Florida State University • University of Florida • Los Alamos National Laboratory

NHMFL REPORTS

National High Magnetic Field Laboratory

WINTER 1999

Volume 6 • No. 1

From the Chief Scientist's Desk

Robert Schrieffer

Previewing the 1998 NHMFL Annual Report—Volume 1, Research

The first volume of the soon-to-be-published NHMFL Annual Report is dedicated to the expanding science and research activities of the laboratory. This significant publication should be available in printed form and on the internet (*www.magnet.fsu.edu/publications/1998annualreport*) by mid-March. Volume 2 addresses the progress of specific program areas of the laboratory and will be published in late summer.

Volume 1 presents 293 brief reports from fifteen scientific disciplines, including biology, chemistry, geochemistry, materials engineering, magnet technology, cryogenics, and all aspects of condensed matter physics. While the growing number of reports is noteworthy—a 15 percent increase over last year—the quality and interdisciplinary nature of the research activities are greater measures of the strength and maturity of the scientific program of the laboratory.

We are pleased to focus this issue of *NHMFL Reports* on several projects included in our Annual Report that are of broad interest. There are many others that could have been highlighted and reprinted here, as readers of the comprehensive Annual Report will see. A summary of the work follows, and the reports themselves appear elsewhere in this newsletter.

Biology

One of the most fundamental processes in cellular communication is the controlled flow of ions across the membrane of a cell in response to external stimuli. In particular, virtually every activity in the brain or peripheral nervous system involves flows of ions across cells to create small electrical currents and changes in voltage of the cell. The presence of such currents has

BIOLOGY continued on page 3

Chemistry

A most important challenge in analytical chemistry has been the development of experimental techniques with which one could determine the atomic composition and structure of complex chemical systems such as proteins and fossil fuels. In terms of mass resolving power, the progress in this area has been hampered by the lack of techniques with mass resolution above 1,000,000. Recently,

CHEMISTRY continued on page 3

Superconductivity—Basic

The study of fluctuation effects in high temperature superconductors can shed light on many of the important issues surrounding the nature of the superconducting state, including the effective dimensionality of the sample and the symmetry of the superconducting order parameter. With a well controlled theoretical model of the effect, one can also often extract important materials

SC-BASIC continued on page 3

From the Director's Desk

Before addressing plans for the future of the laboratory, I want to recognize, one final time, the efforts of the late Governor Lawton Chiles on behalf of the National High Magnetic Field Laboratory. As most of you are probably aware, the Governor passed away unexpectedly on December 12, 1998.

Governor Chiles was a strong supporter of the laboratory from the beginning, and his commitment was marked in many ways. During the difficult budget years in the State of Florida, it was Governor Chiles who made the NHMFL one of the highest priorities within the budget process and instructed then Chancellor Charles B. Reed that he would work within restricted budget constraints. In 1992, the NHMFL was the only item in the State University System budget that received full funding. Governor Chiles frequently touted the NHMFL as a symbol of the new "high tech" Florida that he envisioned, and he chose the laboratory as the site for several economic development and *Enterprise Florida* summits.

The Governor's commitment to the laboratory endured long after the laboratory's dedication in 1994. He was particularly supportive during NSF external reviews and, during the renewal site visit in the fall of 1995, his speech about the laboratory and Florida's commitment to it was remarkably eloquent. I was astounded by his comments, as he used no talking points. I have been told by members of the External Review Committee and NSF that the commitment of Florida—symbolized by Governor Chiles' presence and presentation—were major factors in the extremely positive review and the 50% funding increase received by the laboratory for the second five-year period.

Governor Chiles served Florida and the United States for most of his life. In recognition of his steadfast support for the laboratory, NHMFL colleagues made a donation to The Lawton and Rhea Chiles Center for Healthy Mothers and Babies at the University of South Florida. This organization supports programs for prenatal and young children, helping the next generation get a good start in life. If members of the extended NHMFL community would like information about making similar donations—either individually or collectively—please do not hesitate to contact me.

With the staunch support of Governor Chiles, Chancellor Reed, and many others, the NHMFL is now well established as a world-class facility for magnet-related research and technology. At this juncture, however, the *future* of the laboratory is at hand. During 1999, the NHMFL will be developing its second five-year renewal proposal to NSF. To this end, the leadership and faculty of the laboratory are holding a series of retreats and meetings to develop the vision that will shape the laboratory for the next decade. In addition, NHMFL facility managers are canvassing users, and several meetings with the NHMFL Users' Committee and External Advisory Committee are scheduled that should prove to be invaluable.

Most of our discussions will be focused along the following lines:

- What are the *critical* scientific and technological problems that need solving during the next decade or two? These would be issues that do not necessarily relate to your specific area of science and research.
- Are there fundamental contributions that research in high magnetic fields can make toward solutions to these problems?
- How can the laboratory better serve the user community through the development and implementation of innovative instrumentation that would open new scientific opportunities?
- On the always difficult topic of *priorities* and *resources*: From your perspective, what facilities, services, faculty hires, and so forth, should the laboratory be looking at in the next five years; in other words, how can we improve what we offer you and other users of the laboratory. For one example, see Bruce Brandt's discussion of a horizontal bore, split coil, radial access magnet in the DC Fields Facility in Tallahassee (*Attention Users*, page14).

I strongly encourage you, as members of the worldwide science and engineering communities, to join this important discussion through the NHMFL Users' Committee, through NHMFL facility directors, or through conversations with NHMFL faculty.

Jack Crow, Director and Co-Principal Investigator, FSU
Don Parkin, Co-Principal Investigator, LANL
Neil Sullivan, Co-Principal Investigator, UF

WINTER

BIOLOGY continued from page 1

been known and measured for years. Recently, electro-physiologists have developed techniques in which the currents from single ion channels can be directly measured, yielding a detailed understanding of the kinetics and activation profiles of these channels. Despite the wealth of physiological data, almost nothing is known about the underlying "black box" controlling these currents and the types of ions that can pass. Cross and coworkers are making significant advances in cracking open the "black box." Over the last several years, the Cross laboratory has generated the highest resolution structure of a membrane ion channel, gramicidin A. Using the detailed structural information from gramicidin A, the Cross laboratory is now using high field NMR to make strong inroads toward explaining its function, including the mechanism of binding cations, the role of water in cation transport, and the observed specificity of cation selection. Results from the structural studies of the relatively simple gramicidin A will provide important insights into the functions of much more complicated channels whose detailed structures are not expected for some time.
See Tian *et al.*, page 5.

CHEMISTRY continued from page 1

however, Marshall and coworkers have helped solve this problem by enhancing the mass spectral resolution to 8,000,000. This record-setting resolution enhancement has been made possible by the availability of a wide bore, 9.4 T magnet at the NHMFL. Utilizing this spectrometer, Marshall, Rogers, White, McIntosh, Andersen, and Hendrickson, were able to determine the structure of a tumor suppressor protein and the difference in the structures of a system as complex as diesel fuel before and after sulfur-removal through chemical processing. Such a study would not have been possible without this added resolution. These studies thus open a whole new avenue for the understanding of the chemical structure and reactivity patterns of complex biological and chemical systems with an accuracy as well as sensitivity unsurpassed by any other structural characterization methodology.
See Marshall *et al.*, page 6.

