CHAPTER 2. RESEARCH REPORTS

An Overview

The Science Program of the NHMFL continued to grow in strength during 2000. Users and NHMFL faculty submitted 295 research reports in 16 categories, with interdisciplinary activities clearly on the rise. There also appears to be increased collaboration between in-house research staff and external users. Reports sponsored by the NHMFL In-House Research program are denoted by ◤**IHRP**◢ in the text.

The breakout of reports by category is as follows: biology (47), chemistry (27), cryogenics (5), engineering materials (6), geochemistry (13), instrumentation (16), kondo/heavy fermions (19), magnetism and magnetic materials (36), magnetic technology (6), molecular conductors (19), magnetic resonance techniques (19), other condensed matter (10), quantum solids (3), superconductivity applied (16), superconductivity basic (26), and semiconductors (27). We highlight research activities from these areas to give an overview of the projects underway at the laboratory. Other projects of comparable importance could have been chosen as the reader will see from this report.

Biology

The biological effects of magnetic fields on cell survival and animal behavior were studied by Haik *et al.* (page 28) and Houpt *et al.* (page 31). The first group found profound (7-fold) increases in the death rate of leukemia cells following exposure to 1 to 12 T fields for 2 hours. Thus, the potential of therapeutic applications of magnetic fields in treating some cancers is very real. The second study focused on the effect of magnetic fields on the sensory systems of animals exposed to magnetic fields. The increased usage of magnetic resonance imaging (MRI) coupled with the drive to higher fields demands reassessment of health hazards of high field exposure. Rats placed in the magnets developed taste aversion, balance problems, and walked in tight circles in the direction dictated by the direction of the field. Houpt and coworkers conclude that the vestibular apparatus of the inner ear might be perturbed, which should be looked for in human patients.

The development of a new technique in solid state NMR by Cross and his group (page 52) has generated much excitement. The cyclical correlation between the N-H dipolar interactions and the chemical shift PISA wheels (Polar Index Slant Angle) identifies uniquely the helical tilt and the rotational orientation of an α-helix in the lipid membranes. The method avoids lengthy

assignment procedures, which are a bottleneck in structure determination by NMR. Tian *et al.* (page 47) have applied the method to the influenza A virus M2 protein, which is a proton channel that plays a major role in replication of viral particles. They found that M2 was a homotetrameric complex with axial symmetry within the membrane. Considering the preponderance of α-helices in integral membrane proteins, PISA wheels might revolutionize the structure determination of membrane proteins.

Chemistry

Crude oil has until now defied attempts at detailed characterization. It contains thousands of chemically different constituents, and no single technique has been able to separate and identify them. In the report by Qian *et al.* (page 68), 3,000 different elemental compositions were resolved in a single positive-ion mass spectrum. A comparable number of different compounds has since been resolved in a single negative-ion mass spectrum. Elemental compositions, in turn, reveal the number of heteroatoms (O, N, and S), number of rings plus double bonds, and extent of alkylation of each molecular type, to yield the most extensive chemical characterization ever achieved for such a complex mixture by a single measurement.

The inherent timescale of an EMR experiment is inversely proportional to the frequency in use, thus higher frequencies allow for faster measurements. In time-resolved EMR, this enables the study of systems with very short lifetimes and/or fast relaxation rates. This prompted van Tol (page 258) to develop a new high field spectrometer with both fast detection and optical access for excitation of paramagnetic excited states and/or creation of paramagnetic reaction intermediates. The spectrometer operates at 120, 240, and 360 GHz. This last frequency of 360 GHz is 4 times higher than what is available outside the NHMFL. van Tol and Angerhofer from the University of Florida (page 76) used the new machine to study the lowest excited triplet state in free base porphyrin. Their results will enable a better interpretation of the measurements obtained in porphyrin-containing biological systems.

