NATIONAL HIGH MAGNETIC FIELD LABORATORY

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FROM THE DIRECTOR'S DESK

Greg Boebinger

Summer may be a slower time for some universities and school districts, but this is certainly *not* the case for the Magnet Lab at Florida State University. As the cover story on summer education programs reports, the corridors, cubicles, and experimental areas of the laboratory are packed with students and teachers during June and July. We have 19 interns—representing 17 institutions of higher learning and 15 states—participating in the **Research Experiences for Undergraduates** program. Two of these outstanding students are working with our Physics faculty at the University of Florida. The **Research Experiences for Teachers** program is hosting 11 K12 teachers for science research internships, and summer institutes and workshops attracted additional educators for professional development. These activities and others capitalize on the broad range of research already underway at the laboratory and help us to promote science literacy and interest in careers in science and engineering. **At the heart of these programs are the NHMFL faculty mentors**, who volunteer their time, energy, and resources to help develop and guide the next generation of science leaders. I would like to publicly thank the mentors and the director of our education programs, Dr. Pat Dixon, and her colleagues in the Center for Integrating Research and Learning for their dedication and extra efforts. For the full story on these and other education activities underway at the lab, see pages 11-13.

Other articles in this issue feature ***new science*** in the High B/T facility at UF (Vicente *et al*., page 4), at the Pulsed Field (Crooker and Smith, page 14), and at NMR facilities in Tallahassee (Brüschweiler and Zhang, page 6); the ***new 75 T pulsed magnet*** and how it was used in an investigation of the Aharonov-Bohm effect in carbon nanotubes (Swenson and Crooker, page 9); and ***new opportunities in materials processing using ultrahigh magnetic fields*** (Ludtka and Kalu, page 16). Once again, this issue of *NHMFL Reports* reflects the diversity of our R&D activities, so there is something of interest for all of our readers.

I am pleased to defer the balance of my space this issue to my friends George Srajer and Frank Klose who report on a very significant—and successful—workshop held at the lab in May.

Best wishes for a great summer, Greg Boebinger

Summary of the *Probing Matter at High Magnetic Fields with X-Rays and Neutrons Workshop*

G. Srajer, Argonne National Laboratory, Advanced Photon Source
F. Klose, Oak Ridge National Laboratory, Spallation Photon Source
A. Lacerda, NHMFL/LANL Pulsed Field Facility Director and NHMFL Associate Director for User Operations

The goal of the workshop, held at the NHMFL from May 10 - 12, 2005, was to identify grand challenges in science at high magnetic fields that should be addressed using neutron and X-ray scattering techniques. The workshop was used to define a roadmap for development of the next generation of instrumentation at major user facilities that would enable these challenges to be met. In particular, this roadmap was to identify:

- New instrumentation and techniques that would enhance our present capabilities to explore materials at high magnetic fields using X-rays and neutrons;
- Both short- and long-term R&D needs in areas such as magnet technology, sample environment, optics and detectors; and
- Required developments in theory, modeling and simulation, advanced computing, and large-scale data analysis.

The workshop was organized and sponsored by the National High Magnetic Field Laboratory, the Advanced Photon Source, and the Spallation Neutron Source. It brought together the staff, users, and management of all three facilities. Numerous experiments using high magnetic fields were presented and their impact on science were discussed. The format was designed to promote interaction among researchers using photons and neutrons in their studies. There was an international flavor because many of the 50 attendees came from outside of the United States. Representatives from the National Science Foundation and Office of Science, Department of Energy also attended.

The workshop clearly demonstrated that the scientific community would benefit greatly from high field magnets at neutron and synchrotron sources, as they would open new scientific areas of research in condensed matter physics and material science, just to mention a few areas. The next step is to prepare a proposal that would launch the development of high field magnets tailored to neutron and synchrotron experiments. This is both a wonderful and an exciting opportunity!

FROM THE CHIEF SCIENTIST'S DESK

NHMFL-based investigations have a long history of revealing new states of two-dimensional systems of electrons hosted in semiconductors. In this article, a team from Princeton, Columbia, Lucent, and the NHMFL present an experimental tour-de-force employing a hydraulically-driven stage to tilt the sample in high magnetic field at ultra-low temperature. The results allow for the identification of some newly-observed phases of two dimensional electrons as solids in which the electron spins are not fully polarized, and in which antiferromagnetic order may exist.

J. Robert Schrieffer

Tilt Induced Melting of the Electronic Solids of the 2nd Landau Level

C.L. Vicente, NHMFL/UF, Physics
G.A. Csathy, Princeton, Electrical Engineering
J.-S. Xia, NHMFL/UF, Physics
E.D. Adams, NHMFL/UF, Physics
N.S. Sullivan, NHMFL/UF, Physics
H.L. Störmer, Columbia, Physics/Bell Labs
D.C. Tsui, Princeton, Electrical Engineering
L.N. Pfeiffer, Bell Labs
K.W. West, Bell Labs

Introduction

It has recently become apparent that at the lowest temperatures extremely clean two-dimensional electron systems exhibit exotic many particle phases.[1] These phases were unknown just two years ago and they are not fully understood even today. The electronic phases present in the second Landau level, the objects of our study, are examples of such phases. Because of a resurgence of interest in various newly discovered quantum solid phases such as the bubble and stripe phases of the 2D electron gas[2] as well as the supersolid phase in 4-He and stripe phases in superconductors, we think that our results are of interest to a broad audience.

Experimental

Because of the extreme temperature conditions required to observe these phases, the High B/T Facility of the NHMFL at Gainesville is a unique venue for the study of these electronic phases. We report here on the properties of these phases in tilted magnetic fields using dc transport techniques. The sample is δ-doped 30 nm wide GaAs/AlGaAs quantum well of an exceptionally high mobility of 2.7×10^7 cm^2/Vs at the density of 3.0×10^{11} cm^{-2}. The experiment would not have been possible without the use of the innovative hydraulically-driven rotator developed by Jian-Sheng Xia[3] that allows an *in situ* tilting of the sample at temperatures in the millidegree range.

Results and Discussion

In Fig. 1, we summarize the evolution with the tilting angle of the longitudinal and diagonal resistances as function of the perpendicular magnetic field taken at a temperature of 9 mK. At zero tilt, i.e., when the sample is perpendicular to the magnetic field, we observe the reentrant integer quantum Hall behavior at ν=2.30, 2.44, 2.57, and 2.70. The reentrant behavior, marked by the dotted lines of Fig. 1, has been attributed to the formation of electronic solid phases also known as charge density waves. As shown in Fig. 1, with increasing tilt these

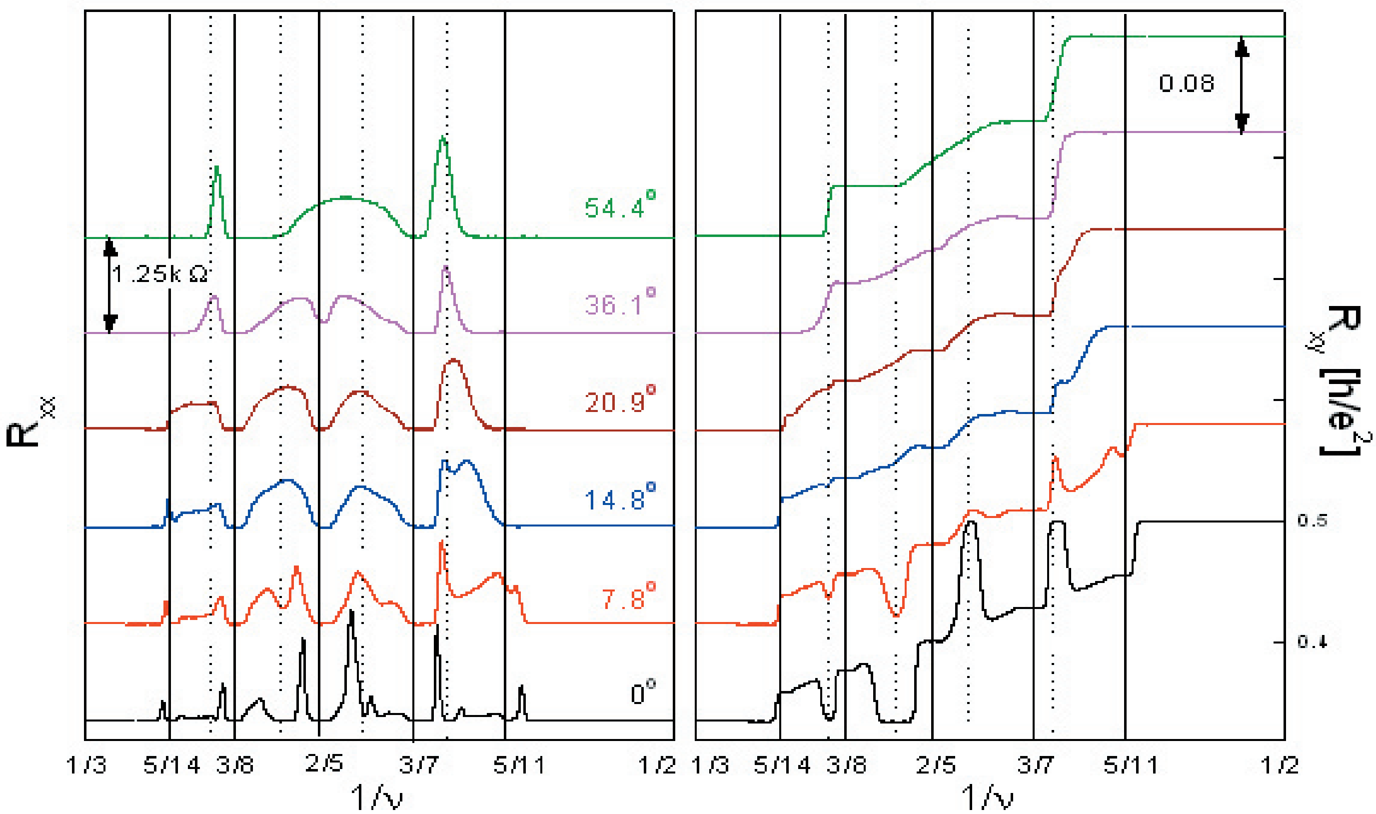


Figure 1. The dependence of the longitudinal (R_{xx}) and diagonal (R_{xy}) resistances on the perpendicular magnetic field at various tilt angles measured at 9 mK. Dotted lines indicate the location of solid phases while continuous lines mark fractional quantum Hall liquids at zero tilt angle.

