The National High Magnetic Field Laboratory

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Abstract. The National High Magnetic Field Laboratory, established in 1990 with support from the National Science Foundation, the State of Florida, and the US Department of Energy, is a facility open to external users around the world. The experimental capabilities are distributed in three campuses. In Tallahassee, Florida, continuous magnetic fields are produced by means of superconducting and resistive magnets reaching fields of up to 33T (resistive), and 45T (hybrid). EMR, ICR, and a 900MHz wide bore NMR magnet are also available. The facility in Gainesville, Florida, is devoted to generating extremely low temperatures in the presence of external magnetic fields (15T, down to 0.4mK), and large MRI imaging capabilities. In Los Alamos, New Mexico, a 9 kV-capable capacitor bank and a number of different liquid Nitrogen-cooled resistive magnets produce repetitive pulses up to 75 T and now a single-shot pulsed up to 300T.

1. NHMFL sites and capabilities
The National High Magnetic Field Laboratory (NHMFL) is a world class facility open to qualified national and international researchers in areas such as physics, materials science, geoscience, chemistry and bioscience. The NHMFL main goal, sponsored by the National Science Foundation (NSF) and the State of Florida, is to develop experimental capabilities that drive and support the highest quality scientific research at the highest achievable magnetic fields, and to facilitate the opening of new regions of parameter space to explore magnetic phenomena. It is the largest and highest powered magnet laboratory in the world, outfitted with the world’s most comprehensive assortment of and highest performing magnet systems, many of which were designed, developed and built in house in collaboration with industry partners.

The NHMFL at Florida State University (FSU) houses the main facilities of the laboratory in a 330,000 sq. ft. complex in Tallahassee, Florida. This complex houses the continuous field magnets of the NHMFL, a Condensed Matter/Theory Group, a Condensed Matter NMR Group, a Magnet Science and Technology Group, the Center for Interdisciplinary Magnetic Resonance, and the Geochemistry facilities. This facility is powered by a 40 million watt (MW) power supply that is highly regulated and represents 10 percent of Tallahassee's total generating capability. The user program operates 12 magnets, including 2 superconducting magnets that operate up to 20 T, 9 resistive magnets that produce up to 33 T with bore diameters varying with design from 195 mm to 32 mm, and one 32mm-bore 45T hybrid magnet, unique in its class and the crown jewel of the NHMFL. These magnets are complemented with portable dilution 3He/4He, pumped 3He and 4He refrigerators, in addition to a broad selection of solid state physics probes such as pressure cells, millimeter and sub millimeter wave resonant cavities, magnetooptics, magnetometry and magnetotransport adapted for operation at
high fields. In addition, the NHMFL site at FSU also hosts the Center for Interdisciplinary Magnetic Resonance (CIMAR), a large-scale integration of NMR, MRI, EMR, and ICR spectroscopies, and a program in geochemistry centered around the use of trace elements and isotopes to understand the Earth processes and environment.

Figure 1: a) The Fabry-Perot geometry photonic-bandgap resonator with waveguide coupling. b) A $\chi$-(BEDT-TTF)$_2$Cu(SCN)$_2$ sample loaded in the dielectric resonator. c) The GHz-frequency magnetoconductivity measured at 2.1K and a frequency of 64-GHz, in a pulsed magnet. Note the Josephson plasma resonance at low field and the quantum oscillations at higher fields. The insets show the Fourier spectrum of the quantum oscillations and the associated Fermi-surface orbits. d) Magnetic field profile (red, left y-axis) and Faraday rotation signal (blue, right y-axis) obtained in the single turn coil. The inset sows the copper coil.

The NHMFL's sister university at University of Florida (UF), Gainesville, Florida, is home to user facilities in magnetic resonance imaging (MRI) and ultra-low temperature, ultra-quiet environment for experimental studies in the High B/T (high magnetic field/low temperature) Facility. The MRI and spectroscopy capabilities of the NHMFL are located at UF in the Advanced Magnetic Resonance Imaging and Spectroscopy (AMRIS) facilities. AMRIS is part of the McKnight Brain Institute and house a wide variety of state-of-the-art instrumentation for studies including biological solid-state NMR, solution NMR, microimaging, animal imaging, and human imaging. In addition, a 750 MHz wide bore NMR/MRI magnet system is capable of taking very high quality 3D images. The High B/T Facility housed within the UF Microkelvin Laboratory provides experimental capabilities for studies requiring temperatures just above absolute zero (0.4 mK) and fields up to 20 tesla.

