Higgs Modes in Superconductors

Luc Schnell

December 7, 2017

The detection of the Higgs boson by CERN's Large Hadron Collider, providing strong evidence for the Higgs mechanism of mass acquisition in the Standard Model, attracted lots of attention in the scientific community. The ideas that led to the postulation of the Higgs mechanism can be traced back to superconductivity theories. In recent years, researchers have claimed the detection of Higgs-like excitations in superconductors, thereby closing the loop and bringing the Higgs back to its roots. I will start my explanations with a short overview over the history of the Higgs mechanism. Then I will give information on what exactly these modes are and why they can be observed in superconductors. Finally, I will report on two different experimental setups that enabled the detection of the superconductor Higgs.

1 Theory

1.1 Origins of the Higgs Mechanism

The Ginzburg-Landau model (1950) provided a framework to explain many of the properties found in superconductors [1]. It was later replaced by the theory of Bardeen, Cooper and Schrieffer (BCS) [2], but I will base the following theoretical explanations on Ginzburg-Landau, as it provides a more intuitive insight into the physics of superconductors. In this model, the electrons taking part in the superconducting state are assumed to form a superfluid. The whole system is described by the complex order parameter

$$\Psi(\mathbf{k}) = |\Psi(\mathbf{k})| \cdot \exp(i\phi),$$

where $|\Psi(\mathbf{k})|$ is the fraction of the electrons that has condensed into a superfluid [1, 3]. Above the critical temperature T_c, the potential $V(\Psi)$ of the system has a single minimum at $\Psi = 0$ [1], meaning that there is no superconductivity present in the ground state. Below T_c, however, the potential acquires a "Mexican hat shape" (see Figure 1) with a ring of degenerate minima [3]. The minima are no longer located at $\Psi = 0$, therefore a non-vanishing part of the electrons now forms the superconducting superfluid in the ground state. During the transition, the superconductor arbitrarily falls into one of the states on the ring of degenerate minima, which is referred to as "spontaneous symmetry breaking" [4]. In the original theory, the order parameter was assumed to be fixed [2]. A few years later, however, three papers published independently by Anderson (1958), Bogoliubov (1958) and Nambu (1960) showed that the order parameter being held constant leads to the violation of local gauge symmetry, which is a fundamental principle of quantum field theory [5]. This can be solved by introducing order parameter fluctuations into the theory [2]. Anderson, Bogoliubov and Nambu came up with the so-called Nambu-Goldstone phase mode that corresponds to fluctuations of the order parameter in transverse direction (along the red line in Figure 1) [3, 2]. The possibility of an additional order parameter fluctuation in radial direction was not given special attention, probably since it was not needed to get a consistent theory of superconductivity [2].

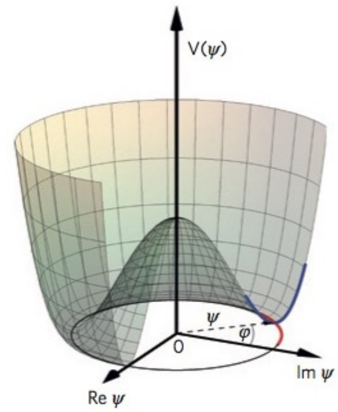

Figure 1: The "Mexican hat potential" of spontaneous symmetry breaking. In the ground state, the system arbitrarily falls into one of the states on the ring of minima. Excitations along the red line are the Nambu-Goldstone phase modes, excitations along the blue line the Higgs amplitude modes. **Source:** [3].

Nambu, Higgs and others soon realized that a similar theory with spontaneous symmetry breaking could explain the masses of fundamental particles. In the Standard Model of particle physics, fermions and the gauge bosons of the weak interaction having non-zero masses leads to local gauge symmetry breaking (similar to the gauge symmetry problem in the Ginzburg-Landau model) [5]. Higgs made a relativistic spontaneous symmetry breaking model with the "Mexican Hat" potential to provide a mass acquiring mechanism for particles in the Standard Model [2]. He showed that excitations of the order parameter in radial direction (along the blue line in Figure 1) can be interpreted as mass terms of the field [5]. Since these excitations are quantized, he introduced the Higgs particle as fundamental quantum of the Higgs field. The existence of the Higgs particle could be verified experimentally by the ATLAS and CMS experiments at CERN's Large Hadron Collider, which led to Higgs winning the Physics Nobel Prize in 2013 [6].