states weaken until they are completely destroyed. The diagonal resistance evolves from the integer values characteristic to the reentrant behavior towards the classical Hall value. We interpret this behavior as melting of the electronic solid with tilt into the classical electron gas. The solid-to-classical gas transition can also be viewed as delocalization transition as the solid phase is pinned by the disorder present in the sample.[2]

Marked by continuous line in Fig. 1, there are well-developed fractional Hall liquid states at the filling factors ν=2+1/5, 2+1/3, 2+2/3, and 2+4/5 at zero tilt. We find that as the tilt angle is increased at the above filling factors, the Hall conductance evolves from a fractional value of the resistance quantum toward an integer number. Such a behavior is interpreted as a transition from a fractional quantum Hall liquid into an electronic solid. The fractional liquids thus undergo a localization transition with tilt.

Conclusions

While it has been suggested and obtained from simulations that the reentrant integer quantum Hall states are localized electronic solids, our results are among the first unequivocal experimental proofs of such a state of affairs. Furthermore, to our surprise we find that these solid phases melt quickly with increasing tilt angle. Since a fully spin polarized phase is not expected to be modified by tilting, our results hint toward the formation of an antiferromagnetically ordered solid at least in the vanishingly small disorder limit. Such a phase has not been anticipated by theory. We propose that the antiferromagnetic coupling is a result of ring exchange processes of particles of the second Landau level. We also found that the fractional quantum Hall liquids of the second Landau level are spin polarized.

1 G.A. Csathy, *et al.*, *Phys. Rev. Lett.*, **94**, 146801 (2005).
2 R.W. Lewis, *et al.*, *Phys. Rev. B*, **71**, 081301 (2005).
3 J.-S. Xia, *et al.*, *Int. J. Mod. Phys. B*, **16**, 2986 (2002).

News from CIMAR

Covariance NMR Spectroscopy

R. Brüschweiler, NHMFL Center for Interdisciplinary Magnetic Resonance
F. Zhang, NHMFL-CIMAR

Modern nuclear magnetic resonance (NMR) spectroscopy provides unprecedentedly detailed information on the structure and dynamics of biomolecules in solution. Important progress has become possible by the availability of ever increasing magnetic fields and by the resolution enhancement offered by multidimensional Fourier transform experiments, such as the widely used NOESY experiment that yields valuable information about distances between atoms in molecules.[1] A drawback of this and other two-dimensional experiments is their significant time consumption because the indirect time dimension needs to be adequately sampled by sequentially collecting many time points to achieve good spectral resolution that allows the identification of individual cross peaks.

We have recently introduced a new approach to this long-standing challenge by replacing the traditional 2D Fourier transformation (2D FT) by a novel NMR processing scheme.[2,3] The scheme builds on the construction of a covariance matrix from a time-domain matrix $s(t_1, t_2)$ that after 1D FT along t_2 yields a mixed time-frequency matrix $s(t_1,\omega_2)$, which represents a set of N_1 1D spectra that belong to different evolution times t_1. Instead of applying a second FT along t_1 to $s(t_1,\omega_2)$, as is done in 2D FT NMR, a covariance analysis is performed, which identifies correlated changes of the magnetizations from the set of 1D spectra represented by the N_1 x N_2 matrix $S(k,l) = S(k \cdot \Delta t_1, \omega_2(l))$ by constructing the N_2 x N_2 covariance matrix $\boldsymbol{C}$ with elements

$$C_{ij} = \frac{1}{N_1 - 1}\sum_{k=1}^{N_1} (S(k,i) - \langle S(i)\rangle)(S(k,j) - \langle S(j)\rangle) \quad (1)$$

Element C_{ij} is the mathematical covariance between the peak amplitudes at frequencies $v(i)$ and $v(j)$ ($i, j = 1, \ldots, N_2$) (Fig. 1). It directly reflects whether two spins with these resonance frequencies have interacted with each other by exchanging magnetization during the mixing period. Because the covariance matrix is symmetric, both frequency axes, termed ω_2 and ω_2 , are equivalent. In contrast to 2D FT, the spectral resolution in the covariance spectrum $\boldsymbol{C}$ is determined along both dimensions by the favorable resolution achievable along the detection dimension ω_2, which does not depend on the number of t_1 increments. Since the covariance matrix

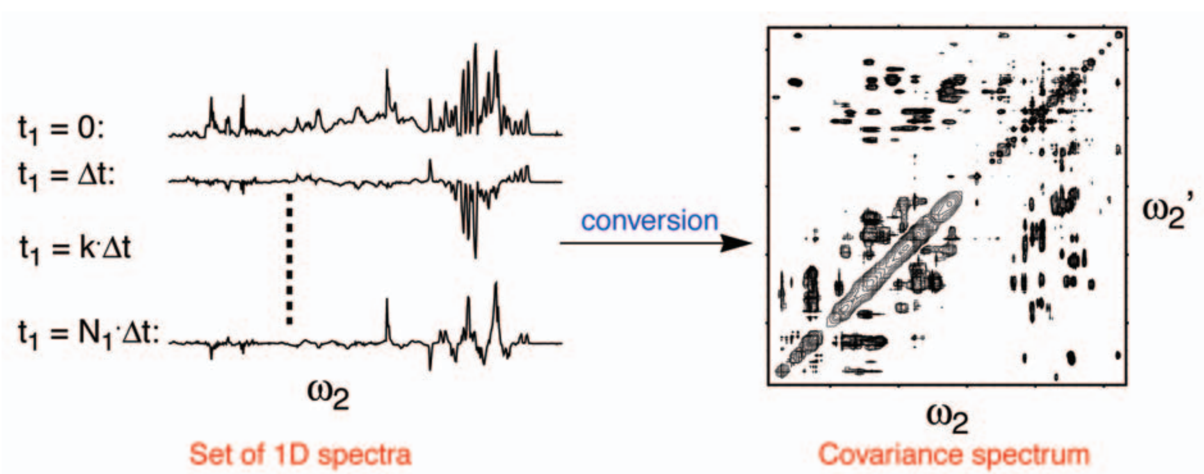


Figure 1. Concept of covariance spectroscopy: covariances between pairs of columns of 1D experiments provide access to correlation information.

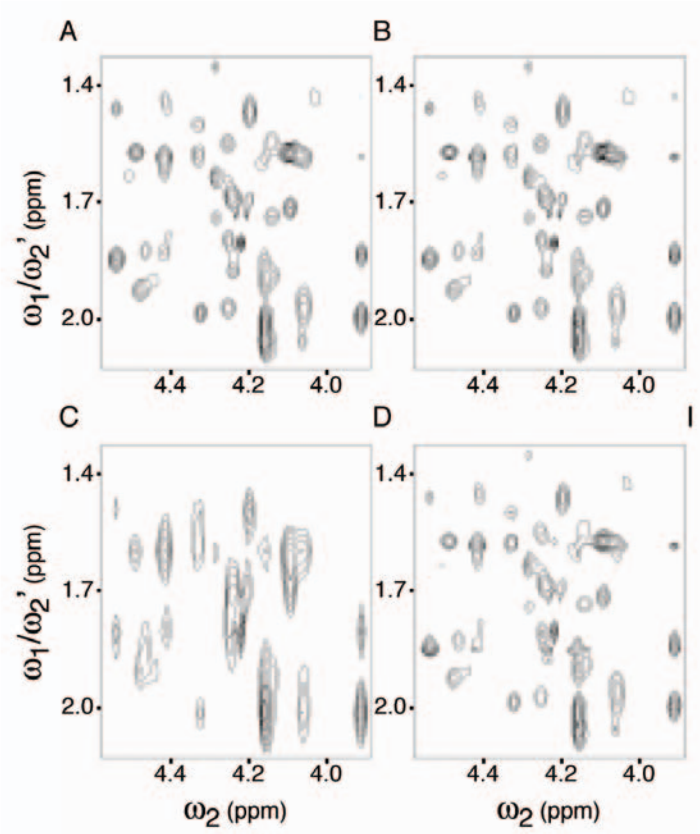


Figure 2. Comparison of spectral H^N-H^α region of a 2D NOESY experiment of ubiquitin processed by 2D FT and covariance methods. Panels A and C were produced using the standard 2D FT method, Panels B and D depict the covariance spectrum calculated by the covariance method. Panels A, B correspond to 1024 t_1 increments, whereas Panels C, D were processed using only the first 256 t_1 increments.

