laid the cylinder into the [INAUDIBLE] of a simple induction motor energized from outside the dewar. The four horizontal coils you see provide the torque which turns the cylinder.

The liquid helium is electrically non-conducting. The coil exerts no torque on it directly. Yet as we turn on our motor, the liquid layer bounding the cylinder is dragged along behind it. The boundary layer in turn drags on the next layer, and so on outward.

Finally a circulation showing up in the helium due to its own viscosity and the wooden panels we [INAUDIBLE] is turned along. What we have just seen occurred in helium I, the normal phase at 4.2 degrees Kelvin. That is to say, this demonstration is consistent with our results for helium I by capillary flow. Helium I is viscous.

Here you see the liquid cooled down and passing into the superfluid phase, helium II. Let's turn on the motor. The paddle wheel starts again. What does this mean?

First of all, let me emphasize that, like helium I, helium II is also non-conducting in the electrical sense. In other words, the circulation in the experiment can only have been caused through viscous drag. So we conclude from the rotating cylinder observations that helium II is viscous and from the method of capillary flow that it has zero viscosity.

Our experimentation has come up with a paradox. No normal classical liquid is known to behave so inconsistently, in capillary flow on the one hand and in bulk flow on the other. This state of affairs forces us to think of helium II, the superfluid, not as a single, but as a dual liquid. It appeared as if helium II had two separate and yet interpenetrating component liquids.

We shall call one component normal. It is this component which we call responsible for the appearance of viscosity below the lambda point in the rotating cylinder experiment. The normal component, as the name suggests, behaves like a normal liquid, and therefore as viscosity. It is the one which the cylinder drags along as its turned. But the normal components cannot flow through the narrow channels of the ceramic disc because of its viscosity.

The second component has zero viscosity, and it's called the superfluid component. We think that it does not participate at all in the rotating cylinder experiment below the lambda point. It stays at rest.

On the other hand, it can flow through channels of one micron diameter with the greatest of ease and countering no resistance whatever because it has no viscosity. As we'll see later, this flow is not repeated even when the capillary diameters are made far smaller than one micron. This [INAUDIBLE] construction is called the two fluid model for liquid helium II. Whether it is correct or not depends on further tests comparing the theory based on this model with experimental results.

We now go on to another phenomenon, the fountain effect. What you see here is a tube which narrows down and then opens into a bulb. A small piece of cotton is stuffed into the [INAUDIBLE] section between the tube and the bulb. And the bulb has been tightly packed with one of the finest powders available, [INAUDIBLE].

And second wad of cotton keeps the powder in the bulb. This powder presents extremely fine capillary channels. Their average diameter is a small fraction of 1 micron. This device has been placed in the dewar. The liquid helium is below the lambda point. We submerge the bulb, and then we'll send a beam of light from this lamp to a point near the top.

You will see the light beam when the lamp is turned on. It focuses some heat in the form of infrared radiation on the point in question. The temperature will rise above the temperature of the rest of the apparatus. Let us turn it on.

Liquid helium flows through the hole in the bottom of the bulb, through the fine powder, and rises above the level of liquid helium outside. The height to which it will go depends on the temperature increase produced bu the lamp focused on the bulb. We can very well ask, where does the mechanical energy come from that does the work necessary to pump the liquid above the ambient level?

Before we attempt to discuss this question, there are two other facts that should be noted. The first is by now obvious. The upward flow through the bulb must clearly be a superfluid. Only the superfluid component of helium II could get through.

The second fact is more significant. Let me explain it this way, the superfluid flows spontaneously from a to b,from a cooler to a warmer place. Point a is in the cold liquid, but b is being heated with infrared rays. The second law of thermodynamics positively says that heat cannot of itself flow from a point of lower to a point of higher temperature.

What does this mean to us here, knowing as we do that the superfluid is flowing from a colder to a warmer spot? Simply this, it carries no heat, no thermal energy. Any internal energy [INAUDIBLE] is no longer thermally available. To say it precisely, it has zero entropy.

We have discovered another remarkable property of helium II. Its superfluid component not only is friction free, it also contains no heat. The heat energy contained in helium II as a whole resides, all of it, in the normal component. We may, of course, add heat to the superfluid component, as we are doing when it passes the spot heated by the lamp. But in doing so, we are converting it into the normal component.

Let me return briefly to a question posed earlier. Mechanical work is done in pumping the liquid above equilibrium level. Where does it come from? I cannot answer this question here in full, but it suffice to tell you that we are dealing here with a heat engine.