1.2 Higgs Modes in Superconductors

The importance of radial modes in the Higgs model of mass acquisition raised interest to search for analogous modes in superconductors – which was fruitful. In several papers published in recent years, researchers claim to have measured fluctuations of superconductors' order parameters in radial direction (along the blue line in Figure 1) [3, 7]. These are called amplitude or Higgs modes. It might seem surprising that Higgs modes can be found in the low-energy regime of superconductors, while on the other end of the spectrum in particle physics, high energies are needed to detect the Higgs boson. In a paper published in 2002 [8], Varma elaborates on the reasons behind this. He claims that essentially the (approximate) particle-hole symmetry incorporated in superconductivity theory leads to the resulting equations of motions being similar to the ones obtained in a relativistic model of spontaneous symmetry breaking. Without the symmetry, only the Nambu-Goldstone phase modes could occur in superconductors. Despite this similarity in the equations of motion that follow from the theory, the superconductor Higgs is different in nature compared to its high energy counterpart. It is a collective mode of the condensed superfluid electrons that form the superconducting state. While the Higgs boson in the Standard Model arises from a relativistic theory and requires the addition of terms in the Hamiltionian describing the system, this is not the case for the amplitude mode in superconductors, which arises naturally from the Ginzburg-Landau model [2].

2 Experiment

The detection of Higgs modes in superconductors is very challenging. The collective amplitude excitation of the order parameter does not carry any spin or charge, from which follows that it does, in principle, not couple directly to any external probe [7]. Another difficulty is that the mode normally (in low disorder superconductors) decays very rapidly to particle-hole pairs [3]. It is therefore not surprising that the Higgs boson, despite having its theoretical roots in condensed matter physics, was first detected experimentally in particle physics. In recent years, however, several experiments looking for Higgs modes in superconductors ended in success. Two of them are presented here, discussing the methods they used to overcome the mentioned experimental obstacles.

2.1 Detection using Raman Spectroscopy

In a paper published in February 2014 [7], Méasson et al. describe the detection of excitations in superconductors that can be convincingly attributed to the Higgs mode. The underlying idea of this experiment is to use a superconductor that exhibits both superconductivity and the charge density wave order (CDW). Similar to superconductivity, CDW is a superstructure that forms as ground state in some materials at very low temperatures [9]. The crucial point is that the amplitude mode of the CDW order couples to the Higgs mode of the superconductor by changing the density of states at the Fermi level [7]. This affects the fraction of electrons forming the superfluid, which corresponds essentially to a fluctuation of $|\Psi|$ (amplitude mode). The superconductor-to-CDW coupling can be observed analyzing the inelastic scattering of photons (Raman scattering) at a sample that exhibits both modes (see Figure 2).

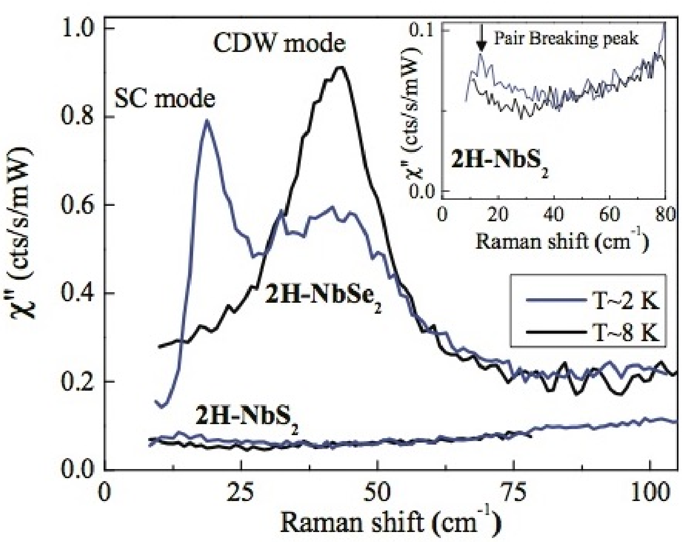

Figure 2: Experimental evidence for the Higgs mode in superconductors using Raman spectroscopy. The CDW mode couples to the SC (Higgs) mode, which can be seen as a shift of the spectral weight in the 2H-NbSe$_2$ plot. **Source:** [7].

The x-axis in Figure 2 corresponds to the wavelength difference between the incoming and outgoing photon, the y-axis shows the Raman susceptibility, which can be understood as a measure of the excitation of the sample due to Raman scattering. Plots for the samples 2H-$NbSe_2$ (exhibiting both CDW and superconductivity) and 2H-NbS_2 (only exhibiting superconductivity) at two different temperatures are displayed. The $T \sim 8$ K plot for 2H-$NbSe_2$ shows a large peak that can be attributed to the CDW mode. The SC (superconductivity) mode is not visible, since this measurement was taken above the critical temperature for superconductivity T_c. The Raman spectroscopy plot for 2H-$NbSe_2$ is very different at $T \sim 2$K, which lies below T_c. Here the SC mode peak is dominating. It should be noted that the spectral weight was transferred from the CDW to the SC mode, since the CDW peak is now less strongly pronounced. Indeed, Méasson et al. showed in their paper that the total integral of the susceptibility

$$S = \int_{\omega_1}^{\omega_2} \chi''(\omega)\ d\omega$$

only varies by $\pm 4\%$ among 7 measurements taken in the range between 2 and 8 K. This is in good agreement with the idea of the CDW mode coupling to the Higgs mode of the superconductor, thereby transferring the spectral weight in the Raman scattering plot and leaving the total susceptibility integral unchanged.