C scales quadratically with the input data, application of the matrix square-root operation $\boldsymbol{F}=\boldsymbol{C}^{1/2}$ yields a spectrum that resembles a corresponding idealized 2D FT spectrum.

The inherent power of covariance NMR is illustrated in Fig. 2, which shows a section of a 2D NOESY spectrum of the protein ubiquitin processed by the traditional 2D FT method (Panels A, C) and by the covariance method (Panels B, D). When the number of t_1 increments is decreased by reducing the total measurement time, the covariance spectrum retains high spectral resolution along ω_2', whereas the resolution along ω_1 of the 2D FT spectrum quickly deteriorates. The principles of covariance NMR spectroscopy can be applied to a wide range of multi-dimensional NMR experiments. A few examples are given in the following.

A well-known restriction of traditional 2D NMR experiments is the need to directly observe one of the spin species of interest during the NMR detection period. Because ^{1}H protons is one of the most sensitive spin species, almost all biomolecular NMR spectra have at least one proton dimension, even if one is not interested in the proton resonances themselves. On the other hand, for ^{13}C-^{13}C correlation experiments the relatively low ^{13}C magnetization needs to be detected in the NMR coil leading to prolonged measurement times, which scales with γ^3_{obs} where γ_{obs} is the gyromagnetic ratio of the detected spin species.

This limitation can be overcome by *indirect covariance* NMR spectroscopy,[4] which yields homonuclear spectra where both dimensions are determined by the nuclear spin dynamics during the indirect t_1-evolution period. The indirect covariance spectrum $\boldsymbol{C}(\omega_1,\omega_1')$ can be computed from the 2D FT spectrums by

$$\boldsymbol{C}(\omega_1, \omega_1') = \int \boldsymbol{S}(\omega_1, \omega_2)\boldsymbol{S}(\omega_1', \omega_2)d\omega_2 = \boldsymbol{S} \cdot \boldsymbol{S}^T \quad (2)$$

which is then subjected to the matrix square-root operation, $\boldsymbol{F} = \boldsymbol{C}^{1/2}$. Spectrum ***F*** is again symmetric displaying, however, along both dimensions spin resonances sampled during the indirect time t_1. Application of the method to the ^{1}H-^{13}C HSQC-TOCSY experiment of the fully ^{13}C-labeled cyclic decapeptide antamanide is shown in Fig. 3. It yields a homonuclear ^{13}C-^{13}C spectrum that has a 8-fold higher sensitivity than a spectrum that is directly detected on ^{13}C spins. The simplicity of the symmetric TOCSY-type spectrum allows the straightforward assignment and analysis of the spin-coupling topology network.

We have mentioned that the matrix-square root operation of covariance spectra yields spectra that are better comparable with their 2D FT analogues than the covariance spectra themselves. Because the straightforward implementation of the matrix-square root requires the diagonalization of typically rather large spectral matrices (e.g., 2048 x 2048 points), which on a modern computer workstation can take several minutes, we have developed a substantially faster approach that is based on the singular-value decomposition (SVD) of non-square matrices as frequently encountered in NMR practice.[5] A speed-up by an order of magnitude can be easily achieved without sacrificing any accuracy. The information obtained from the SVD is equivalent

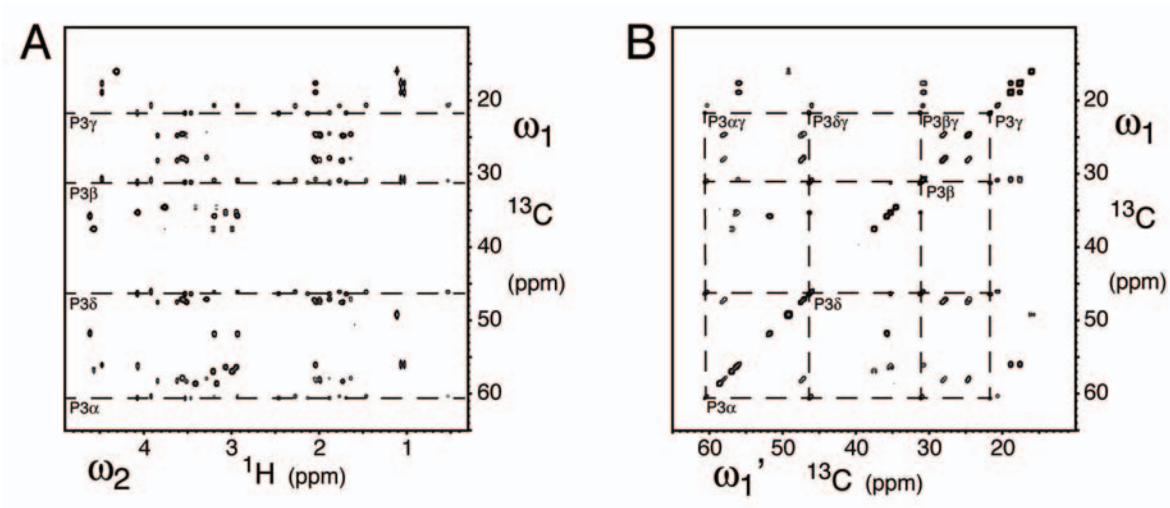


Figure 3. Indirect covariance NMR spectrum of HSQC-TOCSY experiment of the fully ^{13}C-labled cyclic decapeptide antamanide. (A) Traditional 2D Fourier transform spectrum. (B) Indirect covariance spectrum calculated according to Eq. (2).

to a principal component analysis (PCA) providing important information about the spin correlation networks that dominate the spectrum.[6]

A large number of NMR correlation experiments monitor double quantum (2Q) rather than single quantum coherences along the indirect frequency dimension. The interpretation of such spectra is somewhat hampered due to the fact that the 2Q dimension does not directly correspond to individual spins. To address this issue, a covariance-based biasing procedure has been developed that converts these types of spectra into symmetric correlation spectra that are better amenable to analysis and interpretation.[7] The procedure works well for INADEQUATE-type experiments that are widely used for the characterization of molecular ligands at natural ^{13}C abundance. By restricting the covariance terms to contributions that fulfill the double-quantum condition a significant gain in signal-to-noise can be achieved.

In summary, covariance NMR spectroscopy provides a significant speed-up for homonuclear and certain heteronuclear multidimensional NMR experiments and it facilitates their analysis. Such capability is critical for the fast-throughput and semi-automated application of NMR in the structural genomics arena for rapid spectral assignment and biomolecular structure determination and in the emerging field of metabolomics for the identification and quantitation of chemical components in biological fluids.[6]

Acknowledgements: This work was supported by the National Institutes of Health (Grant GM-066041).

1 R.R. Ernst, *et al.*, *Principles of Nuclear Magnetic Resonance in One and Two Dimensions*, Clarendon Press, Oxford (1987).
2 R. Brüschweiler, *et al.*, *J. Chem. Phys.*, **120**, 5253-5260 (2004).
3 R. Brüschweiler, *J. Chem. Phys.*, **121**, 409-414 (2004).
4 F. Zhang, *et al.*, *J. Am. Chem. Soc.*, **126**, 13180-13181 (2004).
5 N. Trbovic, *et al.*, *J. Magn. Reson.*, **171**, 277-283 (2004).
6 F. Zhang, *et al.*, *ChemPhysChem* **5**, 794-796 (2004).
7 F. Zhang, *et al.*, *J. Magn. Reson.*, **174**, 219-222 (2005).

Editor's Note: *First author Rafael Brüschweiler joined the faculty of FSU in December 2004 as the NHMFL Associate Director for Biophysics.*

News from Magnet Science & Technology

NHMFL Pulsed Magnet Achieves 75 T Operations

C. Swenson, NHMFL Magnet Science and Technology
S. Crooker, NHMFL-LANL

A new 75 T pulsed magnet prototype is now in operational evaluation at the NHMFL Pulsed Field Science Facility. Testing started in November 2004. The testing protocol required: (1) Operation at 75 T and (2) 100 pulses at 70 T to validate reliability.

The magnet attained 75 T on November 16, 2004. The magnet's insert reached a cumulative total of 100 pulses at 70 T on May 23, 2005. To date the insert assembly has accumulated 12 pulses at 75 T. The prototype will continue operations over the summer to evaluate insert performance above 70 T. The magnet is available for science experiments during this evaluation period.

The 75 T magnet project is part of the NSF effort to develop insert magnets for the NSF-DOE 100 T Multi-shot (MS) Magnet Program.[1] An important objective of the 75 T project is to gain experience operating insert-like coils in the same temperature, stress, and strain ranges that will be encountered at 100 T.

This work is integrated with the technical development of higher field pulsed magnets for the NHMFL Pulsed Field Science Facility at Los Alamos. The new 75 T magnet will be available for science until an 80 T prototype comes online for testing in the fall of 2005.