The double resonance character of the ENDOR technique has important advantages. The nuclear resonance is detected through the absorption changes of the electron magnetic resonance. Currently, ENDOR measurements are limited to about 100 GHz. Saylor and van Tol developed a spectrometer that works between 110 and 330 GHz. High field ENDOR will permit us to use the increase in g-factor resolution of high frequency EPR to map the angular dependence of the hyperfine interactions in a randomly oriented sample with a small g-value anisotropy. The added advantage will be to probe distances well over 10 Å, and to be able to study such low nuclei as 13C, 2H, 15N, and 31P. Together with Maniero, Maresch, and Brunel, van Tol and Saylor (page 71) studied a nitroxide radical with delocalized spin density. The simulations allow for much better accuracy in the determination of the g and A tensors components than single crystal work at lower frequency. For instance, one can distinguish the contributions from two protons that appeared identical at X band.

World record resolution has been achieved in resistive magnets by two complementary approaches. Brey and Murali of the NHMFL in collaboration with Warren at Princeton University and his postdoc, Lin (page 237) applied an intermolecular zero-quantum detection approach (Lin *et al.*, Phys. Rev. Lett **85**, 3732 (2000)). Gan *et al.* (page 252) at the NHMFL developed a HeteroNuclear Phase Correction method to compensate for phase fluctuations in the time-domain signals. Resonance line widths in signal averaged spectra approaching two orders of magnitude narrower than would be implied by the magnetic field temporal stability have been achieved (<0.04 ppm). Since resistive magnets reach field strengths far in excess of the stable and homogeneous superconducting magnets, these novel approaches to resolution enhancement open unique opportunities to observe solution NMR phenomena at very high magnetic field strengths that may not be available in superconducting magnets for decades to come.

Cryogenics

Liquid helium fluid dynamics continues to be a major focus area for cryogenics research. This work is particularly beneficial to large cryogenic installations such as particle accelerator facilities and future high field magnet facilities. Two reports, Choi *et al.* (page

277) and Fuzier *et al.* (page 278), focus on the study of He II at high Reynolds number. One of the fundamental questions in quantum fluid dynamics concerns the extent to which fluids like He II display classical behavior. In flow experiments in tubes and around spheres, these reports show that the pressure profile in He II is very similar to that which occurs in classical fluids. In the case of flow around a sphere, however, some temperature dependence is displayed, a result that suggests importance of superfluid properties. Such a result, if confirmed, would be in conflict with the results for flow in tubes. Further experiments are planned to confirm these findings.

Geochemistry

The past year has seen an increase in activities in environment-related research in the geochemistry division. Determining the impact of pollution and the onset of ecosystem changes requires reliable and early indicators of ecosystem change. Known early indicators are at the bottom of the food chain and are often based on micro-organisms. In the Everglades, the ecosystem is changed because waters with high phosphorous levels enter an ecosystem in which phosphorous is the limiting nutrient. Research by Wang and colleagues (page 87) in the Everglades has shown that the radiocarbon signature of dissolved organic matter can be taken as one of the earliest indicators of ecosystem change. Furthermore, the radiocarbon method allows a quantitative assessment of the progress of change in a single measurement. This makes this technique the method of choice to measure impact of land use change on the Everglades or to monitor the progress of a wetland restoration project.

Instrumentation

HENPEC approach toward high resolution NMR using the Keck Magnet (page 252). The high homogeneity (1 ppb) superconducting magnets used for analyzing chemical structures are limited by present technology to fields of about 20 T. DC resistive magnets reach fields more than twice that, but lack the required homogeneity and stability. Gan, Murali, and Brey in the NMR group of the NHMFL in Tallahassee have developed a method for cleaning up the signal from the nucleus of interest, using information about the field fluctuations and inhomogeneity obtained by measuring the signal from a nucleus in the solvent. Their "HENPEC" method leads to a proton line width of about 40 ppb, which is about one tenth as wide as the uncorrected width. If they succeed in their quest, researchers will be able to study larger molecules than are possible now.

