C. R. Physique 12 (2011) 433–435

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Superconductivity of strongly correlated systems / Supraconductivité des systèmes fortement corrélés

Foreword

This year we celebrate the centennial jubilee of the discovery of superconductivity. On April 8, 1911 Heike Kamerlingh Onnes at Leiden observed for the first time the transition of mercury to the state with no resistance. The scientific community appraised very quickly the importance and the potential applications of this phenomenon, and already in 1913 Kamerlingh Onnes was awarded the Nobel Prize for his success in helium liquefaction and discovery of superconductivity. About 17 Nobel laureates have since been rewarded for superfluidity or superconductivity, a strong indicator of the fruitfulness of this phenomenon!

A microscopic theory of superconductivity has been proposed more than 40 years after its discovery in 1957, by Bardeen, Cooper and Schrieffer. This BCS theory explained the occurrence of superconductivity through a pairing mechanism based on the electron–phonon interaction and described quantitatively the main properties of superconductors. Furthermore the BCS theory elucidated the basis of the phenomenological theory of superconductivity proposed by Landau and Ginzburg and developed by Abrikosov, which had already lead to many discoveries, like the existence of two types of superconductivity characterised by a completely different behaviour under high magnetic field.

The discovery in 1986 by Müller and Bednorz of high temperature superconductivity became the next major milestone in the history of superconductivity, revitalising the quest for room temperature superconductivity and giving an unprecedented impulse to the general subject of strongly correlated electron systems, as it became soon very likely that these strong correlations are at the heart of the new mechanism allowing for such high critical temperatures. Nowadays the maximum critical superconducting temperature exceeds 140 K and superconductivity can be routinely observed at liquid nitrogen temperature (77 K at 1 atm) instead of liquid helium temperature (4.2 K at 1 atm).

The physics of conventional superconductors, known before the high-T_c era, may be considered as completely understood in the framework of BCS–Eliashberg electron–phonon coupling theory. In fact, conventional superconductivity is even a paradigm of a completely solved many-body problem, still a rare case in condensed matter physics. The highest critical temperature observed for “conventional superconductors” is $T_c \approx 40$ K, in the recently discovered MgB_2 superconductor, a clear cut example of multi-gap superconductivity which is again well-characterised and understood.

This volume however is dedicated to some of the main issues debated nowadays in the field of superconductivity, concentrating therefore on what is not yet fully understood! A large part is therefore devoted to “unconventional superconductivity” in strongly correlated systems (high-T_c cuprates, iron pnictides, heavy fermions and organics). Indeed, the mechanisms of high temperature superconductivity (including superconductivity in the recently discovered doped Fe pnictides) are still debated. Even 25 years after the discovery of high temperature superconductivity, the elaboration of a theory of these strongly correlated, quasi two-dimensional electron systems, remains a challenging task. Besides the articles on issues of these different families of superconductors, we have also chosen to add two papers on very fundamental problems at the two ends of the field: one on the actual progress on a completely new path leading to the occurrence of superconductivity from insulating materials, the other on the long standing problem of the quantitative theoretical prediction of the critical temperature, already for “simple” systems.

Deliberately, we did not include use of superconductivity in “nanoscience”, a subject of its own with the quest for the realisation of intricate electronic states, qubits, hybrid systems (normal-superconducting, ferromagnetic-superconducting...), new logic based on current impulsions (Rapid Single Flux Quantum), single photon detectors, or hybrid magnetic sensors... Neither did we review the recent progress on the use of high-T_c cuprates for current transport, which, for example, raises the prospect of magnetic field generation up to 30 T or above with all superconducting technology.

The main subject of this volume is the progress on novel superconducting materials. The discovery of the high temperature superconductivity somewhat shadowed the “exotic” superconductivity which has been observed in heavy fermions and organic systems several years before. Now it becomes clear that the understanding of superconductivity in these strongly correlated systems is ultimately related to the elucidation of the mechanisms of high temperature superconductivity. Moreover, probably the most astonishing discovery during the last decade in the field of superconductivity is the observation of a superconducting transition in the ferromagnets UGe_2, URhGe and UCoGe. Most likely it is a triplet (equal spin pairing) superconductivity and this exemplifies the intimate relation between magnetism and superconductivity in those novel su-

1631-0705/$ – see front matter
doi:10.1016/j.crhy.2011.05.003

perconductors. However, these ferromagnetic superconductors also display a completely unusual robustness to an applied magnetic field, surviving to fields above 30 T despite sub-Kelvin critical temperatures! Another promising emerging field of discoveries of new types of superconductors is coming from a completely different area, namely that of oxide heterostructures, where superconductivity blossoms at the interface between two insulators.