The most fundamental objective of this work is the development and delivery of the highest field pulsed magnets for research at the NSF-NHMFL Pulsed Field Science Facility. The benefits of these engineering developments are being realized scientifically. Therefore, it is appropriate to highlight aspects of the first science experiment performed in this magnet. The investigation was on the manifestation of the Aharonov-Bohm effect in carbon nanotubes.

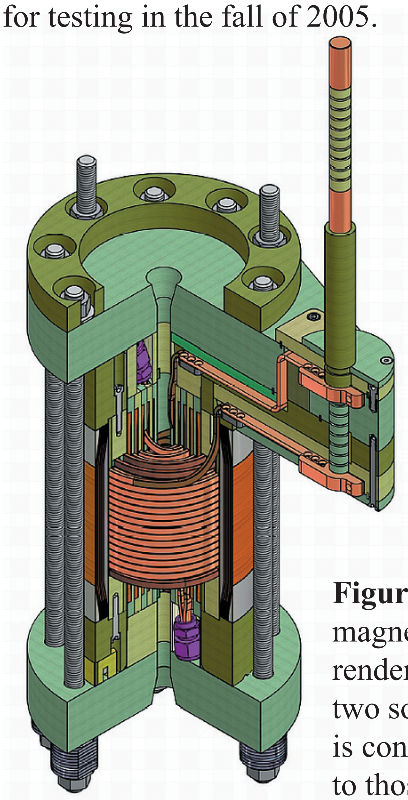
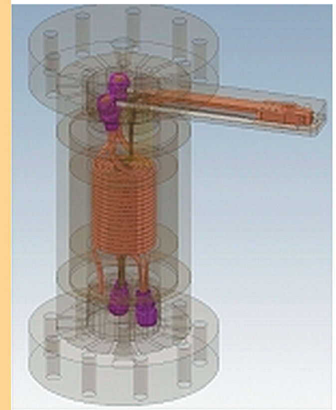
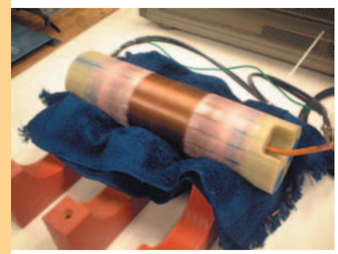


Figure 1. Quarter-section view of 75 T prototype magnet with windings and electrical power bus rendered in 3D. The 75 T magnet assembly comprises two solenoid coils nested together. The inner "A" coil is constructed with materials and techniques identical to those planned for the 100 T inserts.

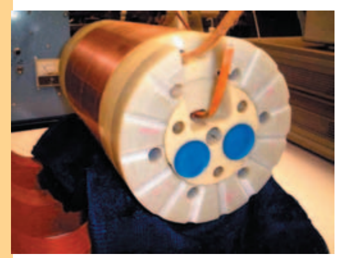
Design Concept



Insert Prototype



Nested Coils



75 T Prototype Assembly

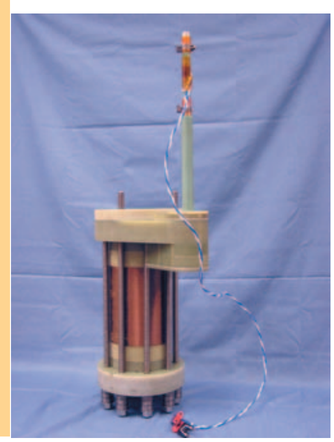


Table 1. Physical attributes of 75 T pulsed magnet prototype designed and built at the NHMFL.

Magnet	Units	Value
Peak Field	[T]	75.0
Bore Diameter	[mm]	15.5
Rise Time	[ms]	5.0
Inductance	[micro-Henry]	662
Coil Constant	[A/T]	627

Graduate student Sasa Zaric, from Prof. Jun Kono's research group at Rice University, worked with NHMFL-LANL scientist Scott Crooker to measure polarization-dependent optical absorption in single-walled carbon nanotubes in magnetic fields up to 75 T. These high-quality carbon nanotubes, prepared by Prof. Richard Smalley's research group (also at Rice University), are individually suspended by micelles in an aqueous solution, which allows them to rotate freely and orient in large magnetic fields via their anisotropic magnetic properties. Magnetic flux through the bore of aligned individual nanotubes alters the band structure of the nanotube itself through an exotic manifestation of the Aharonov-Bohm effect. This non-intuitive quantum effect is predicted to monotonically decrease the band gap of semiconducting nanotubes with increasing magnetic field, ultimately transforming them into metallic nanotubes at magnetic fields of order 2,000 T (for tube diameters ~ 1 nm). In 75 T, the observed broadening and splitting of the interband absorption peaks in semiconducting nanotubes signals the onset of this Aharonov-Bohm effect, and quantitative measurements allow direct comparison with existing theories for this effect.

This work is part of a scientific collaboration between Rice University, the NHMFL, and the High Magnetic Field Laboratory in Toulouse, France. This work represents a continuation of Zaric and Kono's previous studies, published in *Science*[2] last year, of carbon nanotube absorption and emission in the 45 T Hybrid magnet.

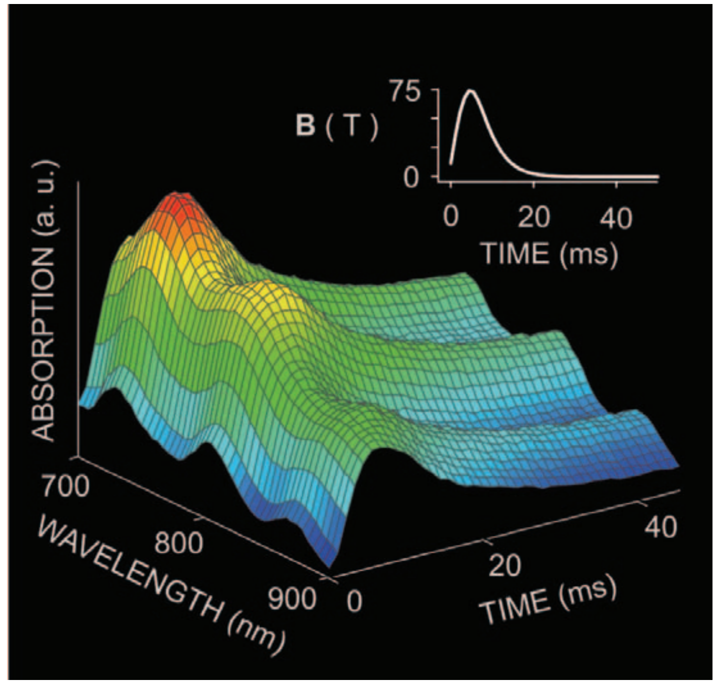


Figure 2. Optical absorption of magnetically-aligned carbon nanotubes to 75 T. Peaks in the spectra correspond to particular helicities of nanotubes.

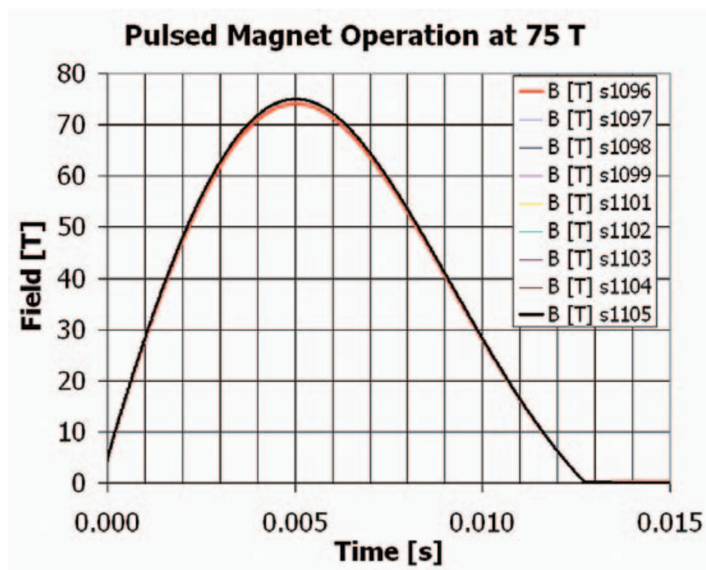


Figure 3. Multiple 75 T pulsed field waveforms integrated from B-Dot signal.

Critical members of the magnet team responsible for this work are: Ed Miller, Ken Pickard, Scott Marshall, Scott Bole, Mark Collins, Ke Han, and Steve Kenny. Dwight Rickel, Josef Schillig, Mike Gordon, and Alan Paris were essential in the execution of the 75 T high-field shots at Los Alamos.

1 C.A. Swenson, *et al*., *Physica B*, **346-347**, 561-565 (2004).
2 S. Zaric, *et al*., *Science*, **304**, 5674, 1129-113, 21 May (2004).

EDUCATION at the NHMFL

The summer months are anything but quiet at the NHMFL as the halls fill with students of all ages, teachers, and community groups. The Center for Integrating Research & Learning, with its diverse offerings that range from magnet outreach to school groups to professional development for educators, continues the tradition of quality educational programming that translates complex science conducted at the NHMFL.