The material 2H-NbS_2 (lower curves in Figure 2) is very similar to 2H-$NbSe_2$, but does not exhibit the CDW mode. Accordingly, the CDW peak is not visible at $T \sim 8$ K, neither is the SC mode at $T \sim 2$K. This provides further evidence for the CDW-to-SC coupling picture, since the SC mode cannot be observed without the CDW mode being present. The small peaks in the 2H-NbS_2 plots (showed in more detail at the top right of Figure 2) can be attributed to the superconducting Cooper-pair-breaking. Clearly this effect is much less intense than the SC mode in 2H-$NbSe_2$, which shows that this cannot be its origin. Therefore, Méasson et al. were able to observe an SC mode that couples to the CDW mode in 2H-$NbSe_2$ and that can be convincingly attributed to the amplitude excitation of the order parameter in superconductors, Higgs mode in short.

2.2 Detection using Optical and Tunneling Spectroscopy

Sherman et al. released a paper in 2015 [3] presenting the detection of Higgs modes in superconductors using optical and tunneling spectroscopy. The used samples were highly disordered two-dimensional systems close to the superconductor-insulator transition. The reason for this is that the energy scale of the Higgs mode, m_{H}, is suppressed in the presence of disorder. This has the effect that the dynamical conductivity $\hat{\sigma}(\omega)$ (the conductivity under changing electric fields) exhibits a contribution due to the Higgs amplitude mode at high disorder, in addition to the usual conductivity predicted by superconductivity (BCS) theory:

$$\hat{\sigma}(\omega) = \hat{\sigma}^{\mathrm{BCS}}(\omega) + \hat{\sigma}^{\mathrm{H}}(\omega).$$

By measuring the dynamical conductivity $\hat{\sigma}(\omega)$ using optical spectroscopy and comparing it to the dynamical conductivity $\hat{\sigma}^{\mathrm{BCS}}(\omega)$ expected theoretically from BCS, one can therefore determine the contribution $\hat{\sigma}^{\mathrm{H}}(\omega)$ from the Higgs mode. The experimental results are given in Figure 3.

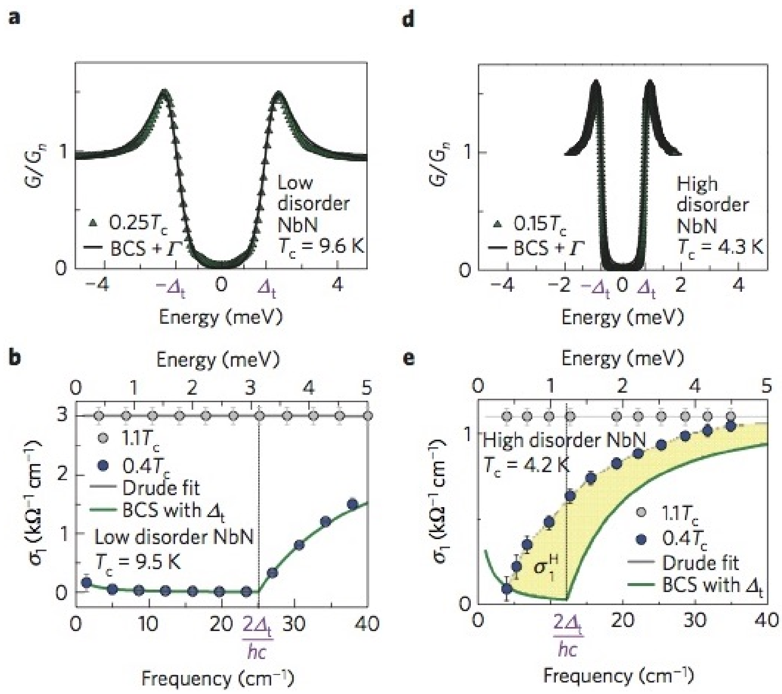

Figure 3: Experimental evidence for the Higgs mode in superconductors using optical and tunneling spectroscopy. A dynamical conductivity σ_1 different from what would expect theoretically from BCS was measured in the high disorder NbN sample (highlighted in yellow in plot e). This deviation from theory is due to the Higgs mode being present in the sample. **Source:** [3].