SC-BASIC continued from page 1

parameters such as the coherence length and the magnetic penetration depth. In many cases, however, the interpretation of the data is complicated, since there may be many different contributions to the property being measured. For instance, for the conductivity there is the "Aslamazov-Larkin" contribution as well as the "Maki-Thompson" term, and unraveling these competing effects is difficult. In addition, Varlamov and collaborators have discovered a "density of states" contribution, which was apparently overlooked in earlier theoretical treatments of these phenomena; experimental evidence for this effect in transport measurements has been indirect.

The recent high-field NMR measurements of the Pauli spin susceptibility and the spin-lattice relaxation rate in YBCO by Bachman *et al.* address exactly the issues raised above. For symmetry reasons there is no Aslamazov-Larkin contribution to the spin lattice relaxation rate, and the fluctuation effects are dominated by the density of states contribution, which simplifies the analysis. By comparing to a theoretical model that accounts for the effects of high magnetic fields (by summing over Landau levels) as well as Fermi liquid effects, the authors show that their data is only compatible with a superconducting state in which the order parameter

SC-BASIC continued on page 4

SC-BASIC continued from page 3

has d-wave symmetry, and in which the fluctuations are effectively two dimensional. This work could also have implications for our understanding of the "pseudogap" phenomena in the underdoped cuprate superconductors, which may involve exactly the sort of density of states suppression that the authors have observed in these experiments.
See Bachman *et al*., page 7.

Quantum Solids

One of the challenges in studies of the quantum solids formed by solid hydrogens has been to determine the nature of their order/disorder transitions in two dimensions (2D). Ortho hydrogen molecules are quantum rotors with angular momentum J=1, and as a result of intermolecular interactions are expected to order orientationally at extremely low temperatures. Because of the frustration of the interactions, new 2D locally ordered quadrupolar states were predicted. High sensitivity NMR studies have been used to show that long range order is obtained only for high ortho concentrations, and with the introduction of 32% disorder (by dilution with para hydrogen molecules, J=0) a new two dimensional spin-1 glass state has been observed.
See Sullivan and Kim, page 8.

Kondo Effect and Heavy Fermions

A leading experimental challenge in measurements at high magnetic field is that of obtaining data that is of direct use in theoretical models. This problem is particularly acute in pulsed high fields where the short duration of the pulse severely limits the kinds of measurements possible. The main experimental probe here in condensed matter has been electrical resistivity and, more recently, certain optical measurements. In the past year, a significant development has been heat capacity measurements by Jaime *et al.* in the NHMFL's new 60 T Long Pulse magnet at Los Alamos. They have succeeded in measuring the heat capacity of an interesting intermediate valence material $YbInCu_4$ that undergoes a field induced first-order phase transition. They also operated their experiment in a mode where the pulsed field was operated either in sweep mode or at a series of steps and found that thermal equilibrium could be achieved. The heat capacity allows a determination of entropy changes that are of crucial relevance to any theoretical model. This experimental innovation has now significantly widened our experimental phase space in pulsed magnetic fields.
See Jaime *et al*., page 9.

Semiconductors

Among the wide range of semiconductor experiments performed at the NHMFL, we call particular attention to two projects resulting from new capabilities at the NHMFL that have enabled the extension of research in two dimensional electron systems. The first report by W. Pan *et al.* summarizes experiments on the fractional quantum Hall effect (FQHE) in a high quality GaAs/$Ga_{1-x}Al_xAs$ sample at extremely low temperatures (4 mK) in magnetic fields up to 15 T. The observation of a fully developed FHQE state at ν = 5/2 featuring vanishing resistivity R_{xy}, relied on the availability of extremely low temperatures produced by the nuclear demagnetization refrigerator at the NHMFL High B/T Facility at the University of Florida. Substantial high magnetic field research supports the existence of a degenerate system of composite fermions at half integer filling in the lowest Landau level. The results of Pan *et al.* indicate that the ground state at half integer filling in the second Landau level is instead a two-component fractional quantum Hall state.
See Pan *et al*., page 12.

The second report, Crooker *et al.*, describes photoluminescence measurements on recently available magnetic semiconductor quantum wells using the newly-commissioned 60 T Long Pulse magnet at Los Alamos. Due to the presence of Mn ions in the quantum well, the two-dimensional electron system becomes highly spin polarized even at low magnetic fields. In this regime Zeeman shifts of the photoluminescence peaks do not follow the anticipated Brillouin-function dependence on magnetic field and instead show unexpected and as yet unexplained features near integer filling of the spin-polarized Landau levels.
See Crooker *et al*., page 11.

Cation Transport - Structural Based Selectivity and Efficiency

Tian, F., NHMFL/FSU, Chemistry
Miller, C., Brandeis University, Howard Hughes Medical Inst.
Wang, J., NHMFL/FSU, Chemistry
Fu, R., NHMFL
Cross, T.A., NHMFL/FSU, Chemistry and Molecular Biophysics

Two primary questions surround much of the research on ion channels; how is cation selectivity achieved, and how is efficient conductance achieved while maintaining selectivity. The highest resolution membrane protein, or polypeptide, structural characterization yet achieved by any method is gramicidin A, determined from solid state NMR derived orientational constraints of its monovalent cation selective channel state.[1] While gramicidin A is a model ion channel, recently the first crystal structure of an ion channel has been published, the K^+ channel from *Streptomyces lividans* at a modest 0.32 NM resolution.[2] Many aspects of these important questions can be addressed through the high resolution structure of gramicidin A, and provide clear predictions for the function of many other ion channels including the K^+ channel.

It has been shown through the collection of orientational constraints from dipolar interactions in the presence and absence of cations that there is very little structural change upon cation binding. In fact, the amide groups, which line the cation conducting pathway, change their orientation with respect to the channel axis by less than 2° in all cases except for two sites that tilt by as much as 4°. It can also be seen from the chemical shift results (see Figure 1) that sites that interact with the cations display a significant change in frequency, which is primarily due to a polarizability effect on the chemical shift tensor. These results lead us to the conclusion that the cation-binding site is delocalized over several amide groups, thereby forming a shallow potential energy well for cation binding. As a result the cation is not trapped in a deep well that could be generated if an ideal binding site had been formed as had been predicted by molecular dynamics calculations. This shallow surface implies that the cation can easily be moved out of the binding site and through the channel. The delocalized nature of the binding site also suggests that the entropic penalty associated with binding has been minimized since the cation still has mobility while it is in the channel.