Four programs are highlighted here that represent the depth and breadth of Center activities. Research Experiences for Undergraduates (REU), administered by Assistant Director Gina LaFrazza, enters its seventh year under the aegis of the Center. Research Experiences for Teachers (RET), also administered by LaFrazza, continues a tradition of excellence in providing science internships for elementary, middle, and high school teachers that began in 1999. The two-week RIMS mentorship program (see below) extends a partnership with Florida A&M University providing real world science research experience to talented high school seniors. This is the eighth year of offering teacher workshops designed to provide materials and practice in support of inquiry-based classroom science. The Center continues to demonstrate a national and regional presence and provides quality professional development opportunities and materials.

Regional Institutes for Math and Science (RIMS). For two weeks this summer the NHMFL will provide a unique opportunity for selected students participating in the RIMS. Hosted by Florida A&M University, RIMS is a program for college-bound Science, Technology, Engineering, and Mathematics (STEM) high school students to improve their academic skills in math and science. From June 15-29, 2005, Carlos Villa from the Center works with the students who are placed alongside undergraduate students participating in the NHMFL REU program. Students get valuable exposure to real world science and insight into the college experience. At the end of the program, the RIMS students will present their research to the rest of their group and then to a national audience in a seminar to be held in Tampa, Florida.

Science Summer Institute. Forty-two elementary, middle, and high school teachers work at the NHMFL for four days with Center Director Pat Dixon and LaFrazza to model and practice strategies for increasing scientific literacy. Experts from Florida State University's Center for Reading Research, educational outreach professionals from the Florida Department of Environmental Protection, and Pelotes Island Nature Preserve will provide special sessions to help teachers infuse the science curriculum with reading and writing strategies. The workshop culminates in a mock trial focusing on global warming.

The 2005 REU program is hosting nineteen talented undergraduates from colleges and universities around the country. Evelyn Mervine, from Dartmouth College, participated in the 2003 program and returned this summer to build on her geochemistry research with Vince Salters and Leroy Odom. Mervine recently published her research from the 2003 program in the Dartmouth Undergraduate Journal of Science. The 2005 program runs from June 6 through July 29. Students spend their days working in the lab and participating in weekly seminars, colloquia, and other special events in conjunction with the NHMFL's RET program and the FSU School of Computational Sciences REU program. The REU will culminate with two days of research presentations by the students.

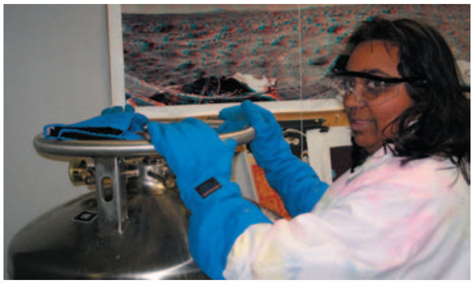
Research Experiences for Undergraduates Class of 2005

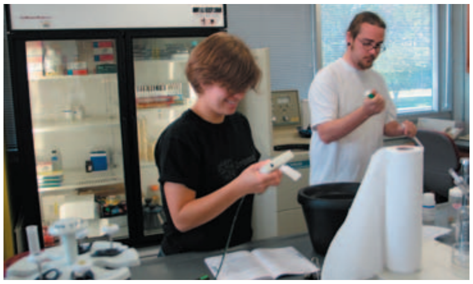
Tallahassee Research Location

Intern	University	Mentor
Emily Carpenter	University of Wisconsin	Sastry Pamidi
Lindsey Channels	Bowling Green State	James Brooks
Brian Chapler	San Diego State University	Stan Tozer
Tim Chiocchio	Florida State University	William Brey
Kristen Downs	University of Florida	Michael Davidson
Sanjiv Goli	Princeton University	Alexei Souslov
Tomi Herceg	Princeton University	Arneil Reyes
Andrew Korinda	University of Delaware	Yan Xin
Stephanie Law	Iowa State	Steve Van Sciver
Andrea Luber	Clarkson University	Tim Logan
Francisco Luongo	Stanford University	Ke Han
Kelly McKirahan	Colorado School of Mines	Dragana Popovic
Evelyn Mervine	Dartmouth College	Roy Odom and Vincent Salters
Claudia Niculas	University of Georgia	Luis Balicas
Elizabeth "Liz" Olhsson	University of Oregon	Justin Schwartz
Kathleen Schwarz	Washington University	Peter Fajer
Charles Stein	Texas Southern University	Irinel Chiorescu

Gainesville Research Location

Intern	University	Mentor
Kimberly Wadelton	Sweet Briar College	Mark Meisel
Marianna Worczak	Clarkson University	Mark Meisel





The 2005 RET program is also underway, hosting eleven teachers from as far as Hawaii. Teachers spend their days working with mentor scientists in the lab and the Center staff translating their research for the K12 classroom. The teachers also participate in weekly seminars, colloquia, research meetings, and other professional development.

Research Experiences for Teachers
Class of 2005

Teacher	School	Mentor
Ann Marie Bissoo	Sabal Palm Elementary	Bob Goddard
Margaret (Margy) Callaghan	Hawks Rise Elementary	James Brooks
Melvin C. Figueroa-Mateo	New River Middle School	Michael Davidson
Helen Follis	Roberts Elementary School	Bob Goddard
Jonathan Hamilton	Buck Lake Elementary	Michael Davidson
Soon Young Kim	Moanalua High School	Hans van Tol
Bronislava Lawhorn	Flagler College	William Brey
Jose Sanchez	Belen Jesuit Prep	William Brey
Marcy Steele	Ruediger Elementary	James Brooks
Donna Steele	Oak Grove Middle School	Alexei Souslov
Amanda Witters	Gilchrist Elementary	Alexei Souslov

Community Classroom Consortium Wins 2005 Sustainable Florida "Best Practices" Award

The National High Magnetic Field Laboratory is proud to be a member of the Community Classroom Consortium, Inc. (CCC), which has been selected as the winner of the Sustainable Florida Non-Profit Award for 2005. The CCC, a coalition of more than thirty cultural, scientific, natural history, and civic organizations in north Florida and south Georgia, provides educational experiences and resources for students, teachers, and the general public. The award, one of nine Sustainable Best Practices Awards, was presented by the Council for Sustainable Florida. On June 1, the CCC was recognized by Governor Jeb Bush and the Florida Cabinet for their achievements.

Based in Tallahassee, the CCC is known for three signature events. **Beyond the Blackboard** is a professional development event for educators that allows Consortium members to share their expertise on a variety of subjects and topics. Through its **After-School Support Project**, CCC members provide enrichment activities for students at two after-school programs in disadvantaged areas of Tallahassee. Students are exposed to hands-on experiences at museums, parks, art centers, and laboratories or receive an outreach program at their after-school center. The CCC's **Teacher Education Grants** provide stipends of up to $400 for three teachers a year to help with equipment, materials, and other instructional costs. The CCC also participates in the NHMFL's annual open house.

The Community Classroom Consortium contributes to the sustainability of Florida communities by enriching the environment, culture, and economics through nontraditional education. In every community, there is a unique assortment of cultural, historic, scientific, and artistic resources that add a distinct flavor through nonformal learning. The CCC harnesses these resources to achieve something that is beyond the reach of its individual members.

For more information about the Consortium, go to *http://communityclassroom.org*

News From NHMFL-LANL Pulsed Field Facility

S.A. Crooker, NHMFL-LANL
D.L. Smith, Theory Division, Los Alamos National Laboratory

Imaging the Flow of Spin Polarized Electrons in Semiconductors

The ability to control and measure electron spin degrees of freedom in semiconductors has been proposed as the operating principle for a new generation of novel "spintronic" devices. Semiconductor devices utilizing electron spin generally require: (i) transport of spin-polarized electrons from one location in the device to another, and (ii) a means to manipulate the electron spin orientation, either directly with magnetic fields or indirectly with electric and/or strain fields that exploit the spin-orbit interaction. Many of these device proposals are based on a field-effect transistor geometry in which electron transport occurs in essentially 2-dimensional structures. In order to design semiconductor structures whose function is based on electron spin it is necessary to understand the transport and flow of spin-polarized electrons, and how it is influenced by electric, magnetic, and strain fields in these 2D structures.

Using methods for scanning Kerr microscopy, we directly acquire 2D images of spin-polarized conduction electrons flowing laterally in bulk epilayers of lightly doped n-type GaAs.[1] The images directly reveal the spatial dependence of spin diffusion and spin drift in the presence of applied electric, magnetic, and—in particular—strain fields. Controlled uniaxial stress along the <110> axes induces spin precession (without magnetic fields), revealing the direct (k-linear) spin-orbit coupling of electron spin to the off-diagonal components of the strain tensor ε. The coupling may be characterized by an effective strain-induced magnetic field $\mathbf{B}_\varepsilon$, which is shown to be orthogonal to the electron momentum **k**, and therefore chiral for radially-diffusing spins. $\mathbf{B}_\varepsilon$ scales linearly with **k**, yielding a spatial precession of electron spins that is independent of electrical bias and is considerably more robust against the randomizing (ensemble dephasing) effects of spin diffusion as compared with precession induced by external magnetic fields.