Kondo/Heavy Fermion Systems

Making reliable physical measurements in pulsed high magnetic fields is an experimental challenge. Such measurements have been limited until recently to optical and transport measurements. The work of Movshovich *et al.* (page 137) and his collaborators now has extended the phase space of possible measurements to the very important thermodynamic property of specific heat. In particular, they have measured the specific heat in fields to 60 T of the Kondo insulator material $Ce_3Bi_4Pt_3$. Kondo insulators are an intriguing class of materials simultaneously at the magnetic/non-magnetic and metal/insulator boundary. Many interesting correlated electron materials appear to owe their unusual properties to proximity to a Kondo insulating state. The magnetic field response of these materials is of central interest in probing their underlying physics. A central question has been whether high magnetic fields drive an insulator/metal transition in such materials. Transport measurements do not provide a clean answer to this question, being dominated by impurity conduction. But the insulator/metal transition stands out clearly for the first time in the specific heat measurements, indicating a first order rather than second order phase transition.

Magnetism & Magnetic Materials

Major efforts in the area of magnetism have focused on exploring novel magnetic materials motivated by the potential for practical application. Thus, the physics of the colossal magneto-resistance in mixed valent perovskites has been the source of intensive study. This past year, however, has brought a breakthrough in our understanding of these complex materials. It is now broadly

accepted, based both on experimental and analytical grounds, that phase separation plays a dominate role in the metal to insulator transition.

A description of these physical ideas may be found in the article by Gor'kov and Kresin entitled *Metal Insulator Transition in Doped Systems as a Percolation Phenomenon* (J. Supercond., **13**, 239 (2000)). Many of the predictions in this article have now been confirmed, often quantitatively, in new studies by Dagotto, Hotta, and Moreo (page 198) (to appear in *Physics Reports* (2001)) using computational techniques. These include the origin of the mixed phases of different conductivity, as well as details such as the role of charge, electron orbital, and spin in the development of the complex phase diagrams found in the manganites. It is of significance that these calculations may find application also in standard (diluted) magnetic semiconductors, where phase separation (magnetic polarons) in lightly doped materials has long been known.

Magnetic Technology

A major focus of the research and development effort in Magnet Technology has been toward improving understanding and performance of high current density superconducting magnets. This activity is particularly valuable for future magnet systems such as high field NMR, high energy physics accelerators, and magnetically confined fusion applications. Several reports this year address the issues. Of particular interest to NMR magnet development are two reports by Dixon *et al.* on technology relevant to the 900 MHz magnet system: one involves mechanical properties of composites (page 273) and the other concerns the performance of a superconducting protection switch (page 272). This magnet system is unique and many of the associated components need to be developed and tested before they can become part of the final system. The results of these two tests add confidence that the 900 MHz magnet system will perform to expectation. Another report by Weijers and Schwartz (page 276) on the development of HTS insert coil technology is in support of future NMR magnet systems. After the 900 MHz NMR magnet, it is probable that future magnet systems will utilize HTS insert coils to exceed 1 GHz resonant frequencies. The present report focuses on developments with Ag/BSCCO test coils. Engineering current densities in excess of 200 A/mm^2 at 25 T have been demonstrated, a value that is sufficient for the present design of the 1.1 GHz magnet system. A design effort is underway for a 5 T prototype insert coil using HTS technology.

Molecular Conductors

Interesting results concerning the superconducting properties of layered organic compounds under field have been reported this year. Mola *et al.* (page 155) report magnetization measurements, at very low temperatures, in the mixed state of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, finding evidence for a crossover from a quantum melting to a thermally induced melting transition of the quasi-two-dimensional vortex lattice of this compound. Zuo *et al.* (page 165) report the angular dependence of the upper critical field (H_{c2}) of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ that exceeds the Pauli paramagnetic limit at low temperatures. The angular dependence of H_{c2} suggests an inhomogeneous two-dimensional superconducting state for this compound.