Figures 3a and 3d show the tunneling spectroscopy plots for low and high disorder NbN superconductors. The x-axis shows the energy corresponding to the applied tunneling voltage, the y-axis shows the superconductor tunneling conductance normalized to the tunneling conductance in the normal state. Both plots show what one would expect from BCS theory: at low energies, no current can flow, since the electrons are contained in Cooper pairs building the SC superstructure. As soon as the energy reaches the critical point $\Delta_{\mathrm{t}} = \frac{1}{2}E_g$ (where E_g is the energy gap at the Fermi level in the superconductor) per electron, however, the Cooper pairs are broken up and a tunneling current flows [10]. These two measurements were performed to be able to predict the theoretical curve for $\hat{\sigma}^{\mathrm{BCS}}(\omega)$ in the two lower plots, for which Δ_{t} must be known.
Figures 3b and 3e show the optical spectroscopy plots again for low and high disorder NbN superconductors. The x-axis shows the frequency of the incoming light, the y-axis shows the real part of the dynamical conductivity $\mathrm{Re}\{\hat{\sigma}(\omega)\}$. In both figures, two lines corresponding to measurements above and below the critical temperature T_c can be seen. The conductivity measurements above T_c, meaning that the NbN sample is not in the superconducting state, are described very well by the simple Drude model. The conductivity measurement below T_c for the low disorder NbN sample follows the predictions from BCS theory, meaning that the Higgs mode is not activated and $\hat{\sigma}(\omega) = \hat{\sigma}^{\mathrm{BCS}}(\omega)$. But this is different in the high order NbN sample. Here a clear discrepancy between the measured conductivity $\hat{\sigma}(\omega)$ and $\hat{\sigma}^{\mathrm{BCS}}(\omega)$ can be observed (highlighted in yellow). The excess conductivity measured experimentally can be attributed to the Higgs amplitude mode. Therefore, in the experiment performed by Sherman et al. the Higgs amplitude mode could be measured in a more direct fashion compared to the one by Méasson et al., since the energy scale of the Higgs mode is suppressed in the presence of disorder close to the superconductor-insulator transition, making it detectable via the dynamical conductivity.

3 Conclusion

The experimental detection of Higgs modes in superconductors is very challenging. Nevertheless, several experiments in recent years trying to measure these collective electron modes ended successfully. Two of them were presented here. Viewed from a historical perspective, this rounds off the Higgs mechanism's discovery almost poetically, closing the arc of the story and bringing the Higgs back to its roots. But the importance of the topic goes far beyond that.

The Higgs modes in superconductors are different in nature than the Higgs particle. They are a collective mode of the electrons condensed in the superfluid forming the superconducting state. While the Hamiltonian of the Higgs mechanism explicitly contains terms corresponding to the Higgs boson, the Higgs mode in superconductors arises more naturally from the underlying theory. This brings up a very interesting question. As Anderson puts it: "If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode [the Higgs particle]? Maybe the Higgs boson is fictitious!" [2].

References

[1] Ginzburg, V.L.: *On Superconductivity and Superfluidity (What I Have and Have Not Managed to Do), as well as on the 'Physical Minimum' at the Beginning of the 21st Century.* ChemPhysChem, Volume 5. 2004.

[2] Anderson, P.W.: *Higgs, Anderson and all that.* Nature Physics, Volume 11. February 2015.

[3] Sherman D. et al.: *The Higgs mode in disordered superconductors close to a quantum phase transition.* Nature Physics, Volume 11. February 2015.

[4] Li, L.-F.: *Introduction to Spontaneous Symmetry Breaking.* http://galileo.phys.virginia.edu/~pqh/Li.pdf. July 2011.

[5] Thomson, M.: *Modern Particle Physics.* Cambridge University Press, 2013.

[6] The Official Web Site of the Nobel Prize: *The Nobel Prize in Physics 2013.* https://www.nobelprize.org/nobel_prizes/physics/laureates/2013.

[7] Masson M.-A. et al.: *Amplitude Higgs mode in the 2H-NbSe$_2$ superconductor.* Physical Review Volume 89, February 2014.

[8] Varma, C.M.: *Higgs Boson in Superconductors.* Journal of Low Temperature Physics, Volume 126. February 2002.

[9] Morales, J.: *Charge Density Waves: An emergent Ground States in the Manganites.* Department of Physics and Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois. December 2009.

[10] Kittel, Ch.: *Introduction to Solid State Physics.* Eighth Edition. John Wiley and Sons, Inc. 2005.