The mechanical energy comes from the heat added at the light spot. An amusing demonstration of the same phenomenon again uses a bulb packed with rouge, but this one opens into a capillary. Light is beamed on a spot just below the capillary, and it produces a helium fountain. The phenomenon in this and the previous experiment has become known as the thermomechanical, or the fountain, effect.

Below the lambda point, the superfluid component of liquid helium creeps up along the walls of its container in an extremely thin film. It is known as a Rollin film. This creeping film is a variety of superflow.

It is difficult to make the film itself directly visible to you. To show it indirectly, we've put some liquid helium into a glass vessel. It is below the lambda point. There is no part porous bottom in this vessel.

The film rises along the inside wall and comes down along the outside, collecting in drops at the bottom. The thickness of this creeping film is only a small fraction of 1 micron and of the order of 200 to 300 angstrom. Its speed, while small just below the lambda point, may reach a value as high as 35 centimeters per second at lower temperatures.

Our next experiment deals with the phenomenon of second sound. We are all familiar with wave motion in elastic materials, be they solids, liquids, or gases. Elastic energy of deformation, carried away from its source in the form of waves with a characteristic speed, the speed of sound.

Liquid helium is an elastic substance both above and below the lambda point. Both helium one and two support sound waves. Now helium II, the superfluid phase, also conducts heat in the form of waves. This remarkable property is shared by no other substance. For better or for worse, it has been called second sound.

Normal heat conduction is a diffusion process. The rate of flow of heat is proportional to the temperature differences. But in helium II it is a wave process. Heat flows through helium II with a characteristic speed, the speed of second sound.

We shall send small heat pulses into helium II from a heater. They will spread away from the heater uniformly, carrying the heat energy with them. The speed of second sound is small just below the lambda point. In the neighborhood of 1.6 degrees Kelvin, it reaches a value of roughly 20 meters per second, and it is in this range that we will run our demonstration.

The experimental procedure is as follows. There are two disks in the liquid helium. They are carbon resistors with the carbon applied in thin layers on one side of each disk. In this way, good thermal contact is established between the resistor and the liquid helium.

The following resistor will be used as a heater. Electric currents will be sent through it in pulses from this pulse generator by means of the cable you see here. The [INAUDIBLE] of the generator is also connected via a second cable to a dual-trace oscilloscope, where it will be recorded on the bottom [? trip. ?] In other words, it will record the heat pulse as it enters the liquid helium.

The pulses have been turned on. They themselves trigger the horizontal sweep of [INAUDIBLE], which records [INAUDIBLE]. It is calibrated at 1 millisecond per unit on the scale. The pulses are 1 millisecond long.

The pulses leave the heater at the bottom in the form of second sound and move up to where they strike the carbon resistor at the top. Being heat pulses, they greatly raise is temperature. The carbon resistor is quite sensitive to changes in temperature. It acts as a thermometer.

So the heat pulse of second sound creates a pulse-like change in the resistance of the [INAUDIBLE] up here. It isn't hard to convert this resistance pulse into a [INAUDIBLE]. What we will do is to maintain a small DC current in the top resistor. It is supplied from a battery in this metal box.

The box shields the circuits in order to reduce electronic noise. The voltage pulse is small. In this second box we have an amplifier.

The amplified output is fed into the oscilloscope, where it will appear on the upper trace. The horizontal timescale on this trace is exactly the same as for the bottom trace. However, the upper trace records both exchanges as they occur in the top resistor, a detector of second sound. The temperature of the liquid is about 1.65 degrees Kelvin.

The battery has been turned on, and now the amplifier. Among noise and other distortions in the upper trace, a clear-cut voltage pulse appears about 4 and 1/2 units to the right, 4 and 1/2 milliseconds later than the pulse entering the heater.

This pulse in the upper trace is also about 1 millisecond long. It is the second sound as it arrives at the upper resistor. The upper trace also shows a strong voltage pulse at the left, simultaneous to the heater pulse. That's due to pick-up by electromagnetic waves with the heater acting as transmitter and the detector as receiver.

We're moving the detector toward the heater. The pulse moves with it to the left. Notice the echos of second sound which appear on the upper trace while the detector is near the heater. They're caused by multiple reflections between the two resistors. A total of three echos is clearly visible.

[END VIDEO PLAYBACK]

PROFESSOR: OK, you can watch the rest of it at home.