This special issue of the "Comptes rendus Physique" starts with four papers on high-T_c cuprates, which review progress on 4 major issues of these superconductors:

- the (d-wave) superconducting order parameter symmetry: the article by J.R. Kirtley is on the probes of the order parameter symmetry by SQUID microscopy. It is a very powerful method, specifically developed for the cuprates, sensitive to the phase of the order parameter, which can identify paired states with angular momentum greater than zero;
- the Fermi surface of cuprates: the paper by B. Vignolle et al. reviews the recent success of revealing unexpected electron Fermi surfaces in the underdoped regime of the cuprates, which has severely revised our knowledge of the normal states of the cuprates, and address directly the strong correlations and the magnetic instabilities, possibly at the origin of the pairing mechanism in these systems;
- the nature of the pseudo-gap state: the paper of P. Bourges and Y. Sidis reviews the latest microscopic probes (mainly neutrons) of the magnetic phase of the cuprates in the so-called "pseudo-gap state". They discuss the possible scenarios compatible with experimental observations, which converge to a truly magnetically ordered state in the pseudo-gap state, a major piece of the puzzle for the physics governing the cuprates;
- the existence of two energy scales in the superconducting phase of the cuprates: the paper by A. Sacuto et al. describes fine spectroscopy in the whole phase diagram of the cuprates. It addresses the major question of the evolution with temperature and doping of the superconducting gap and of the pseudo-gap, building on the knowledge of the evolution of the Fermi surface to propose a unified scenario for these two energy scales, a complement to the neutron results on the nature of the pseudo-gap phase.

As regards the new iron pnictide superconductors, there is very rapid progress in this field, which is however yet much less mature than that of the cuprates. Rather than a summary of the main issues discussed in these systems, we chose to focus on results given by two very fruitful technics:

- Penetration depth measurements: this technic gave the first evidence for nodes of the gap in the cuprates, before truly phase sensitive experiments which evidenced the d-wave symmetry. A. Carrington reviews experiments on the temperature dependence of magnetic penetration depth and thermal conductivity in the iron based superconductors. These studies permit one to determine the structure of the superconducting gap in the recently discovered new family of high temperature superconductors;
- NMR studies: the paper by K. Ishida et al. shows how NMR could yield microscopic information on the phase diagrams of these new iron based superconductors, appearing to be non-universal among the different families, which is also reflected in the contrasted role of magnetic fluctuations in the pairing mechanism, or in the nodal structure of their superconducting gap.

Another series of 4 papers is devoted to the oldest heavy-fermion and organics families. In these systems, by contrast to the cuprates or the new iron pnictides, the intimate interplay of superconductivity and magnetism is very well established, and the low critical temperatures allows exploration of the whole magnetic/superconducting phase diagram under pressure and magnetic field:

- For organics, the article by C. Bourbonnais and A. Sedeki focuses on the mechanisms of the superconductivity in the Bechgaards salts family. A special emphasis is made on the interconnection between antiferromagnetism and superconductivity in these quasi-one-dimensional systems;
- For heavy fermions, the interplay between antiferromagnetism and superconductivity is described in the cerium 115 family in the paper by G. Knebel et al. Extension to other cerium based heavy fermions like the recently discovered non-centro-symmetric superconductors give an overall view of the amazing wealth of new states of matter arising from the interplay between antiferromagnetic and superconducting instabilities;
- The next two papers focus on the theory and experiments in the most challenging uranium based superconductors. As regard theory, V.P. Mineev's article analyses the contribution of the magneto-elastic mechanism to the magnetic transition in the ferromagnet–superconductor UGe_2. As regards experiments, the article by D. Aoki et al. gives a review of the current state of the art of the studies of the properties of triplet ferromagnetic superconductors. Special attention is devoted the (B, T) phase diagram and to the analysis of the reinforcement of superconductivity by the reorientation of ferromagnetic moment.

And last, but not least, two other papers open new prospects in the field of superconductivity:

- X. Blase presents a review of the recently discovered superconductivity in doped clathrates, diamond and silicon, where he discusses the origin of the superconducting transition with special emphasis on the first principle calculations, which made very significant progress in the last years;
- Finally the review by S. Gariglio and J.-M. Triscone gives an introduction to the emerging research field of interface superconductivity in complex oxide heterostructures. They also discuss the intriguing perspectives of changes of the superconducting properties of these structures upon gate voltage tuning and of their possible applications.

So we hope that this volume will give a fair account of the richness of this field, 100 years after its birth, and of the fascinating discoveries and surprises nature continues to provide with each new family of superconductors. As is rather common in science, the Graal of room temperature superconductivity, which motivates so many groups and triggers an incredible excitation each time a new hope is raised, might in the end, when it will be reached, be less interesting than all we will have learned and explored along the quest.

Jean-Pascal Brison
SPSMS, UMR-E CEA/UJF Grenoble 1,
INAC, 17, rue des Martyrs, 38054 Grenoble cedex 9, France
E-mail address: jean-pascal.brison@cea.fr

Alexandre Bouzdine
Laboratoire ondes et matière d'Aquitaine,
universite Bordeaux 1, 351 cours de la Linération, 33405 Talence cedex, France
E-mail address: A.Bouzdine@loma.u-bordeaux1.fr