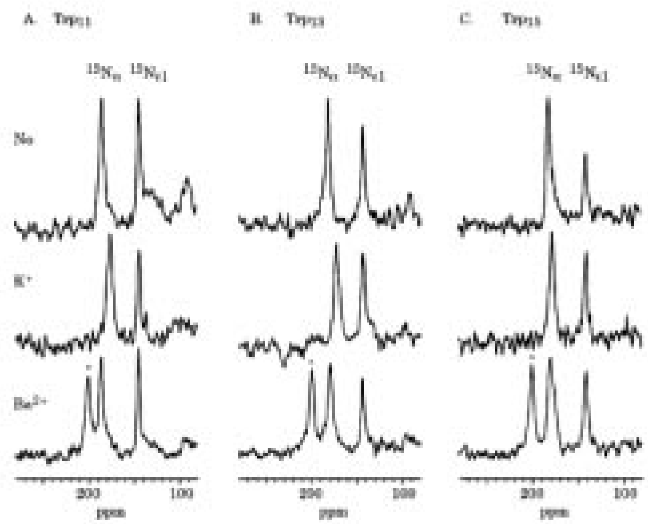


Figure 1. Comparison of K^+ and Ba^{++} effects on the ^{15}N chemical shift spectra of $^{15}N_{\alpha,\varepsilon1}$ labeled gramicidin A in aligned hydrated lipid bilayers. Samples for the Ba^{++} studies contained the additional ^{15}N label in the Ala_3 position. While K^+ induced significant changes in the observed $^{15}N_a$ chemical shift of Trp_{11}, Trp_{13} and Trp_{15}, Ba^{++} only effects the $^{15}N_a$ chemical shift of Trp_{13} and Trp_{15}. Both $^{15}N_{e1}$ chemical shifts of side chains and $^{15}N_a$ chemical shifts of Ala_3 are unaffected by cation binding. Spectra were obtained at 40 MHz (9.4 T) at the NHMFL. * signal from $^{15}N_a$-Ala_3 gramicidin A.

Modeling of water molecules around the cation while in this binding site has shown that the volume is characterized by having at least three water molecules in the primary solvation sphere of the cation at all times. In fact, the larger monovalent cations bind closer to the channel surface so that this rule remains true. To pass through the channel this number of water molecules must be reduced to two, implying that the binding site boundary towards the inner part of the channel is defined by the position at which the third water must be stripped from the cation. This is the most costly water to remove in energetic terms. For gramicidin the presence of three flexible ligands (i.e. the waters) in the binding site explains the observed lack of specificity among the monovalent cations. It is anticipated that the K^+ channel, which has much more specificity among the monovalent cations, will show a rigid binding site, but will possess only two waters in the primary solvation sphere. The deeper potential energy well in the K^+ channel would be a problem for efficient conduction if it were not for the fact that a second cation-binding site is much closer to the primary site in the K^+ channel than in gramicidin. Therefore, efficiency and selectivity result from a careful balance of the non-covalent interactions in the channel.

References:

1 Ketchem, R.R., *et al.*, Structure, 5, 1655-1669 (1997).
2 Doyle, D.A., *et al.*, Science, 280, 69-77 (1998).

Chemistry

Resolution, Elemental Composition, and Simultaneous Monitoring by Fourier Transform Ion Cyclotron Resonance Mass Spectrometry of Organosulfur Species Before and After Diesel Fuel Processing

Marshall, A.G., NHMFL/FSU, Chemistry
Rogers, R.P., FSU, Chemistry
White, F.M., FSU, Chemistry
McIntosh, D.G., NHMFL
Andersen, K.V., Haldor Topsoe (Denmark)
Hendrickson, C.L., NHMFL

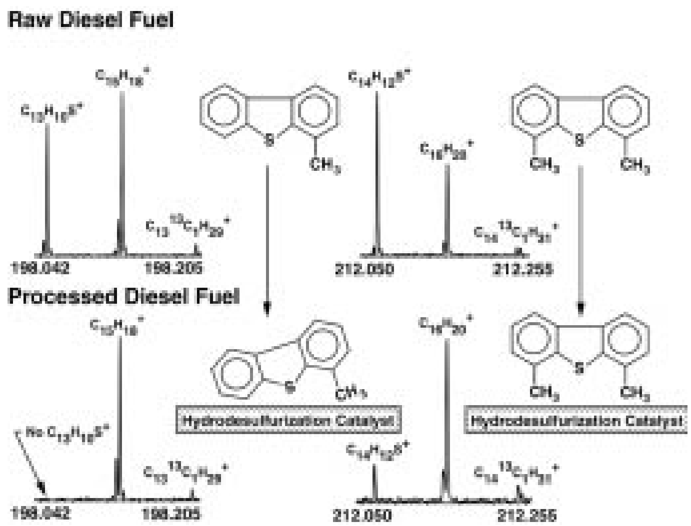


Figure 1. Electron ionization FT-ICR mass spectra of methyldibenzothiophene (left) and dimethyldibenzothiophene (right) before (top) and after (bottom) hydro-desulfurization. Note the complete catalytic removal of methyldibenzo-thiophene, but incomplete removal (due to steric hindrance for the 4,6-isomer) of dibenzothiophene.

Elemental compositional analysis of processed and unprocessed diesel fuels has been obtained with a 5.6 T Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometer coupled to an all-glass heated inlet system (AGHIS).[1] High resolution mass spectra of electron-ionized diesel fuel samples could be obtained from as little as a 500 nL septum injection into the AGHIS, to yield ~500 peaks over a range, $90 < m/z < 300$, with as many as 7 peaks present at the same nominal mass. Molecular formulas (elemental compositions) are assigned from accurate mass measurements with an average error less than ±0.5 ppm.

Comparison of the raw and processed diesel spectra (e.g., Figure 1) showed complete removal of the sulfur-containing species except for dimethyldibenzothiophene and higher alkyl-substituted dibenzothiophenes. These results confirm prior reports of the resistance of these species to hydrotreatment due to steric hindrance of catalytic desulfurization arising from 4,6 dimethyl substitution (see Figure 1). A simple liquid chromatographic separation to isolate N-, O-, and S-containing aromatics from processed diesel fuel simplifies the mass spectrum, and extends the dynamic range of the analysis, making it possible to identify many nitrogen and oxygen homologs of the sulfur-containing species, as well as confirm the presence of sulfur-containing species initially detected in the unfractionated processed diesel fuel.[2]

These results provided the first direct evidence for a proposed steric hindrance mechanism in catalytic hydrodesulfurization of diesel fuel. The technique development aspects of this work have been featured by *Analytical Chemistry*.[3]

References:

1 Rodgers, R.P., *et al*., Rev. Sci. Instrum., 69, 2278-2284 (1998).
2 Rodgers, R.P., *et al*., Anal. Chem., 70, 4743-4750 (1998).
3 Anal. Chem., 70, 567A-568A (1998).

SUPERCONDUCTIVITY – *Basic*

Superconducting Pair Fluctuations in $YBa_2Cu_3O_7$

Bachman, H.N., Northwestern Univ. and Science and Technology Center for Superconductivity
Mitrovic, V.F., Northwestern Univ. and Science and Technology Center for Superconductivity
Reyes, A.P., Northwestern Univ. and Science and Technology Center for Superconductivity
Halperin, W.P., Northwestern Univ. and Science and Technology Center for Superconductivity
Eschrig, M., Northwestern Univ. and Science and Technology Center for Superconductivity
Sauls, J.A., Northwestern Univ. and Science and Technology Center for Superconductivity
Kleinhammes, A., NHMFL
Kuhns, P.L., NHMFL
Moulton, W.G., NHMFL

We report two complementary experiments that probe the magnetic field and temperature effects of superconducting pair fluctuations in $YBa_2Cu_3O_7$: (1) measurement of the Pauli spin susceptibility[1] and (2) measurement of the ^{63}Cu spin-lattice relaxation rate ($1/T_1$).[2] We compare our data with a theory[3] of superconducting fluctuations appropriate for a weak-coupling, quasi-2D, d-wave superconductor. The theory takes exactly into account dynamical fluctuations and includes a sum over all Landau levels to extend the range of validity to high fields and temperatures.