The samples are 1 µm thick, silicon-doped (n-type) GaAs epilayers grown by molecular beam epitaxy on [001]-oriented semi-insulating GaAs substrates. Pieces were cleaved along the [110] natural cleave directions, and ohmic contacts allowed an in-plane, lateral electrical bias along this direction. The samples were mounted

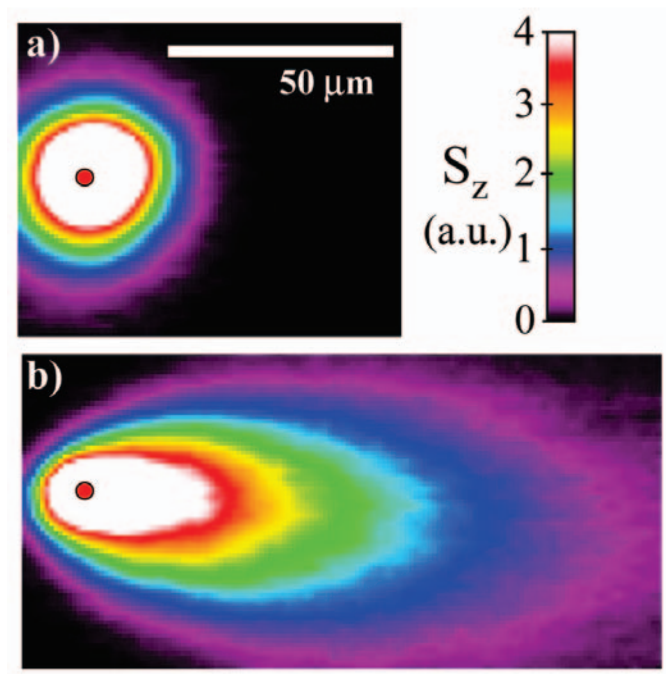


Figure 1. 70 x 140 µm images of electron spin polarization (S_z) in a 1 µm thick n:GaAs epilayer (n=10^{16} /cm^3) at 4 K, acquired via scanning Kerr-rotation microscopy. A circularly-polarized 1.58 eV diode laser focused to a 4 µm spot provides a local, dc source of spin polarized electrons (indicated by the red dot). **(A)** Here there is no applied electric, magnetic, or strain field; therefore this image indicates the 2D diffusion of spin polarized electrons. **(B)** With E=10 V/cm lateral electrical bias, showing spin diffusion and drift. Electron spin polarization can be "dragged" in excess of 150 µm.

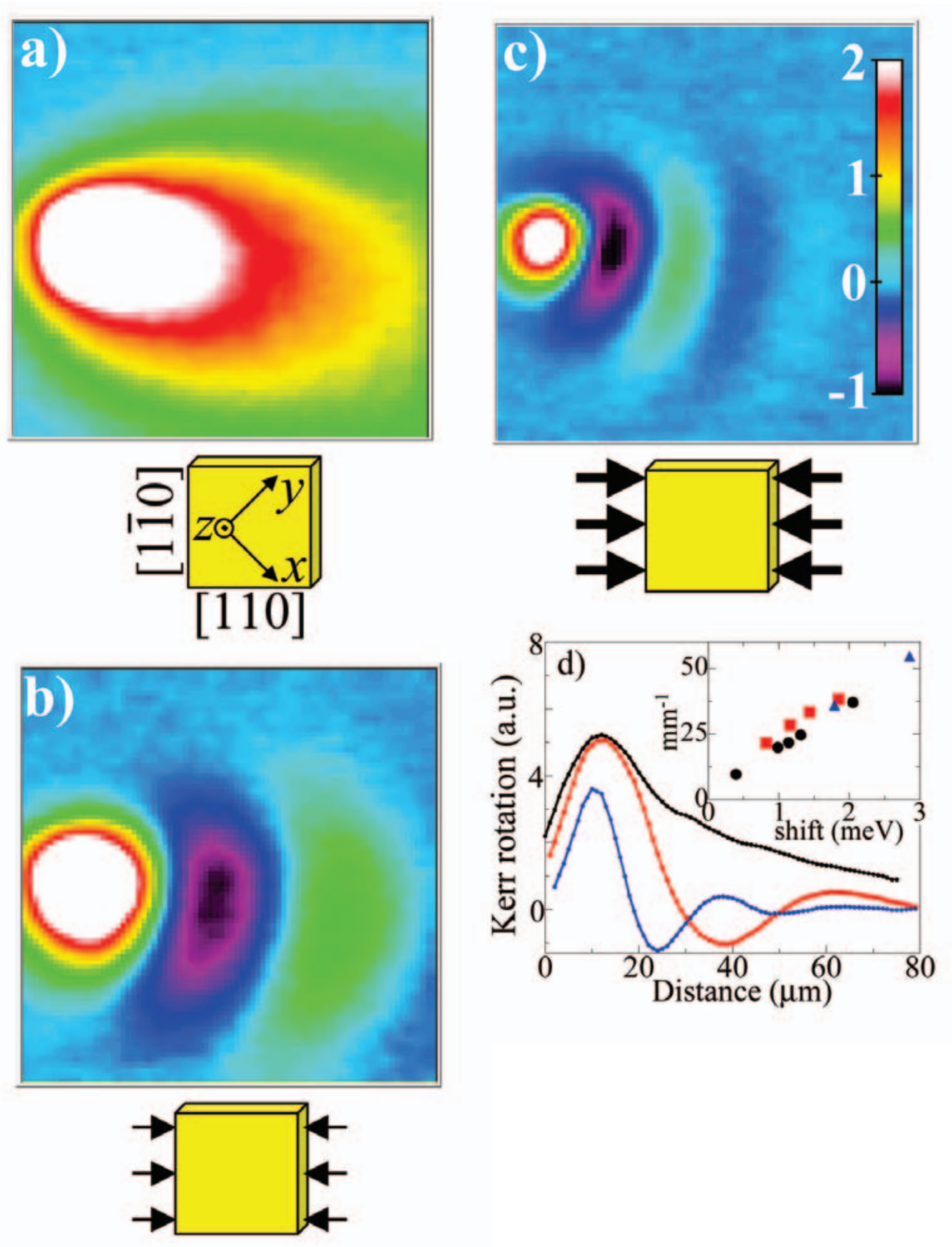


Figure 2. (A-C) 80 x 80 μm images of 2D spin flow (E=10 V/cm) at 4 K, showing induced spin precession with increasing [110] uniaxial stress. There is *no* applied magnetic field. **(D)** Line cuts through the images. Inset: Spatial frequency of spin precession vs. bandedge shift, showing that the strain induced effective field, $\mathbf{B}_\varepsilon$, is directly proportional to the applied shear strain.

in vacuum on the cold finger of an optical cryostat. To apply controlled uniaxial stress along the [110] axis at low temperature, the cold finger incorporated a small cryogenic vise, whose lead screw was adjusted via a retractable actuator.

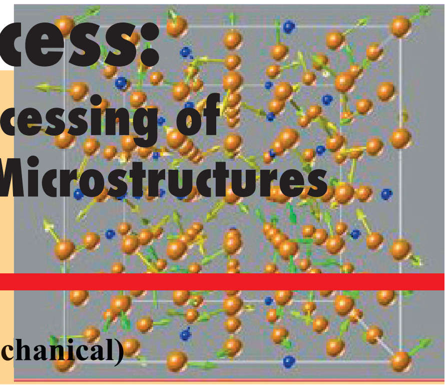
A local, steady-state source of electrons, spin polarized along the sample normal [001], or *z* direction, was provided by a circularly-polarized 1.58 eV diode laser focused to a 4 μm spot on the epilayer. This pump laser injects spin-polarized electrons and holes, the holes spin-relax and recombine rapidly, leaving a net spin polarization of the mobile conduction electrons. These electrons subsequently drift and/or diffuse laterally away from the point of generation. 2D images of the resulting *z*-component of electron spin (S_z) were acquired by measuring the polarization (Kerr) rotation imparted on a linearly-polarized probe laser that was reflected from the epilayer surface and raster-scanned in the *x-y* epilayer plane. The probe beam was derived from a tunable cw Ti:sapphire laser, and also focused to a 4 μm spot.

Images directly reveal the lateral diffusion of spin polarized electrons, and, under the influence of a lateral electric field, the drift of these electrons over 150 μm (Fig. 1). The images also directly show that spin precession of the flowing electrons can be induced—in the absence of a magnetic field—via controlled uniaxial stress along the [110] axis. (Fig. 2).

[1] S.A. Crooker and D.L. Smith, *Phys. Rev. Lett.*, **94,** 236601 (2005).

An *ATTRACTIVE* Material Process:

Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance



G.M. Ludtka, Oak Ridge National Laboratory
P.N. Kalu, NHMFL and FAMU-FSU College of Engineering (Mechanical)

The majority of high magnetic field research efforts deal with condensed matter physics topics where experiments are performed at cryogenic temperatures down to the millikelvin range. Over the last several years, however, key experiments have been conducted at the NHMFL by researchers from the Oak Ridge National Laboratory in collaboration with staff at the NHMFL/FSU/FAMU and Cummins Inc. whereby the influence of high magnetic fields on material behavior at ambient and elevated temperatures has been explored. This "magnetic field processing" endeavor is proving to be an innovative and revolutionary research focus area that is creating the basis for an entirely new research opportunity for materials and materials process development with significant technological ramifications.

