Introduction

In the year 2011, the history of superconductivity will be one hundred years old. For a sub-field of physics, this is a very long period of time. One could have reasonably expected superconductivity to be by now a closed chapter of Physics. Yet, the discovery of the High T_c cuprates by Bednorz and Muller in 1986, showed that there remained more to be discovered and to be understood about superconductivity, than was expected after the consequences of the theory of Bardeen, Cooper and Schrieffer (BCS) had all been explored in depth.

It is the theme of these lecture notes that the cuprates belong to a class of superconductors which are, in many respects, fundamentally different from the conventional superconducting metals and alloys. The cuprates are not the only members of this class: granular superconductors, and at least some of the organic superconductors, discovered earlier, also belong to it, as well as other oxides.

Why do the cuprates have high critical temperatures? This is the question that a large number of researchers have been trying to answer for the last 19 years, so far with limited success only. They are close to an antiferromagnetic state, and this proximity is at the heart of some theories of high temperature superconductivity. But other oxides are not. The one property that all high temperature superconductors have in common, is that they are close to a metal-insulator transition. They are not metals, or alloys, in the ordinary sense: a very small change in composition is sufficient to transform them into insulators. Unfortunately, the enormously successful weak coupling BCS theory of superconductivity is really a theory that applies to metals only. It is not an accident that it did not predict high temperature superconductivity. It was even used by some to predict that high temperature superconductivity could not exist. In fact, it is probably a correct prediction that metals cannot be high temperature superconductors.

Our understanding of the new superconductors is still very imperfect, compared to that of metals and alloys. In these lecture notes, no attempt is made at reviewing the various mechanisms that have been proposed to explain High T_c. My purpose is more modest, and is limited at pointing out, on the basis of the experimental evidence, to the basic phenomenology of these materials. In many aspects of their behavior, they resemble more superfluid Helium than metal-superconductors. This suggests that electron pairs, bosons of zero total spin, may form above T_c — a feature that indeed cannot occur in metals. But there is still no indisputable proof that this is indeed the case.

Because of their high T_c, there has been a tremendous push towards the applications of the new superconductors, a somewhat hazardous enterprise in the absence of a good fundamental understanding of these fascinating materials. Yet, remarkable progress in the control of material quality, necessary for their application, has been achieved. It is also of great help in developing better fundamental experiments, which in turn have greatly improved our knowledge. There is now a substantial experimental basis for a condensation mechanism that is intermediate between BCS and Bose–Einstein. The consequences of this situation, particularly concerning the properties of the vortex state, have not yet been explored in depth. In this regard, we may look at granular superconductors as model systems, and draw on them to give us at least some intuition of the phenomenology of the cuprates.

A more fundamental question concerns the mechanism responsible for pair formation — quite a formidable task. Two schools of thought have been affronting each other. One of them holds that it is entirely due to electron-electron Coulomb interactions, known to be strong since the pristine cuprates are anti-ferromagnets, with the electron-phonon interaction playing no role at all in pair formation. The other holds that the electron-phonon interaction still plays an essential role in the cuprates. We shall try to summarize the main arguments of both schools. Here again, a comparison with granular superconductors proves instructive. Well before the discovery of the cuprates, it was shown that the critical temperature of granular Aluminum increases as Coulomb interactions are increased (here, by reducing the grain size which can by itself modify the electronic structure), up to the point where the metal-insulator transition is reached. This result flew in the face of the BCS–McMillan theory of superconductivity, in which a repulsive Coulomb interaction can only decrease the critical temperature. Evidently, this is a case where both the electron-phonon interaction, and electron-electron Coulomb interactions are at work. This unconventional situation is one of the reasons for reviewing in these notes some of the properties of granular superconductors.

But the main purpose of these notes is to outline what is really new about the cuprates from the standpoint of their phenomenology, and to provide a simple classification that can serve as a guide for practical applications.

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It is clear that in between granular Aluminum and High T_c stands the momentous discovery of Georg Bednorz and Alex K. Mueller, with whom I have enjoyed 20 years of warm relations, and endless fruitful discussions in our quest for understanding these materials.

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