In Figure 1 we show ^{17}O NMR spin shifts that are proportional to the Pauli spin susceptibility, from 2.1 T to 24 T. The temperature dependence can be accounted for by superconducting pair fluctuations that result in a smooth crossover from the normal to the vortex liquid state. A detailed comparison with the theory at 8.4 T accurately reproduces the data down to 85 K.

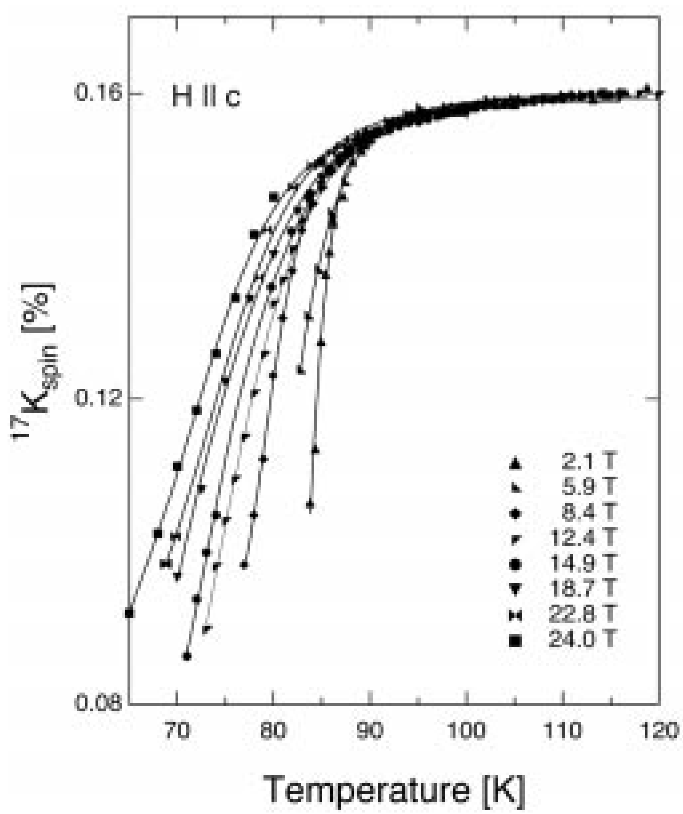


Figure 1. ^{17}O NMR shifts, proportional to Pauli spin susceptibility, in $YBa_2Cu_3O_7$. Lines are guides to the eye.

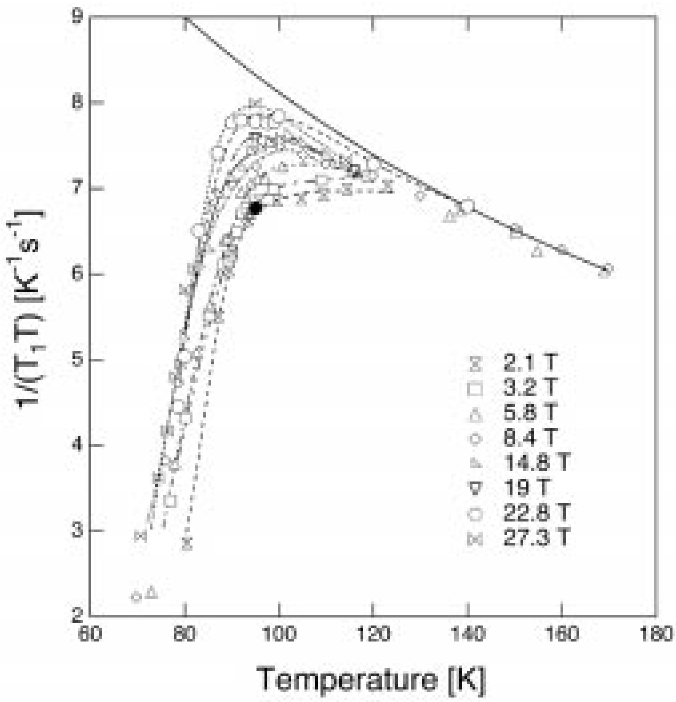


Figure 2. [63]Cu spin-lattice relaxation in $YBa_2Cu_3O_7$. Lines are guides to the eye. The data point at 95 K (●) is taken from Ref. 4, as discussed in the text.

In Figure 2 we show the [63]Cu spin-lattice relaxation rates, $1/T_1T$ from 2.1 T to 27.3 T. For temperatures below 120 K, the spin-lattice rate increases with increasing magnetic field. We account for this increase quantitatively as the suppression of negative contributions to the rate originating from density-of-states superconducting fluctuations with d-wave symmetry. Fluctuation contributions with s-wave symmetry would decrease the rate with increasing magnetic field in contrast with our observations. For comparison we also include a measurement by Gorny, *et al*.[4] Their lower result, shown as a solid circle and field independent for 0, 8.8, and 14.8 T, can be attributed to underdoping of their $YBCO_{7-\delta}$ sample.

Work at Northwestern University is supported by the NSF (DMR 91-20000) through the Science and Technology Center for Superconductivity. The NHMFL is supported through the NSF and the State of Florida.

References:

1 Bachman, H.N., *et al*., submitted to Phys. Rev. Lett.
2 Mitrovic, V.F., *et al*., submitted to Phys. Rev. Lett.
3 Eschrig, M., *et al*., submitted to Phys. Rev. B.
4 Gorny, K., *et al*., Phys. Rev. Lett., 82, 177 (1999).

QUANTUM SOLIDS

New Phases for the Ordering of Quantum Rotors in 2D: NMR Studies

Sullivan, N.S., UF, Physics/NHMFL
Kim, K., Stanford Univ., Physics

NMR experiments at moderately high magnetic fields (~ 7 T) have been carried out to study the orientational ordering of ortho-para hydrogen molecules physisorbed on hexagonal boron nitride. The studies were carried out for layer coverages corresponding to the density expected for the commensurate √3 X √3 structure with one molecule occupying the center of every third hexagon of the hexagonal lattice of the boron nitride. The system consists of a 2D ensemble of interacting quantum quadrupoles (ortho-hydrogen molecules) with angular momentum J=1. The commensurate coverage is especially interesting because of the high geometrical frustration imposed on the ordering of the hydrogen molecules by the triangular lattice for the fixed centers of mass of the molecules.