The angular dependence of the cyclotron resonance, along with its second and third harmonics, in the quasi-two dimensional organic superconductor β''-(BEDT-TTF)$_2$SF$_5$CH$_2$CF$_2$SO$_3$ is reported by Edwards *et al.* (page 148). The results of this study suggest that the Fermi surface of this layered compound is extended along the inter-plane direction, i.e., the interlayer charge transport is coherent. This is in contradiction with recent proposals concerning layered anisotropic organic as well as inorganic compounds. Furthermore, this conclusion seems to agree with a detailed analysis of the magnetic-field-angle dependent studies of the quantum oscillations (QOs) in a variety of quasi-two-dimensional organic metals reported by Symington *et al.* (page 161). In this study, a new attenuation factor (besides the usual damping factors given by the Lifshitz-Kosevich formalism) is proposed for the amplitude of the QOs along with a model that considers the variation of the density of states for scattering at the Fermi surface for a certain wave vector k_z. Also, in the β''-(BEDT-TTF)$_2$SF$_5$CH$_2$CF$_2$SO$_3$ organic metallic compound,

Symington *et al.* (page 163) reports the surprising observation of thermally-activated conductivity at integer Landau-level filling factors.

The previous discussion concerning the nature of the charge transport in layered organic compounds is particularly interesting at the light of the magnetotransport study, reported by Storr *et al.* (page 157), in a τ phase organic conductor. In this compound, Shubnikov de Haas oscillations are reported for the first time, which is a signature of Fermi liquid coherent transport. On the other hand, the angular dependence of the fundamental frequencies of the QOs, the angular dependence of the magnetoresistance, jointly with the absence of frequency beatings in the QOs suggests a FS, which is strictly 2-D. In other words, in this compound the inter-plane charge transport, in contrast with the in-plane one, seems to be incoherent.

The quantum Hall effect associated to the cascade of field-induced spin-density waves (FISDW) has been investigated in detail as a function of field and hydrostatic pressure in the $(TMTSF)_2ReO_4$ compound by Kang *et al.* (page 153). In addition to the previously known "negative" Hall step around 15 T, two more new negatively indexed quantized states have been detected. The negatively indexed phases form their own quantum Hall sequence, *independently* from the positively indexed states. These experimental findings cannot be explained by the so-called "standard" or quantized nesting model that successfully describes the FISDW phase diagram in $(TMTSF)_2PF_6$. This clearly indicates that the superlattice potential, due to the ordering of the ReO_4 anions, affects the original geometry of the Fermi surface playing an important role in this system.

Surprising new experimental results by Harrison *et al.* (page 151) indicate that the high field phase of α-$(BEDT\text{-}TTF)_2KHg(SCN)_4$, and its sister compounds, closely resembles an inhomogeneous superconductor. Notably, AC susceptibility measurements reveal a strong and hysteretic diamagnetic response at high fields at integral Landau level filling factors, precisely where the interlayer resistivity decreases by approximately two orders of magnitude. These observations are quite surprising since this phase has been suggested to be the charge-density wave analog of the Larkin-Ovchinnikov-Farrel-Fulde phase for the superconducting state.

Interesting properties have been observed in magnetic organic conductors like, for example, κ-$(BETS)_2FeBr_4$ or λ-$(BETS)_2FeCl_4$. In these systems, the main goal is to understand the interaction between localized magnetic moments (Fe *d* electrons) and the itinerant low dimensional π electron gas. A very close proximity between antiferromagnetic and superconducting phases has been observed. For example, in the κ-$(BETS)_2FeBr_4$ compound a Néel transition is observed at 2.5 K followed by a superconducting transition at 1.1 K. The Fermi surface (FS) derived from Shubnikov de Haas studies (Balicas *et al.*, page 144) is at odds with band structure calculations, indicating FS reconstruction at the Néel temperature TN, the temperature at which the localized Fe moments order antiferromagnetically. Unusually high effective masses were obtained. Both observations suggest a strong coupling between itinerant and localized spins. In the λ-$(BETS)_2FeCl_4$ compound, the ordering of localized moments is associated to a metal-insulator transition at $T_{MI} \cong 8.0$ K. This insulating antiferromagnetic state is suppressed by the application of a magnetic field (~10 T) that converts the system into a paramagnetic metal.