Our experimental and modeling research efforts[1-7] have clearly demonstrated that phase stability (conventional temperature vs. composition phase diagrams) can be dramatically altered through the application of an ultrahigh magnetic field as shown in Fig. 1. The ability to selectively control microstructural stability and modify transformation kinetics (Figs. 2 through 5) through appropriate selection of the magnetic field strength is being shown to provide a very robust mechanism to develop and tailor enhanced microstructures with superior properties through a new and more efficient processing technology for a broad spectrum of material applications.

These results are possible since high magnetic fields modify the Gibbs free energy such that phase boundaries in the typical temperature vs. composition space become a function of the applied field. This can be explained by the following simple reasoning using ferromagnetic iron as an example. One T augments the free energy by about 5.5 J/mole/μ_{Bohr} (where μ_{Bohr} is defined as a Bohr magneton) and because the Fe moment is 2.2 μ_{Bohr} the impact on free energy that is anticipated for Fe-based materials is ~12 J/mole per T or 360 J/mole for a 30 T magnetic field. This energy compares with energies of mixing, ordering energies, and phase formation energy differences. Since phase boundaries are defined where the free energy difference vanishes, available high field magnet technology has the potential to easily accomplish shifting phase boundaries today. Other low energy phenomena such as stacking faults, twinning, short range order, antisite defects, vacancy site preferences, diffusion barriers, elastic constants, etc. are likewise potential candidates for manipulation by strong magnetic fields. Therefore magnetic field processing has the ability to significantly modify phase equilibria, microstructure, and even deformation behavior and represents a major step toward achieving "materials by design" goals.

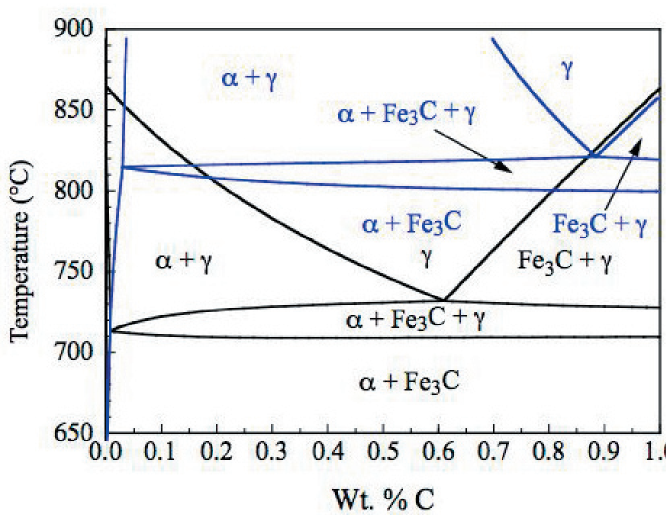


Figure 1. Prediction of the pseudobinary phase diagram for a SAE 1045 steel for conventional equilibrium (black lines) and 30 T magnetically enhanced equilibrium (blue lines). The magnetic contribution to the Gibbs free energy for incorporation into ThermoCalc for the high field prediction was determined from experiments conducted at the NHMFL *(generated using Thermo Calc, Fe-Data database).*

One of the most significant ramifications of this collaboration with the NHMFL is the demonstration that materials scientists and engineers are no longer limited to a single phase diagram (see Fig. 1) or continuous cooling transformation diagram (see Fig. 4) for a material system when defining a material and processing path to develop a specific microstructure with required properties for a custom application. 3-dimensional phase diagrams (in the Temperature-Composition-Magnetic Field Strength space) are now a reality that open boundless opportunities for significant breakthroughs to be achieved in alloy and process development research.

Another major benefit is that application of magnetic fields can augment or even replace thermal processing (temperature transients) as a processing variable. For example, we have shown that an alloy can be magnetically cycled reversibly through a phase transformation under isothermal conditions rather than having to cycle temperature about a specific first-order phase transformation temperature to achieve grain refinement. This approach has two added engineering benefits. First, the microstructure evolution can occur simultaneously and homogeneously throughout a bulk specimen, which is not the case for conventional thermal processing approaches to cause phase decomposition. The second is that the thermal and phase transformation strains that can lead to distortion, residual stress, microcracking, or failure during normal thermal processing approaches can be decoupled and minimized via the isothermal magnetic-field-induced phase transformation approach.

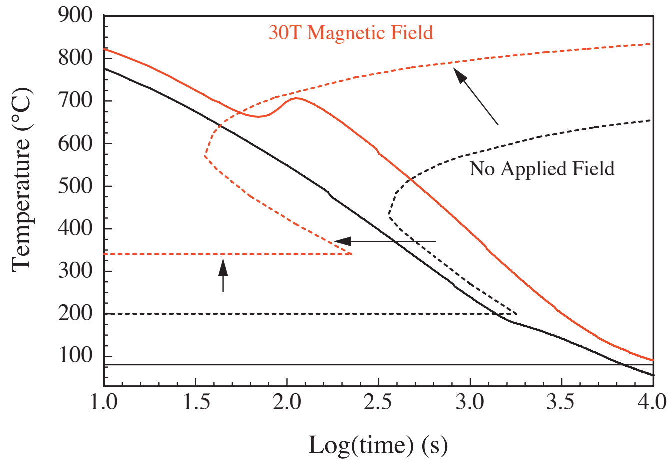


Figure 4. Application of a 30 T magnetic field during continuous cooling moves the transformation start line in the continuous cooling transformation (CCT) curve for the SAE 52100 steel upward to higher temperatures and to the left to shorter times (dotted red line) as compared with the conventional behavior (dotted black line) for this alloy. The solid lines are the cooling paths for the two test specimens with identical initial cooling rates.

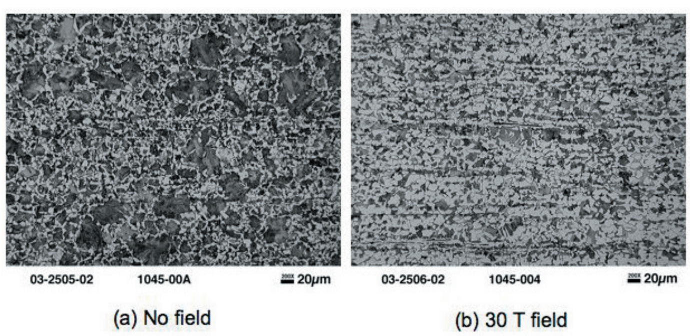


Figure 2. Microstructure for SAE 1045 steel specimens cooled at 10°C/s: (a) 40% ferrite (light phase) formed without an applied magnetic field, and (b) 65% ferrite formed with an applied 30 T field (light micrograph).

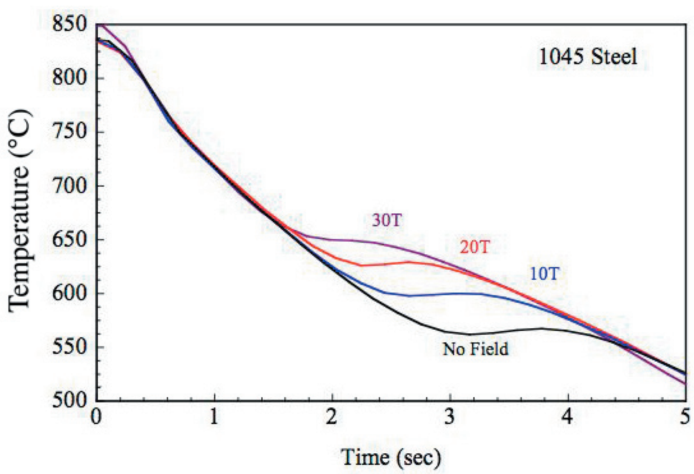


Figure 3. Continuous cooling path information showing the recalescence heat evolution indicative of a phase transformation occurring for the SAE 1045 low-carbon steel alloy for different magnetic field strengths.

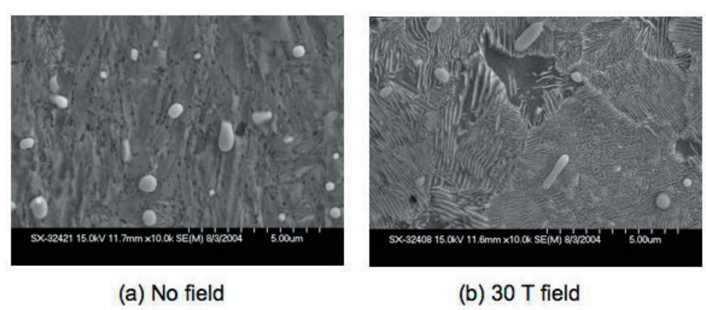


Figure 5. Microstructure of the SAE 52100 alloy samples from Fig. 4 subjected to continuous cooling at a rate that would result in martensite formation, with and without application of a magnetic field. Sample (a) shows martensite and remnant carbide; the application of a 30 T magnetic field with the same cooling rate resulted in the complete transformation to pearlite plus carbide in sample (b).