Distinctly different NMR line shapes are observed for different concentrations and this has been used to identify four different orientationally ordered phases illustrated schematically in Figure 1:

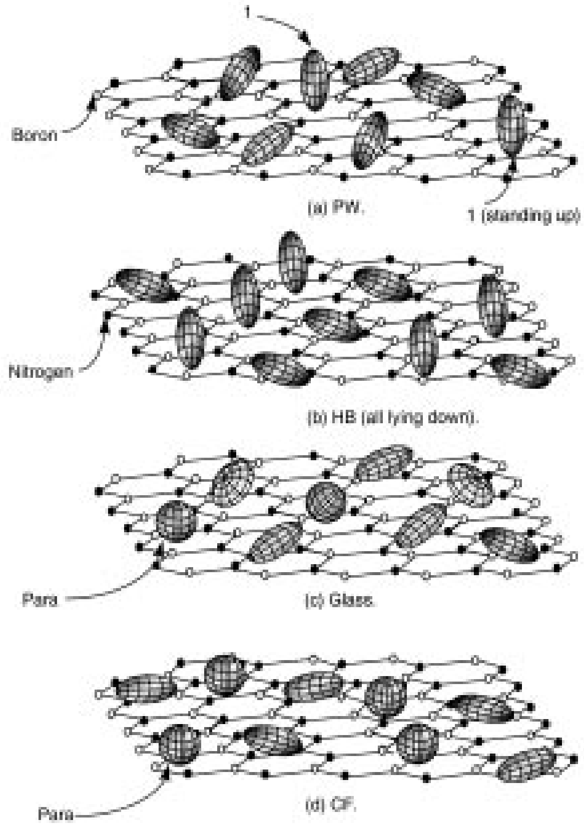


Figure 1. Schematic representation of the different orientationally ordered phases for hydrogen molecules in a √3 X √3 commensurate triangular lattice on a substrate of BN: (a) pinwheel phase (PW), (b) herringbone structure (HB), (c) quadrupolar glass state, and (d) a locally ordered crystal field state (CF).

(1) A high concentration long range ordered pinwheel phase (PW) in which the molecular alignments $S_i = <3J_{zi}^2 - J^2>$ are all –2 at each site with the local axes z_i aligned in a pinwheel configuration
(2) A 2D quadrupolar glass state at intermediate temperatures and intermediate temperatures for which the molecular alignments S and local axes are distributed at random
(3) A herringbone phase (HB) that evolves continuously to a purely local crystal field ordering at low concentrations
(4) An unusual and unexpected hindered rotor state (HR) at very low temperatures for which the orbital magnetization $<J_z>$ is non-zero.

The long-range pinwheel phase is fragile with respect to dilution with non-interacting para-hydrogen molecules (J=0) and there is an abrupt (apparently first order) transition at a critical concentration of 69% to the glass state. The quadrupolar glass state is a tensorial "spin-1" glass and is believed to result from the combined effects of frustration and substitutional disorder.

Kondo / Heavy Fermion Systems

Heat Capacity of $YbInCu_4$ at Very High Magnetic Fields

Jaime, M., LANL
Movshovich, R., LANL
Sarrao, J.L., LANL

The magnetic field produced with the Long Pulse 60 Tesla (LP 60 T) magnet is characterized by the low ramp rate of $dB/dt \leq 400$ T/s, and constant field plateaus of as long as 0.1 s at 60 T. We have built a probe made mostly of plastic materials, which allows us to perform measurements in a vacuum down to a temperature of 1.6 K, in fields up to 60 T. We use a heat pulse method to measure heat capacity, where a known amount of heat is delivered to the sample using a chip resistor as a heater element. The heat capacity of the sample is determined as the ratio of the heat delivered to the sample to the change in its temperature.

Metallic $YbInCu_4$ undergoes a first order valence phase transition at 42 K in zero field, where the specific volume is increased by 0.5% upon cooling,[1] with accompanying rise in the Kondo temperature (T_K) from 25 K to 500 K.[2] It is believed that, unlike in the case of Ce, where the phase transition is described within a Kondo-collapse scenario, the valence transition in $YbInCu_4$ is driven by the band structure effects.[3] The complete magnetic field temperature phase diagram was obtained in dc Bitter magnets at NHMFL-Tallahassee and in capacitor-driven pulsed magnets at NHMFL-Los Alamos.[4] This work showed that the transition can be suppressed down to T = 0 K with an applied field of 34.3 T.

The length of the flat top can be close to 0.5 s in the LP 60 T magnet for magnetic fields less than or equal to 40 T. A sequence of heat pulses can be delivered to the sample within the flat portion of the field profile, with sufficient time for our calorimeter to come to equilibrium before and after each of the heat pulses. This situation is illustrated in Figure 1a for a field of 20 T, where a sequence of five, 10 ms long, heat pulses are delivered to the heat capacity stage during the plateau. The thermometer comes to equilibrium after the heat pulse is delivered well before the next heat pulse, and temperature is determined before and after each of the pulses. In this way a series of five $C_H(T)$ data points are collected in a single "shot" experiment, as the initial temperature for each of the heat capacity experiments is increased due to the previous heat pulse. The data from this, and one zero field "shot," is shown in Figure 1b. We fit the data with a sum of electronic and phononic terms ($A_H T+B_H T^3$). For zero field we obtained $A_0 = 49.5 \pm 0.4$ mJ/molK^2 and $B_0 = 0.85 \pm 0.03$ mJ/molK^4. The value of A was in excellent agreement with available data in the literature.[3] At 20 T we obtained $A_{20} = 80 \pm 5$ mJ/molK^2 and $B_{20} = 0.81 \pm 0.07$ mJ/molK^4. The magnitude of the cubic term due to phonons was field-independent as expected. The increase of the linear term with field was likely due to scaling with magnetic field observed for various properties of $YbInCu_4$.

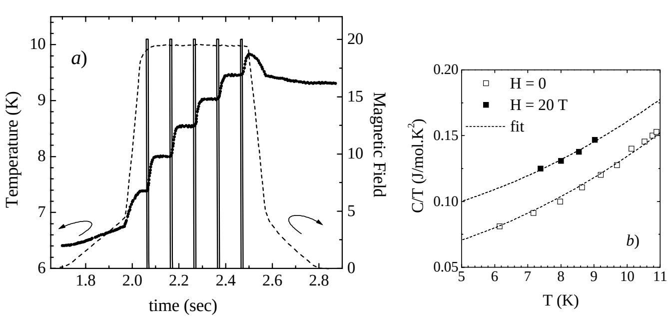


Figure 1. Multiple heat capacity experiments on $YbInCu_4$ during a single 20 T, 0.5 long pulse. *a*) Dashed line – magnetic field. Solid line – voltage applied to the resistive heater. • - Thermometer's trace. *b*) □ - specific heat at H = 0 collected with our probe. ■ - specific heat at H = 20 T obtained from data in *a*).

A series of plateaus at different magnetic fields can be produced in the LP 60 T within a single experiment. Figure 2 displays the data for one such experiment, with four plateaus at 25, 30, 35, and 40 T, each 130 ms long. At each of the magnetic field plateaus the heat pulse is applied to the stage, and a heat capacity experiment is performed. In addition, as the field was changed between 30 T and 35 T through the first order phase boundary, the temperature of the sample was observed to go down on the up-sweep, and up on the down-sweep, due to the magnetocaloric effect. These features are very sharp, and allow direct determination of the phase diagram of $YbInCu_4$.