Magnetic Resonance Techniques

The NHMFL NMR Program is one of the few laboratories that developed PISEMA, a breakthrough in lipid proteins structure determination. PISEMA allows researchers to obtain structural information without making resonance assignments.

In an interdisciplinary work, the NHMFL included solutions of the stochastic Liouville equation (SLE) in the GAMMA platform. This project, involving Smith and Fajer from the NHMFL and Khairy and Budil from Northeastern University (page 245) successfully tackled the challenge of dealing with matrices whose size grows rapidly with the number

of spins involved. These solutions are unapproachable except with GAMMA, an object oriented technique.

Other Condensed Matter

There has been considerable recent interest in the behavior of complex classical systems, for example, the static and dynamic properties of aggregates of granular materials and the mix of classical and chaotic behavior. There has also been a great deal of interest in both the application and physics of magnetic levitation at high fields and large field gradients. Brooks *et al.* (page 222) combined these factors in the study of the trajectories of graphite-composite particles perturbed from their equilibrium positions under the balanced conditions of magnetic levitation. The surprising findings include an amplitude modulation of the oscillations at a frequency of about 0.2 Hz with large fluctuations reminiscent of chaotic behavior superimposed on the classical. The fluctuations were shown not to be due to the temperature gradient driven convection as expected, since the same fluctuations are also present in vacuum. They speculate the fluctuations may arise from fluctuations in the magnetic field coupling to the conducting particles.

Studies of systems at high B/T where the lowest Landau are predominantly populated and Shubnikov-de Haas oscillations are observed have been of considerable current interest and importance in understanding the details of the band structure predictions. Hebard *et al.* (page 225) have studied the oscillations in high purity Bismuth crystals at 20 T and 20 mK. These measurements show that for Landau levels 2 or smaller the carriers are fully polarized. The magnetoresistivity shows an inverse quadratic temperature dependence, inconsistent with the linear dependence predicted by the two band model of a perfectly compensated metal, and requires rethinking the theory.

A very recent development has been a series of NMR experiments in the NHMFL Hybrid Magnet, extending the NMR technique to 42 T, far beyond any previous work. Clark *et al.* (page 224) studied the spin density wave (SDW) fluctuations in the quasi 1-D system $(TMTSF)_2PF_6$ by proton NMR to 34.8 T. Above the SDW transition the data indicate that amplitude fluctuations drive T_1, while below the SDW the power spectrum of the phason fluctuations is observed. Reyes *et al.* (page 101) studied the spin fluctuations in $NdBa_2Cu_3O_7$ by ^{17}O, where Nd is a magnetic ion in contrast to the Y compound.

Quantum Solids

Magnetic Ordering in ^{3}He Nano-Clusters, Adams *et al.* (page 125). The magnetic susceptibility of nano-clusters of ^{3}He imbedded in a ^{4}He matrix has been measured from 10 mK down to 0.5 mK. Applied pressures extend from 2.88 MPa, for which the clusters form as liquid droplets upon phase separation of the mixture, to 3.54 MPa, for which the clusters are entirely solid. At intermediate pressures, partial melting of the clusters was observed, with a solid fraction remaining in the region below the melting pressure where only liquid would be expected. A peak in the susceptibility occurs at about 1.0 mK, which is near the ordering temperature of pure bulk ^{3}He at melting pressure. However, the temperature and field behavior of the susceptibility indicated that the clusters are not ordering in the U2D2 structure of pure bulk ^{3}He. This work suggests that there may be significant surface effects, possibly because of the van der Waals attraction of the dense hcp phase of the surrounding ^{4}He matrix. Leading challenges, on which this work has shed light but which have yet to be resolved, are to understand how the solid fraction exists at pressures below the bulk melting pressure and the effects on the ordering caused by the interface with the ^{4}He.

