1) THEORY AND CONCEPTS :

From conventional to unconventional superconductivity

Prof. Jochen Wosnitza

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Few other phenomena in physics are as fascinating as superconductivity, the re-sistance-free conduction of electric current. Heike Kammerlingh Onnes discovered this effect 110 years ago in mercury. Only after some time, researchers have realized that it is not merely a curiosity of some materials, but that superconductivity is a new state of matter. Nevertheless, it took almost 50 years before Bardeen, Cooper, and Schrieffer published the now famous BCS theory, that describes superconductivity as a microscopic effect caused by a condensation of Cooper pairs. The highest measured transition temperature to the superconducting state stagnated at about 23 K for a long time. A decisive break-through was made in 1986, when Georg Bednorz and Alex Müller came across an oxide ceramic that becomes superconducting at a – at that time – sensational 35 K. A tremen-dous euphoria broke out in the worldwide physics community. Within a very short time during this "gold rush", scientists worldwide found more and more new substances with steadily increasing transition temperatures, even above the evaporation temperature of inexpensive liquid nitrogen at 77 K. This opened new possibilities for a broad technical application of superconductivity. Besides the ceramic oxide, high-Tc materials, research-ers reported many other classes of superconductors, such as iron-based, organic, and so-called heavy-fermion compounds – and, very recently, hydride-based materials that become superconducting near room temperature under very high pressure. For many of these materials, however, the conventional BCS theory is not sufficient to explain the ap-pearance of superconductivity here. The search for the understanding of such unconven-tional superconductors is an ongoing exciting task that challenges physicists all over the world. In my lectures, I will present an overview on the field of superconductivity, from its beginnings in 1911 to our present understanding.

Topological phases and quantum Hall effect

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Topological phases of quantum matter are a very rich and active field of research. After the discovery of the quantum Hall effects in the 1980s, and the discovery of topological insulators in the 2000s, this field expanded dramatically, aiming towards a general understanding of the role of symmetry, dimensionality, strong interactions, and more. This lecture will focus on a 2D topological phase: the quantum Hall (QH) effect and its lattice counterpart, the Chern insulator. Our two main goals will be to introduce the fundamental concepts necessary to describe the topology of QH systems (Berry phase, topological invariant), and to review the microscopic models realizing QH phases, from toy models to realistic ones tied to experimental systems.

Modelling electronic structure and strongly correlated systems

Prof. Gertrud Zwicknagl

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Electronic structure calculations are an important tool in modern material science. Theory and simulation have been shown to provide useful guidelines for materials discovery, design, and optimization. Understanding the collective electronic properties of emergent materials with strong correlations, however, remains a great challenge to condensed-matter theory. Important examples are transition metal oxides, metals containing lanthanide or actinide atoms and organic conductors. At low temperatures, these materials exhibit novel phenomena like metal-to-insulator transitions, heavy fermions, unconventional superconductivity and unusual magnetism which may eventually provide new functionalities. The complex behavior and the high sensitivity with respect to external fields result from the fact that the quantum mechanical (ground) states are determined by subtle compromises between competing interactions.

In this lecture, I will review how band structure calculations can help to better understand the intriguing behavior of materials with strongly correlated electrons. I
will show how the band approach can be modified to incorporate the typical many-body effects which characterize the low-energy excitations. Examples underlining the predictive power of this ansatz are discussed.

Literature: Gertrud Zwicknagl, Rep. Prog. Phys. 79 (2016) 124501 doi:10.1088/0034-4885/79/12/124501

Frustrated magnetism: from concepts to materials and experiments

Prof. Fabrice Bert

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In quantum magnets the rotational symmetry of the spins is preserved. This is at variance with usual magnets with long range ordered spins or spin glasses which feature on site static moments at low temperature. This is also at variance with paramagnets because strong correlations exist between the spins leading to non-trivial ground states, such as spin liquid states, and exotic excitations. However, long range order is usually robust in magnetic materials and avoiding it in favor of quantum ground states often requires a high level of frustration of the magnetic interactions. Frustration can arise from competing interactions, from the geometry of the lattice as in well studied kagome materials featuring a corner-sharing triangular magnetic lattice, or from strongly anisotropic, bond dependent, interactions as in Kitaev materials.
In this lecture, I will introduce, from an experimentalist point of view, the concept of frustration and its relation to quantum spin liquids. I will give several examples of experimental realizations of frustrated models and insist on the experimental hallmarks of their exotic ground states and excitations. In particular, I will introduce basic notions on local probe resonance techniques, NMR and muSR, which are often used, in complement with inelastic neutron scattering technique, to unravel the original properties of the frustrated quantum magnets.

2) EXAMPLES OF CHARACTERIZATION METHODS

Neutron scattering from quantum condensed matter

Prof. Yvan Sidis

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Collective quantum phenomena such as magnetism, superfluidity and superconductivity have been eminent themes of condensed-matter physics for more than one century. Neutron scattering has provided unique insights into the microscopic origin of these phenomena.

Neutron carries a spin, but no electric charge. It is therefore impervious to the Coulomb interaction and can penetrate deeply into most materials. There, it senses the position of atomic nuclei through the strong interaction and magnetic moments through the dipole–dipole interaction. The scattering cross-sections in both channels are precisely understood. No need for theorists to model or simulate the scattering process, they can focus on computing neutron cross-section associated with density-density and/or spin-spin correlation functions. Produced in large scale facilities, (cold, thermal and hot) neutrons have wavelengths comparable to interatomic distances and energies comparable to typical collective excitations in condensed matter. Both static and dynamic correlations are probed precisely in the spatial and temporal range of greatest interest. Exchange and collaboration between neutron scatterers and condensed-matter theorists has thus been an exceptionally fertile ground for cultivating new science. Many of experiments were motivated by theoretical predictions; in turn, they have driven advances in theoretical research.