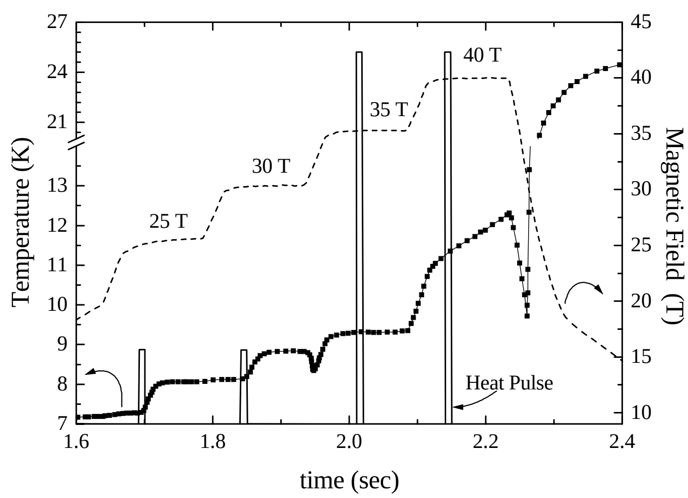


Figure 2. Staircase pulse shape for specific heat experiment on $YbInCu_4$. Dashed line – magnetic field. Solid line – voltage applied to the resistive heater. • - Thermometer's trace.

References:

1 Felner, I., *et al.*, Phys. Rev. B, 33, 617 (1986).
2 Cornelius, A., *et al.*, Phys. Rev. B, 56, 7993 (1997).
3 Sarrao, J.L., *et al.*, Phys. Rev. B, 58, 409 (1998).
4 Immer, C.D., *et al.*, Phys. Rev. B, 56, 71 (1997).

Optical Signatures from Magnetic 2-D Electron Gases at High Fields to 60 Tesla

Crooker, S.A., NHMFL/LANL
Rickel, D.R., NHMFL/LANL
Kikkawa, J.M., Univ. of California-Santa Barbara, Physics
Awschalom, D.D., Univ. of California-Santa Barbara, Physics
Smorchkova, I.P., Pennsylvania State Univ., Physics
Samarth, N., Pennsylvania State Univ., Physics

Recent advances in II-VI molecular-beam epitaxy now permit the growth of two-dimensional electron gases (2DEGs) in *magnetic* semiconductor quantum structures. Unlike their nonmagnetic III-V semiconductor counterparts, these new 2DEGs can be incorporated directly into quantum wells containing local magnetic moments (typically Mn^{2+} ions), allowing for the intriguing possibility of studying the physics of a mobile gas of electrons whose spins are strongly exchange-coupled to a matrix of embedded magnetic moments.

High field photoluminescence (PL) studies of magnetic 2DEG systems have been performed at the NHMFL-Los Alamos in the 60 T Long Pulse magnet. In this field regime, the local Mn moments are driven into nearly complete saturation. The samples are modulation-doped ZnSe/Zn (CdMn) Se single quantum wells with carrier densities n_c~$5*10^{11}$ electrons/cm^2. Owing to the strong $J_{sp\text{-}d}$ exchange interaction in these II-VI systems, the Zeeman energies (spin-splittings) in the conduction band are comparable to or even larger than the cyclotron energies (Landau-level splittings), so that the 2DEG is highly spin-polarized even at low magnetic fields.

PL data reveal a highly anomalous Zeeman shift of the fundamental PL peak with increasing field. As shown in Figure 1, the energy shift of the PL no longer resembles the Brillouin-function-like Zeeman shift that would be expected of paramagnetic Mn^{2+} moments. Rather, there exists a pronounced maximum in the Zeeman shift near ν=2 and a clear kink at quantum Hall filling factor ν=1. In this field regime there also exists a higher-energy satellite peak that appears at low fields, grows in intensity, and finally disappears at ν=1 (its energetic shift is also plotted). The higher energy satellite peak tracks the fundamental PL peak with a constant separation of ~10 meV, and is thus not a higher-lying Landau level. This behavior is observed in many different magnetic 2DEG samples with different magnetic environments and carrier densities, and ongoing experiments are aimed at elucidating its origin.

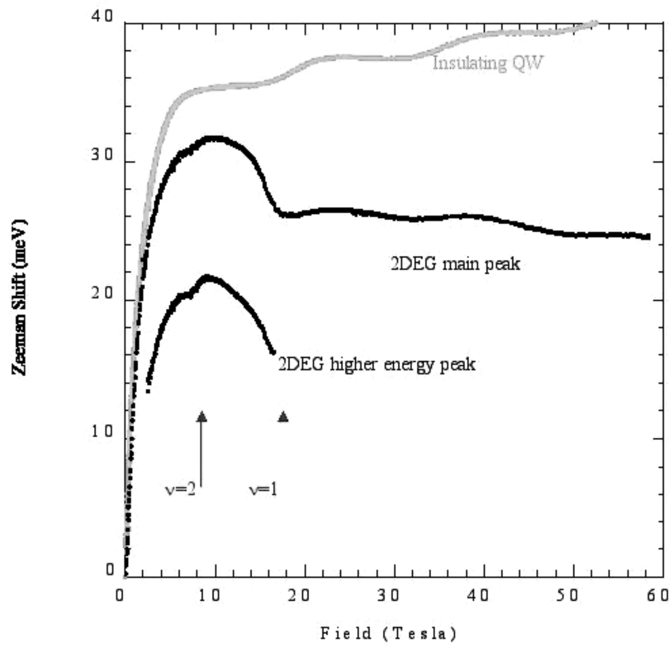


Figure 1. Measured Zeeman shift of the PL peaks from a magnetic 2DEG at 350 mK. Data from an insulating magnetic QW shown for comparison.

SEMICONDUCTORS continued on page 12

SEMICONDUCTORS continued from page 11

Figure 2 shows an example of the clear oscillations in the integrated PL intensity observed in magnetic 2DEG samples. This behavior is a common feature of semiconductor electron gases and corresponds to the Fermi level moving through integer Landau levels. In contrast with nonmagnetic 2DEGs, however, these oscillations correspond to every-integer (rather than even-integer) filling factors arising from the highly spin-polarized nature of the magnetic 2DEG.

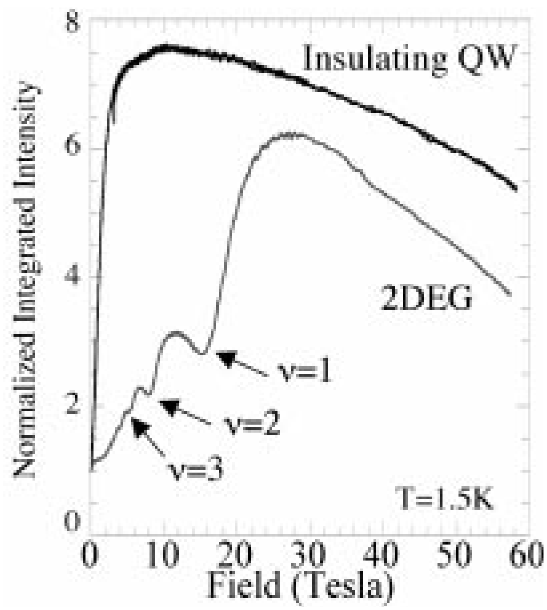


Figure 2. Integrated intensity from a magnetic 2DEG, showing every-integer filling factors. Data from an insulating magnetic QW shown for comparison.