Superconductivity Applied

One of the leading challenges in the quest for superconducting magnets at 25 T is the development of a conductor that is capable of satisfying the electrical, magnetic, thermal, and mechanical requirements of the system. Ultimately, the critical current density (J_c) in magnetic fields up to 25 T is the primary performance characteristic that requires improvement. The accessibility of very high magnetic fields makes the NHMFL user facility a critical element in the development of new high field superconductors. Here, two competing approaches report significant progress: alloyed Nb_3Sn low

temperature superconductor and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) high temperature superconductor. Results from these reports indicate that a 25 T superconducting magnet is a realistic goal within the next few years.

Researchers at Oxford Instruments – Superconducting Technology (OI-ST) (page 110) report increases in the upper critical field (B_{c2}) of Nb_3Sn alloyed with Ti, Cu, Ta, and combinations thereof. By increasing B_{c2}, the corresponding J_c at high field also increases. Their results show that, with proper alloying and heat treatment, the non-Cu J_c is comparable to that of Nb_3Al, which is often considered the lead candidate of the A15 materials for high field magnets. If the high field properties of alloyed Nb_3Sn meet or surpass those of Nb_3Al, then the cost of high field magnets will be more acceptable.

Research at the NHMFL, in collaboration with OI-ST (page 115), has focused on the development of Bi2212 high temperature superconductor for a 5 T insert coil that will be tested in a 19 T background field at the NHMFL. They report significant improvements in the critical current and critical current density over the conductor previously used for the 3 T insert coil. Furthermore, they report microstructural improvements resulting from the addition of Ba to the superconducting powder. Modeling of the transport properties, which was performed in collaboration with scientists at the University of Twente, Netherlands (page 120), shows clear delineation between the weak-link and strong-link current limits within the HTS materials, thus giving a more fundamental understanding to the current limiting behavior of the material and insight into future improvements.

Superconductivity-Basic

Shibauchi *et al.,* (page 103) studied the pseudogap in $Bi_2Sr_2CaCu_2O_{8+y}$ in Zeeman splitting in high magnetic field. The existence of a pseudogap in the region above T_c is a key feature at low doping concentration. Using a wide range of doping, the closing of the pseudogap was studied by measuring the c-axis resistivity as a function of field. The results show a pronounced difference between the field temperature diagram of the pseudo gap and the superconducting state versus a simple Zeeman scaling of the field at which the pseudogap closes and the pseudogap temperature. In lightly doped material, the field dependence of the c-axis resistivity shows a peak that arises from a competition between two tunneling channels corresponding to Cooper pairs at low field and quasi particles at high field. The doping dependence of the low temperature field at which the pseudogap closes and the zero field pseudogap temperature leads to the conclusion that the magnetic field couples to the pseudo gap by the Zeeman energy of the spin degrees of freedom, thus the high field produces spin triplet excitations which are responsible for the suppression of spin singlet correlations responsible for the pseudogap and that the orbital contributions is small.

The existence of a magnetic field induced admixture of a d_{xy} component in the pairing of the $d_{x^2-y^2}$ state has been studied by Hirshfeld *et al.* (page 95). Using a perturbation approach, they obtained the free energy for a superconductor between the upper and lower critical fields. In contrast to the pure $d_{x^2-y^2}$ structure of a single isolated vortex, the behavior of the d_{xy} component leads to superfluid velocity gradients and an orbital Zeeman effect which compete in determining the vortex state. The theory was extended to the many vortex state by including the Doppler shift of the quasi particles. This leads to different thermodynamic behavior under suitable circumstances.

The infrared spectroscopy of $La_{2-x}Sr_xCuO_4$ was studied in high magnetic field by Dordevic *et al.* (page 91). C-axis spectroscopic measurements were carried out in fields up to 17 T. In this configuration, they observed shifts of the Josephson plasma edge showing a substantial decrease of the superfluid density with magnetic field.