In particular, neutron scattering has played a central role in the emergence of modern magnetism. Elastic neutron scattering is a powerful technique to visualize the microscopic arrangement of spins on the atomic scale. Such information is indispensable for any model of magnetism in solids. Advances in instrumentation and data analysis allow now the determination of increasingly complex magnetic structures. Inelastic neutron scattering can probe collective magnetic excitations and allow the determination of magnetic exchange interactions. Nowadays, it provides detailed maps of dynamical correlations in fluctuating quantum systems such as low-dimensional magnets, superfluids and superconductors. Being able to probe static and dynamic magnetic correlations, neutron scattering provides a powerful and direct mean to study the phase transition and critical phenomena, including quantum criticality.

Here I introduce the neutron scattering technique and present a personal selection of neutron scattering experiments without any claim of completeness, they illustrate the contributions of neutron scattering to the development of condensed-matter science.

*Note: this abstract is adapted from a review article of Steven T. Bramwell and Bernhard Keimer, published in NATURE MATERIALS, VOL 13, in AUGUST 2014 (www.nature.com/naturematerials.)

Advanced X-ray Absorption Spectroscopy

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X-ray absorption spectroscopy (XAS) is well-known local probe of the electronic and geometric structure of materials. It is inherently element specific technique and can likewise be applied to gases, liquids, and solids. Almost any material like catalysts, minerals or biological tissue (in its natural aqueous environment) can be investigated. It is widely used to study bulk materials, surfaces, interfaces, buried layers, and impurities at very low concentrations. Development of the third generation synchrotron radiation sources has boosted x-ray absorption spectroscopy, as illustrated by the discovery of a variety of new experimental techniques associated with the exploitation of the polarisation properties of x-rays.

X-ray magnetic circular dichroism (XMCD) discovered in 1987 has ushered in a new era of magnetism research with objectives that previously would have been unattainable. Because of their inherent element and orbital specificity and ability to probe extremely small sample volumes, this spectroscopy has become an indispensable experimental method in studying the magnetism of complex materials. Moreover, derivation of magneto-optical sum rules has greatly strengthened the XMCD, offering a unique capability to deduce from the experimental spectra the orbital and spin contributions to the total magnetic moment carried by the absorbing atom.

The existence of x-ray natural circular dichroism (XNCD) in chiral systems was first demonstrated in 1998. The effect stems from the interference terms which mix multipole transition moments of opposite parity: the Electric Dipole-Electric Quadrupole (E1.E2) and the Electric Dipole-Magnetic Dipole (E1.M1) and could be observed only in structures with broken space inversion symmetry. XNCD offers a unique possibility to study chirality of matter at the atomic level and can give access to the absolute configuration of chiral absorbing centers. Moreover, exploitation of small x-ray beams available at extremely brilliant synchrotron sources allows XNCD mapping of chiral twins in crystals with submicron resolution. Finally, a fascinating interplay of magnetism and structural chirality is manifested with x-ray magnetochiral dichroism (XMχD) that was experimentally evidenced in 2002. This dichroism is observable in magnetoelectric systems or chiral molecular magnets and is polarization independent phenomenon. Sum rules applied to the experimental XMχD spectra give access to the orbital toroidal moment carried by an absorbing atom.
The most prominent examples are selected to show applications of these advanced x-ray spectroscopies to solve current problems in physics of solids and chemistry.

3) EXAMPLES OF APPLICATIONS

From spintronics to molecular nanospintronics

Prof. Franck Balestro

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The continuous progress in patterning, instrumentation and simulation over the past decades has made possible the investigation of low-dimensional magnetic elements such as thin films and nanostructures. New properties arise in these due to the reduction of dimensionality and the ability to build artificial stackings. Beyond the development of fundamental knowledge, these bring new functionalities of interest for technology. Such is the case for Giant Magneto-Resistance, an effect combining together electronics and magnetism, as the resistance of a stacked device may strongly depend on the arrangement of magnetization in the sub-stacks. It was discovered in the mid 80's and led to the Nobel prize in Physics in 2007, and enters many applications such as magnetic sensors and encoders, data storage and processing. In the race of miniaturization, molecular spintronics is an interdisciplinary field at the interface between organic spintronics, molecular magnetism, molecular electronics and quantum computing, which is advancing fast and promises large expectations.

Semiconductor quantum devices

Prof. Natalia Ares

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The development of semiconductor quantum devices that can be controlled with exquisite precision and in time scales as short as tenth of nanoseconds is opening up exciting possibilities both for the advancement of novel technologies and for answering fundamental questions in quantum mechanics and quantum thermodynamics.
I shall give an overview of the techniques developed to control semiconductor quantum devices, with their strengths and limitations. I shall also discuss the potential of these devices to be the building blocks of complex quantum circuits, which are required for the realization of quantum computing among other quantum technologies. To conclude, I shall show exciting findings from experiments performed in semiconductor quantum devices, including one from our lab in which we revealed the thermodynamic cost of timekeeping.

Chemistry and molecular functional materials

Prof. Jesper Bendix

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Synthetic chemistry holds the key to unlocking the potential of miniaturization and bottom-up approaches to functional materials. The ultimate goal of property engineering requires synthetic control, however, the level of control achieved in synthetic organic chemistry is nowhere reached for the synthesis of inorganic molecule based materials. The lectures and discussion will be centered on strategies towards enhanced synthetic control for coordination compounds. Specifically, focus will be on ways of tailoring local symmetry, exchange pathways and topologies of polynuclear systems.