FQHE at Ultra-Low Temperatures and High Magnetic Fields

Pan, W., Princeton Univ., Physics/NHMFL
Xia, J.S., NHMFL/UF, Physics
Shvarts, V., NHMFL/UF, Physics
Adams, E.D., NHMFL/UF, Physics
Stormer, H.L., Columbia Univ., Physics/Lucent Technologies
Tsui, D.C., Princeton Univ. Physics
Pfeiffer, L.N., Lucent Technologies
Baldwin, K.W., Lucent Technologies
West, K.W., Lucent Technologies

Three GaAs/$Ga_{1-x}Al_xAs$ samples, with various fixed density, were studied at ultra-low temperatures down to 4 mK and high field up to 15 T. The samples, with their 8 contacts directly soldered to separated silver power sintered heat exchangers, were immersed in the liquid ^3He, which was cooled by a powerful 5 mole $PrNi_5$ nuclear stage refrigerator recently built at the University of Florida. The data analysis shows that the two-dimensional electron system (2DES) was successfully cooled down to 4 mK with liquid ^3He bath being around 2.5 mK.

For the sample with density $n = 2.3\times10^{11}$ /cm^2 and mobility $\mu = 1.4\times10^7$ cm^2/Vs, Figure 1 shows a vanishing R_{xx} at $\nu=5/2$[1] and, for the first time, a precisely quantized Hall resistance R_{xy} to the value of $2h/5e^2$ in the magnetic field range between 3.63 T and 3.70 T at T = 8.0 mK. The activation energy gap Δ at n=5/2, defined by $R_{xx} \sim \exp(-\Delta/T)$, was found to be 54.0 mK. The activation energy at other FQHE states, $\nu=7/3$ and $\nu=8/3$, were also measured and found to be very similar to the activation energy at $\nu=5/2$ within our experimental error. The experimental details and more data will be published in elsewhere.

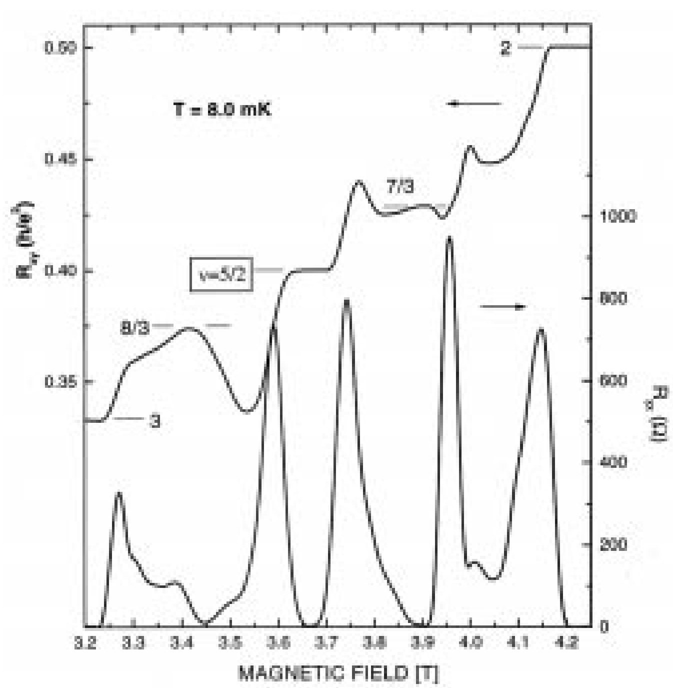


Figure 1. FQHE in GaAs/$Ga_{1-x}A1_xAs$ at $\nu=5/2$.

Reference:

1 Willett, R.L., *et al.*, Phys. Rev. Lett., 59, 1776 (1987).

Education Group Expecting Very Busy Spring & Summer

The National High Magnetic Field Laboratory is once again in the spotlight through its Center for Integrating Research and Learning. The educational programs of the laboratory have been receiving attention through its diverse programs. In March, statewide attention will be focused on the laboratory as we launch our Science, Tobacco & You program. In Georgia, at the American Physical Society's Centennial Celebration, education at the NHMFL will be featured through exhibitions and presentations.

The Center is moving into the final delivery phase of our contract with the Florida Department of Health. *Through this $1.6 million dollar contract, we have developed and will be delivering a science curriculum resource package ("Science, Tobacco & You") to over 1500 elementary schools across Florida.* The ultimate goal of Science, Tobacco & You is to encourage students to become "scientifically literate" citizens by developing their skills to ask questions and determine the answers derived through inquiry. Through scientific analysis and captivating multi-sensory experiences, students will explore and understand the harmful effects of tobacco on their bodies. To facilitate the integration of the program into the schools, during the month of March we will be training 335 teachers who will in turn train additional teachers in each of Florida's 67 counties. You can explore the web-based portion of the program at *http://scienceu.fsu.edu*.

This year the laboratory will host as many as 20 undergraduate students through the 7th Annual NHMFL Summer Research Internship Program. For two months, interns will be integrated into ongoing science and engineering projects at the three NHMFL sites. Past projects have included studies in low temperature; low noise transport measurements; analysis of circuits containing a magnetic core; studies of electrical design and operation in high field magnet systems; NMR microscopy and spectroscopy; and high field investigations of various conductors and materials. More information on this program is available at *http://k12.magnet.fsu.edu/intern*.

New this year is our NHMFL Research Experience for Teachers (RET). The RET will recruit five middle school teachers with three to five years of teaching experience and pair them with five rising senior preservice students from the education colleges at Florida State University and Florida Agricultural and Mechanical University. The teachers will be placed with researchers at the NHMFL for six hours per day for five weeks. The remaining time at the NHMFL will be focused on pedagogical issues, strategies for classroom implementation, and science content. This program will be aligned with the Summer Research Internship program, further enhancing the experiences for the students, teachers, and researchers.

For more information on these programs or any of our other educational projects, please contact Sam Spiegel, director of the Center for Integrating Research and Learning at *spiegel@magnet.fsu.edu*.

ATTENTION USERS

Bruce Brandt
Director , DC Field User Programs

I would like users to send me their advice about a magnet that the NHMFL is considering building. This column will describe the magnet. Please let me know what you think.

Last September Chuck Agosta, Chair of the NHMFL Users' Committee, sent an e-mail message to many users inviting their opinions for and against developing and installing a horizontal bore, split coil, radial access magnet in the DC Fields Facility in Tallahassee. Such a magnet would allow a number of experiments not possible in the vertical bore, axial access solenoids now in use. Scattering experiments would be possible if there were multiple radial access ports at several angular positions. Optical absorption experiments with longer path lengths and different sample orientations could be done. A horizontal field split coil magnet also would provide a magnetic force perpendicular to the local gravitational force for separating microgravity effects on biological samples from those due to the high magnetic fields.

Most of the users who responded to Professor Agosta's letter were interested in being able to rotate the sample in the magnetic field when the sample holder was too long and rigid to rotate within the bore of a standard solenoid. The 20 T, 20 cm bore magnet already on hand could not be used for the desired experiments, though it provides much more rotating room than the typical high field solenoids. A horizontal bore, radial access magnet would allow the experimenter to rotate the entire probe or even the whole cryostat relative to the field direction.

One class of experiments that requires the horizontal bore, radial access magnet includes those that couple the sample to the measuring instruments via rigid coaxial cable or wave guides. Similar problems confront far infrared magneto-optical experiments because the light is coupled to the sample via a rigid light pipe. Such inserts simply cannot be rotated in a standard solenoid.

One user of the Francis Bitter Magnet Lab measured the combined effects of strain and magnetic field on superconductors. Having the strain and sample current perpendicular to the field was important so a horizontal bore, split coil magnet was used. A system for doing similar measurements to fields of 13 T is already available at the NHMFL. We need users to describe to us their needs for similar measurements to higher fields.

