Majorana experiments - Michael Wimmer

Now that we know how to make Majorana systems in principle, lets look at the current experimental status.

We ended the previous video with the picture of the Delft experiment where Majorana bound states were observed for the first time.

Remember that Majoranas only appeared by tuning the system into a topological phase.

In particular, they only appear at a finite magnetic field.

In order to observe Majorana bound states, one needs to measure them.

How do you actually measure Majoranas?

It turns out that a standard current-voltage measurement is enough.

Apply a voltage between a normal contact and the superconducting part – where the Majoranas are located - and measure the current that flows across a tunnel barrier.

This so-called conductance spectroscopy is one of the standard techniques to actually find Majorana bound states.

I want to spend a little bit of time to explain how this works.

Let us first understand how current flows in normal-superconducting junctions in general.

We have a normal metal in contact with a superconductor.

We want current to flow from the normal metal to the superconductor.

This should be possible, as the superconductor has no resistance.

However, the transport processes turn out to be a little bit more involved.

Let us first consider the case of a normal superconductor and forget about Majoranas for a while.

We are interested in current flowing from the normal metal to the superconductor.

Current in the normal metal is carried by electrons.

However, when an electron comes to the superconductor something funny happens.

The superconductor has a quasiparticle gap, which doesn't allow single electrons in the system.

If an electron comes there, naïvely one would say the electron is just reflected, but this would result in no current through the superconductor.

We now have to remember that current in a superconductor is carried by Cooper pairs, which are pairs of 2 electrons.

So, when a single electron arrives at the superconductor it can actually go into the superconductor as a Cooper pair, but it needs a second electron.

The second electron comes from the Fermi sea, leaving a hole in the normal metal.

This hole then travels backwards in the metal.

This process carries then a current, because the electron is negatively charged and travels to the right, the hole is positively charged and travels to the left.

It is called Andreev reflection, and is the fundamental process of current flowing in a normal-superconducting junction.

Conductance spectroscopy is usually done in the presence of a tunnel barrier in the junction.

If the bias voltage is small, then current is carried by Andreev reflection.

In this case the electron has to go through the barrier and the hole has to come back, so there are two tunnelling events.

Each process has a small tunnel probability T.

The total probability of this process is thus proportional to T^2.

For a bias voltage larger than the superconducting gap, the electron can just enter the superconductor as an electron.

It thus has to go only once through the barrier, so the conductance is then just proportional to the tunnelling probability T.

Since T is smaller than 1, this probability is higher than the previous case.

Inside the gap the conductance is thus lower than outside the gap.

Right at the gap there is a resonant behaviour, so that in total the conductance has this particular shape as shown on the slide.

Note that one can directly read off the superconducting gap Delta from such a measurement.

What happens if you have a Majorana bound state there?

A Majorana bound state always sits at zero energy, and gives rise to a resonant process at zero bias voltage.

In the conductance, we thus observe a peak at zero bias voltage.

Since this is a resonant process, the conductance is actually quantized at the value of 2E^2/h – at least for zero temperature.

At finite temperature, this peak can actually be lower, if thermal broadening exceeds the tunnel coupling.

Common to both scenarios is that we expect to see a peak at zero bias voltage inside a superconducting gap, as a signature of Majorana bound states.

This particular measurement was done 2012 in Delft.

I show here the conductance at zero magnetic field.

We see the gap structure that I explained to you before, a supressed conductance inside the gap, and conductance peaks at the value of the induced superconducting gap.

This was first a zero magnetic field, so no Majoranas.

The measurements for finite magnetic field are all the additional curves that are shown here in this plot.

The magnetic field increases as you go further to the top.

We observe that as a magnetic field is increased, suddenly a peak at zero bias voltage is emerging.

This is the signature of a Majorana bound state.

Now, this was already six years ago.

The signatures then were non-ideal: the peak is not quantized as we might have hoped for.

Also, there are other effects that might induce a peak at zero bias, besides Majoranas.

However, since 2012 experimentalists have very worked hard on establishing Majoranas more in their system.

I want to highlight 2 milestones in this field.

The first one was the experiment in 2016 in the group of Charlie Marcus in Copenhagen.

They showed that the states in these nanowires have an energy that is exponentially close to zero as a function of the length of the nanowire.

This shows the exponential protection of Majoranas experimentally.

Another important milestone was again in Delft in the group of Leo Kouwenhoven.

After optimizing the nanowires, they found a quantized conductance peak of the Majorana bound states.

If you take all of these experiments together, there is actually very strong evidence that we have Majorana bound states in these nanowire systems.

I told you in detail about the nanowire platform for Majorana bound states.

Before I end, let me emphasize that there are more possible systems hosting them.

I show one other particular example here.

It was predicted that a chain of magnetic atoms on top of a superconductor would also host Majoranas.

The group of Ali Yazdani built this system using a STM, and indeed found states localized at the ends of these magnetics chains.

I also want to mention that actually Majorana particles do not only exist in superconducting systems as I showed you, but they can also appear in interacting systems, for example superfluid Helium or fraction quantum Hall effect.

So far, nanowire-based systems remain the most technologically advanced.

Experimentalists are working now hard on realizing the first topological qubit there.

How such a qubit would work is the topic of the next MOOC videos.