The topology of the Fermi surface of the organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ has been studied by Symington *et al.* (page 106) using Fermi surface traversal resonances. These studies reveal corrugations of the Fermi surface that have been previously undetected. These effects are of importance in spin fluctuation theories

of superconductivity because nesting enhances the antiferromagnetic fluctuations responsible for pairing. The isotope effect on the Fermi surface topology has been studied with magnetic breakdown being much more prominent in the deuterated samples than the hydrogenated material. These results favor the spin fluctuation mechanism of $d_{x^2-y^2}$ pairing as opposed to the phonon mechanism of low temperature superconductors as the origin of the isotope effect.

Semiconductors

Probing Anisotropic States at ν = 9/2 and 11/2 in a Square Well Quantum Hall Sample. Over the last few years, one of the central problems in the study of the two-dimensional electron gas in a magnetic field has been understanding the nature of the anisotropic states observed at high, even-denominator filling fractions (ν = 9/2, 11/2, etc.). These anisotropic states are characterized by an "easy" direction in which the resistance is low, and a "hard" direction in which the resistance is high. One plausible theoretical description for these states is that a unidirectional charge density wave forms at these filling fractions, and detailed Hartree-Fock calculations have shown that this is possible. But the question remains: How can one prove this description is correct?

The report by Pan *et al.* (page 182) represents an important step toward addressing this question. It summarizes experiments performed at the NHMFL on the formation of anisotropic states in a square well quantum Hall sample in which more than one electronic subband is occupied. While the addition of a second subband may seem to be an added complication, it actually provides a unique opportunity to test the theoretical models of these anisotropic states. Pan *et al.* observe that, upon tilting the magnetic field, the "easy" direction of the anisotropic state is oriented parallel to the in-plane component of the magnetic field (provided this component is less than 10 T). This is the exact opposite of what has been observed in single subband samples, but it is precisely what the theoretical calculations predicted should happen for a multi-subband sample. As the in-plane field is increased beyond 10 T the "easy" direction reorients, this time perpendicular to the in-plane field, and this reorientation is again consistent with the theoretical calculations. The fact that such complex behavior agrees so well with theoretical calculations strongly suggests that the charge-density wave description of the anisotropic states is correct.

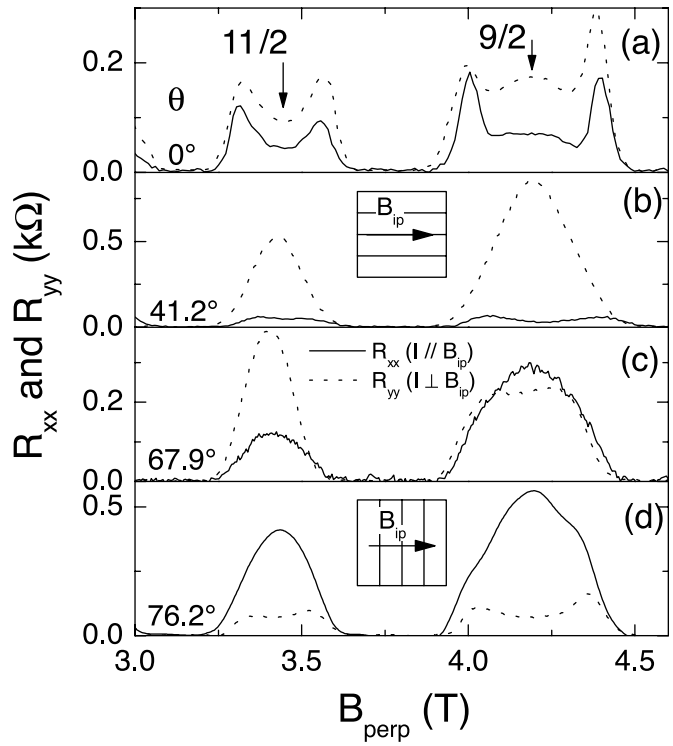

Figure 1. R_{xx} and R_{yy} as a function of in-plane magnetic field, B_{perp}, at filling fractions ν = 11/2 and 9/2 for a square well quantum Hall sample in which two electronic subbands are occupied. The complex behavior is in quantitative agreement with theoretical models based on the formation of a unidirectional charge density wave.