Vibrating sample magnetometry with the field perpendicular to the vibration stroke and other measurements of the magnetic properties of large anisotropic samples would be possible, or at least easier, in the proposed type of magnet.

At one time, almost all optical measurements were done using split coil magnets with several radial access ports to allow detectors to be placed at several angles relative to the stimulating beam. Most optical experiments in the last several years have used optical fibers because they enabled experiments in simple solenoids and allowed measurements in much higher magnetic fields. Some experiments cannot be done with optical fibers for a variety of reasons. A split coil magnet would make them possible.

Some experiments, particularly in optics, would benefit from having a split coil magnet with the bore vertical and the radial access ports in a horizontal plane. The need for both horizontal and vertical bore configurations could be satisfied with multiple magnets. It might also be possible to make a single magnet that could be operated in either configuration.

NHMFL staff and the users who responded to Chuck Agosta's e-mail have thought of many possible uses of a split coil, radial access magnet. To ensure that we make good use of our resources, however, we would like to identify as large a pool as possible of people who have experiments that they would like to do in such a magnet. We also need to know other experimental requirements that might affect the magnet design.

- Describe your experiment briefly; include sample size and temperature.
- Discuss the need for fields stronger than 13 T.
- Explain, if it isn't obvious, why your experiment cannot be done in the 20 T, 20 cm bore solenoid magnet, or the 13 T, 15 cm bore superconducting radial access, split coil magnet.
- How much room is needed under the magnet?
- How large should the radial access port or ports be?
- How many radial access ports are needed?
- Should the ports be equally spaced?
- What should the diameter of the magnet bore be, keeping in mind that larger bore means smaller field?
- What orientation of the *bore* of the magnet do you require?

Please send me brief descriptions of what you would like to do. Be as specific as possible about the experimental details and the need for fields above 13 T. I look forward to hearing from you. *brandt@magnet.fsu.edu*, 850-644-4068.

Conference and Workshop Activity

BFGoodrich —

Directors of Industrial Research, Analytical Group Meeting
February 17-19, 1999
Tallahassee, Florida

Fifty NMR directors and managers, representing the major chemical companies, pharmaceuticals, and "Big Three" automobile companies attended the Winter Meeting of DIR-AG, hosted by The BFGoodrich Company. The meeting was held in Tallahassee this year so that members of the group could tour the NHMFL and meet with laboratory directors and faculty.

Second North American FT-ICR Mass Spectrometry Conference

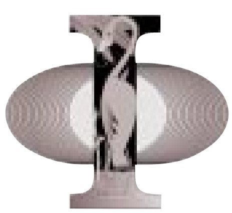
March 18-20, 1999
USGrant Hotel
San Diego, California

This very successful new conference series is being held in downtown San Diego this year. The First FT-ICR MS conference was held in 1997 at the NHMFL in Tallahassee. The format will be in the style of Sanibel and Asilomar conferences, namely, invited oral and poster presentations (all plenary—i.e., no parallel sessions), as well as contributed posters. Oral and poster sessions will include a broad range of FT-ICR MS topics. Contributed posters will be on display throughout the meeting, with authors present on Friday evening.

Welcoming remarks on March 19 will be given by Charles B. Reed, Chancellor of the California State University System. The concluding conference dinner on March 20 will feature a talk on the "Early Days of ICR" by John D. Baldeschwieler, California Institute of Technology.

Conference chair is Alan Marshall, director of the FT-ICR Program at the NHMFL. For more information, see www.magnet.fsu.edu/2ndfticr/ or contact Jo Ann Palmer (850-644-1933, palmerj@magnet.fsu.edu, fax 850-644-8350).

16th International Conference on Magnet Technology (MT-16)



September 26-October 2, 1999
CHANGE OF VENUE:
Sawgrass Marriott Resort, Ponte Vedra Beach, Florida, 35 miles southeast of Jacksonville International Airport
Abstract Deadline: June 15, 1999
Early Registration Deadline: August 15, 1999.

MT-16 will bring together approximately 500 scientists, engineers, and experts from around the world to focus the latest developments in technology, operation, applications of research and industrial magnets, and magnet materials.

The meeting will combine technological and scientific aspects of magnet technology. Basic investigations involving magnet materials, electrodynamics, stability of superconductors, heat transfer, He II cooling, cryogenics, etc., will be an integral part of the conference program. System optimization, magnet analysis, design strategies, new instrumentation, and related issues also will be included.

A major emphasis will be on industrial applications, such as magnets for NMR and MRI, energy storage, levitation, and separation. Several sessions will be dedicated to new developments in high and low temperature superconductors and other magnet materials for reinforcement, impregnation, and insulation.

Industrial & Scientific Exhibition. A special exhibition will be held in conjunction with the conference displaying a wide range of products in the field of magnet technology, as well as achievements and services offered by industry, academia, and research laboratories. Organizations interested in participating in the exhibition should contact conference organizers as early as possible.

MT-16 will be held at the Sawgrass Marriott Resort, located approximately 35 miles southeast of Jacksonville International Airport. Jacksonville is easily reached from major air hubs such as Atlanta, Orlando, New York, Miami, and Charlotte. It is a spectacular setting for the conference, with the Atlantic Ocean just minutes away.

Complete information and registration is available online at *www.magnet.fsu.edu/mt16*. Interested individuals or organizations also may contact Jo Ann Palmer (850-644-1933, *mt16@magnet.fsu.edu*, fax 850-644-8350).

30th Southeastern Magnetic Resonance Conference (SEMRC)

October, 1999
NHMFL, Tallahassee

Planning is underway for this conference, which will feature invited and contributed papers and posters in NMR, MRI, EPR, and ICR. Topics will include time-resolved and multidimensional spectroscopies, high magnetic fields, and applications of magnetic resonance technologies in materials science, physics, chemistry, biology, and medicine. For further information, e-mail *semrc@magnet.fsu.edu* or fax 850-644-8350.

Florida State University•University of Florida•Los Alamos National Laboratory

NHMFL REPORTS

National High Magnetic Field Laboratory

Published by :

National High Magnetic Field Laboratory
1800 East Paul Dirac Drive
Tallahassee, Florida 32310
850-644-0311

Director
Jack Crow

Deputy Director
Hans Schneider-Muntau

Director, Governmental & Public Relations
Janet Patten

Editors/Writers
Kathy Hedick
Jeff Simon

Design/Production
Educational Media & Communications
Walter Thorner
Curtis Hendrickson
Laurie Anne Lusk

This document is available upon request in alternate formats for individuals with print-related disabilities. Contact Kathy Hedick for more information.

If you would like to be added to our mailing list please write us at the address above, call 850-644-6392, or e-mail *hedick@magnet.fsu.edu.*

Look for the NHMFL on the Internet: *http://www.magnet.fsu.edu.*

INSIDE THIS ISSUE

WINTER 1999 Volume 6 • No. 1

Florida State University•University of Florida•Los Alamos National Laboratory

NHMFL REPORTS

National High Magnetic Field Laboratory

1800 EAST PAUL DIRAC DRIVE, TALLAHASSEE, FLORIDA 32310

Non-Profit
Organization
U.S. Postage
PAID
Tallahassee, FL
Permit No. 55