The NHMFL Pulsed Field Facility (NHMFL-PFF) is located within Los Alamos National Laboratory in New Mexico. The NHMFL-PFF is an integral component of the NHMFL, providing researchers with experimental capabilities in non-destructive capacitor-bank driven pulsed magnets producing fields to 75 T. A 100 T multi-shot magnet is being developed jointly by the Department of Energy and the NSF. The pulsed power infrastructure that drives these unique magnets includes a 1.43 gigawatt motor generator and five 64 megawatt power supplies. The 1200-ton motor generator is the centerpiece of the NHMFL-PFF and its first task is to power the 60 T Long-Pulse magnet. A broad variety of experimental probes including magnetotransport, magnetization, quantum oscillations, ESR/EPR, specific heat, EPR, optical spectroscopy and photoluminescence have been adapted for
pulsed field operations by NHMFL scientific and technical staff members. Two of the most recent additions to the NHMFL-PFF capabilities are EPR measurements and a single-turn coil magnet.

Probing the excitations of correlated electron systems in high magnetic fields provides invaluable insight into their behavior. In many systems of interest, the energy scale of these excitations corresponds to light with a frequency $60\text{GHz} \approx 3\text{K} \approx 1/4\text{meV}$. Members of the NHMFL-PFF have developed novel non-metallic GHz-frequency apparatus enabling the extension of complex conductivity measurements to pulsed magnetic fields. The observation of quantum oscillations in the GHz conductivity of an organic superconductor (see fig 1a-c) exemplifies the sensitivity of the microwave resonator system. These techniques probe also the sample permittivity and permeability allowing measurement of insulating systems and spin physics.

A new Ultra-High magnetic field capability extends condensed matter physics experimentation to fields beyond 100 T. This magnetic field generation system is based on the single turn coil technique [ref O. Portugal], a method that employs a low inductance “fast” capacitor discharge circuit capable of circulating electrical currents approaching 4 MA in a ~10 µs duration pulse. The copper magnet coil is destroyed with the pulse, but the sample and cryostat survive since the Lorentz forces are directed radially outward. Dynamic finite element models of the containment structure as well as the electrical collector bus predict that the system is capable delivering 10,000+ full energy pulses. The coil inside diameter is 10 mm, which results in a sample space of 5.3 mm at a base temperature of 2.5 K. Experimental techniques under development include magnetic susceptibility, radio frequency electrical transport, GHz conductivity/transmission, and visible optics spectroscopy. Figure 1d shows a proof of principle optics experiment in which the magnetic susceptibility of terbium gallium garnet (TGG) is measured via the Faraday rotation effect in fields well above 100 T.

2. Exciting Physics at high fields

A strong research program accompanies the state of the art experimental capabilities of all three branches of the NHMFL, as evidenced by the number and quality of results submitted by users and NHMFL personnel for publication in peer-reviewed journals. More than 35 publications in the Physical Review B/Letter and one in Nature where reported just in the first half of 2006 for all three facilities (with an average of 88/year for the last 6 years). Space limitations prevent us from giving a proper account of all topics being explored theoretically and experimentally at the NHMFL at the time of writing this manuscript, and we are forced to mention just a couple of examples.

Torque magnetometry experiments performed at the DC Facility in Tallahassee in the quantum spin system BaCuSi$_2$O$_6$, also known as Han Purple, were used by S. Sebastian and I. Fisher from Stanford University, N. Harrison, C.D. Batista and M. Jaime from Los Alamos, L. Balicas from NHMFL-Tallahassee, and collaborators, to explore the very low temperature critical exponents when a magnetic field is used to tune a magnetic quantum critical point in the system. The phase boundary $(T_c,H_c)$ between a quantum paramagnetic state and a field-induced XY-antiferromagnetic state regarded as a Bose-Einstein condensate of magnons was measured in a dilution refrigerator, and a clever idea allowed for an independent determination of the zero temperature critical field $H_c$ and the critical exponent $\nu$ in the expression $T_c \propto (H-H_c)^{\nu}$ when the external magnetic field tunes $T_c \rightarrow 0$. Their results [2], show compelling evidence for a crossover from a 3D-BEC critical exponent $\nu = 2/3$ observed between 0.6 K and 1.5 K, to a 2D-BEC critical exponent $\nu = 1$ when the temperature is reduced below 0.6 K. The authors interpreted these results as consequence of both geometrical frustration built in the crystal lattice of BaCuSi$_2$O$_6$, and the presence of a magnetic quantum critical point at $H_c = 23$ T.

The recent discovery of an experimental method to separate out a single layer of atomically thin graphite layers ignited an intense experimental and theoretical research focus on graphene. Continuing initial efforts at Columbia, the accessibility of high magnetic fields up to 45 Tesla at NHMFL-Tallahassee now allowed Y. Zhang, P. Kim, Y. Tan, H. Stormer, and collaborators to study the magneto-transport in graphene in the extreme quantum limit [3]. Quantum Hall (QH) plateaus at filling factors $\nu = 0, \pm 1, \pm 4$ are discovered at magnetic fields $B > 20$ T, indicating the lifting of the
fourfold degeneracy of the previously observed QH states at $\nu = \pm 4(|n|+1/2)$, where $n$ is the Landau-level index. In particular, the presence of the $\nu = 0, \pm 1$ QH plateaus indicates that the Landau level at the charge neutral Dirac point splits into four sublevels, lifting sublattice and spin degeneracy. The investigators are presently focusing their efforts in increasing the mobility of graphene samples, in order to explore the possibility of a fractional quantum Hall regime.

The behavior of electronic phases of the second Landau level under tilted magnetic fields was recently investigated at ultra low temperatures at the High B/T facility at University of Florida, Gainesville by G. A. Csáthy and D.C. Tsui from Princeton University, J.S. Xia, C.L. Vicente from UF, L.N. Pfeiffer and K.W. West from Bell Labs among others. They report that the fractional quantum Hall liquids at $\nu = 2+1/5$ and $2+4/5$ and the solid phases at $\nu = 2.30, 2.44, 2.57$, and $2.70$ are quickly destroyed by increasing magnetic field angle. This behavior can be interpreted as a tilt driven localization of the $2+1/5$ and $2+4/5$ fractional quantum Hall liquids and a delocalization through the melting of solid phases in the top Landau level, respectively. The evolution towards the classical Hall gas of the solid phases, the authors speculate in an article published in the Physical Review Letters [4], is suggestive of antiferromagnetic ordering.

A extensive collaboration between researchers at Rice University, the LNCMP, Toulouse, France, NHMFL-PFL and NHMFL-Tallahassee used 75T pulsed fields to thread magnetic flux through the bore of a carbon nanotube; this breaks the time-reversal symmetry of the left- and right-circular wavefunctions around the nanotube, which results in a bandgap splitting that is observable in the absorption spectrum [5]. In these experiments, carried at Los Alamos by S. Crooker, near-infrared magneto-optical spectroscopy of single-walled carbon nanotubes reveals two absorption peaks with an equal strength at high magnetic fields (>55 T). They show that the peak separation is determined by the Aharonov-Bohm phase due to the tube-threading magnetic flux, which breaks the time-reversal symmetry and lifts the valley degeneracy. This field-induced symmetry breaking thus overcomes the Coulomb-induced intervalley mixing which is predicted to make the lowest exciton state optically inactive (or dark).

In an article recently accepted for publication A. Narduzzo and N.E. Hussey, from University of Bristol, F.F. Balakirev from NHMFL-PFL, S Horii from University of Tokyo, and collaborators report on the experimental realization of dimensional crossover phenomena in the chain compound PrBa$_2$Cu$_4$O$_8$ using temperatures between 1.5 K and 80K, pulsed magnetic fields up to 65 T and disorder as independent tuning parameters. In purer crystals of PrBa$_2$Cu$_4$O$_{8}$, a highly anisotropic three-dimensional Fermi-liquid state develops at low temperatures. This metallic state, Narduzzo et al. claim, is extremely susceptible to disorder however and localization rapidly sets in. They show, through quantitative comparison of the relevant energy scales, that this metal/insulator crossover occurs precisely when the scattering rate within the chain exceeds the inter-chain hopping rate(s), i.e. once carriers become confined to a single conducting element.

In summary, the National High Magnetic Field Laboratory has succeeded year after year since its creation in creating a fertile environment where the most challenging technical difficulties in producing the highest magnetic fields in the world motivate an ingenious team of engineers to create experimental conditions that are used by both theoretical and experimental scientists to attack topical problems in a variety of areas.

References
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