Research efforts around the world have only begun to understand the significant potential for utilizing magnetic field processing to develop the next generation of materials. Our future magnetic processing research initiative plans include investigating ferromagnetic, paramagnetic, bulk amorphous glass, bulk nanocrystalline, and carbon nanotube material systems. Our goal for developing a more fundamental understanding of the mechanisms and science behind magnetic processing will be accomplished through future *in-situ*, time-resolved characterization experiments using neutrons (initially at the High Flux Isotope Reactor and then the Spallation Neutron Source facilities of the Oak Ridge National Laboratory) to analyze these material systems while under the influence of high magnetic fields.

[1] Ludtka, *et al*., *Scripta Materialia*, **51**, 171-174 (2004).

[2] Nicholson, *et al*., *J. Appl. Phys*., **95**, 11, 6580-6582 (2004).

[3] R.A. Jaramillo, *et al*., *Scripta Materialia*, **52**, 461-466 (2005).

[4] Ludtka, *et al*., *Proceedings of the "International Workshop on Materials Analysis & Processing in Magnetic Fields,"* at the National High Magnetic Field Laboratory of Florida State University, H.J. Schneider-Muntau and H. Wada, editors, Tallahassee Florida, March 16-19, in press (2004).

[5] Ludtka, *et al., Oak Ridge National Laboratory Technical Report*, ORNL/TM-2005/79, April 2005.

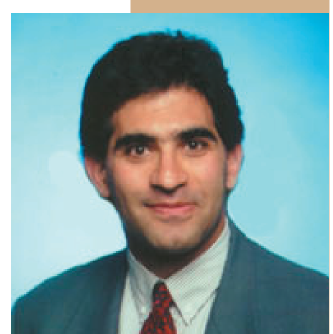
[6] Jaramillo, *et al., Proceedings of the TMS Conference "Solid-Solid Phase Transformations in Inorganic Materials 2005,"* May 29-June 3, 2005, Phoenix, AZ.

[7] Jaramillo, *et al., Proceedings of the TMS Conference "Solid-Solid Phase Transformations in Inorganic Materials 2005,"* May 29-June 3, 2005, Phoenix, AZ.

PEOPLE IN THE NEWS

ANETA PETKOVA

Aneta Petkova, a biological physicist, has joined the NHMFL/UF group. She will perform experiments at the Advance Magnetic Resonance Imaging Spectroscopy (AMRIS) facility at UF and at 900 MHz facilities in Tallahassee. She received her Ph.D. in chemical physics from Brandeis University. From April 2004 to July 2005, she was a research fellow at the National Institutes of Health in Maryland where she studied the structure and growth mechanisms of amyloid fibrils using solid state NMR and other biophysical and biochemical methods. Other research and teaching include: IRTA Postdoctoral Fellow, National Institutes of Health, 2000 to 2004; Postdoctoral Research Associate, Francis Bitter Magnet Laboratory, 1999 to 2000; Graduate Research Assistant, Brandeis University, 1994 to 1999; and Graduate Teaching Assistant, Brandeis University, 1992 to 1994. Petkova received a National Institutes of Health Fellows Award for Research Excellence in 2002 and 2004.



JUSTIN SCHWARTZ

Justin Schwartz, Professor of Mechanical Engineering, has been named the Jack E. Crow Professor of Engineering. FSU's Named Professorships recognize and honor outstanding faculty who exemplify standards of excellence in the performance of teaching, research, and service within a specific discipline/profession. Schwartz was recruited by Dr. Crow, the founding director of the NHMFL, in 1993 from the University of Illinois to support the development of the newly established laboratory. According to David C. Larbalestier, Director of Applied Superconductivity Center of the University of Wisconsin-Madison's College of Engineering, Schwartz "is THE forefront young leader in the magnet-oriented, applied superconductivity community." He has a very well demonstrated talent for leadership and has developed a broad range of collaborations, nationally and internationally. He received his Ph.D. in nuclear engineering from Massachusetts Institute of Technology and his B.S. from the University of Illinois at Urbana. His research interests include HTS applications (processing of HTS materials and their electromagnetic behavior). In endorsing the award on behalf of her late husband, Mrs. Joan Crow said "many thanks for continuing Jack's legacy."

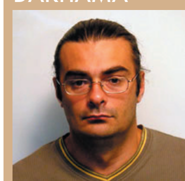
The NHMFL Welcomes Seven New Postdocs

VÍCTOR CORREA

Víctor Correa earned his M.D. in Physics from Universidad Nacional de Tucumán, Argentina and his Ph.D. from Instituto Balseiro, Argentina in 2002. His work focused on vortex structure properties in high-temperature superconductors studied by ac susceptibility, magnetization, and transport experiments. He did postdoc work at NHMFL/LANL, with the research mainly focused on heavy fermions and quantum magnet systems studied by thermal-expansion and specific heat experiments. He joined the NHMFL in Tallahassee (DC Field, User Operations) in March. His current project is the development of a thermal-expansion cell for high magnetic fields, with a focus on the spin-lattice coupling of heavy fermions and actinides at high fields, low temperatures and, in the future, high pressures. He is working with Dr. Stan Tozer.

ABDELLAH DAKHAMA

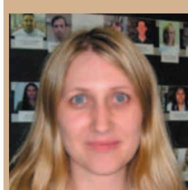
Abdellah Dakhama obtained a first Ph.D. in Theoretical and Statistical Physics in 1999 from Hassan-II University Casablanca (Morocco) and a second PhD in Condensed Matter experiment in January 2005 from Northeastern University in Boston. His thesis work was "Magnetic and Electronic Properties of Magnetic GaCrAs and Near-Field Scanning Spectroscopy Imaging." In February 2005, he joined the NHMFL in Tallahassee (DC Field, User Operations). In 1999-2000 and 2000-2001 he won the ***Lawrence Award for Academic Excellence***. In September 2002 he won the ***International Student Retention Fund*** and in June 2002 he won a prestigious grant to participate in the Summer Institute in Mathematical Studies (SIMS) on Quantum Information Theory. In 2004, Abdellah was listed in **Who's Who Among Students in American Universities and Colleges.** His areas of interest are the design and development of equipment for transport measurements and infrared spectroscopy, suitable for high magnetic fields and low temperatures. He will study the zero-resistance states in ultra-high mobility 2d electron systems under Infrared illumination in high magnetic fields (up to 30 T) and very low temperatures (300 mK). He is working with Dr. Yong-Jie Wang.



GEORGY FEDOROV

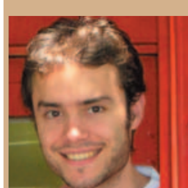
Georgy Fedorov obtained his MS at the Moscow Institute of Physics and Technology in 1994. His diploma work has been made at the Kapitza Institute for Physical Problems. He received his Ph.D. from RNC "Kurchatov Institute," Moscow in 2002. His thesis work was "Magnetic Properties of Mixed Dysprosium-Yttrium Iron Garnets at Low Temperatures." He joined the NHMFL in Tallahassee (DC Field, User Operations) in March. His current project is "Magneto-spectroscopy of and with IR and THz quantum Cascade structures." He has also worked in LNCMP, Toulouse on a project concerning transport properties of carbon nanotubes under strong magnetic fields. He is working with Dr. Dmitry Smirnov.

Catalin Martin received his Ph.D. in physics from Clark University under Dr. Charles Agosta. Originally from Romania, he received his B.S. in Physics from the University of Buchares. From 1996 to 1999, he was a research assistant at National Institute for Laser Physics in Bucharest, working on thin films deposition using the Laser Ablation technique. The title of his thesis was "RF penetration depth study of superconductivity in high magnetic field at low temperatures and under pressure." He joined the DOE / NHMFL effort on light actinides and related material as a postdoc where he will be working on experimental studies of superconductivity and fermiology of $CeCoIn_5$ and uranium under pressure in pulsed and dc fields with Dr. Stan Tozer.



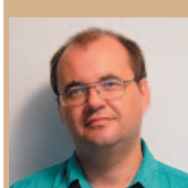
IZABELA MIHUT

Izabela Mihut received her Ph.D. in 2005 from Clark University. Her thesis was "Normal state properties of the organic superconductor κ-*(BEDT-TTF)*$_2$*Cu(NCS)*$_2$." At the NHMFL/LANL, she will work with Dr. Migliori and develop the 3ω thermal conductivity technique for pulsed magnetic field experiments in high-Tc superconductors. She will also conduct RUS measurements on correlated electron systems and superconducting materials and be involved in new projects related to measurements on DNA and proteins. Mihut was awarded a Physics Department Fellowship at the University of Bucharest in Romania from 1990 to 1994.



GAVIN MORLEY

Gavin Morley completed his Ph.D. in 2005 at the University of Oxford with Arzhang Ardavan and Andrew Briggs. The title of his thesis was "Designing a Quantum Computer Based on Pulsed Electron Spin Resonance." His undergraduate physics degree was completed in Oxford, where he received the Scott Award for teaching physics, and the Examiners' Commendation for practical work. He graduated with distinction with his Master's degree in Low Temperature Physics at Royal Holloway College (University of London), studying thin films of ^3He below 1 mK. Morley has joined the NHMFL EMR group in Tallahassee to continue his research into pulsed ESR of $N@C_{60}$ at high magnetic fields. He looks forward to doing ESR experiments that involve transient laser excitation and electrical detection. Morley will have the opportunity to use the free electron laser in Santa Barbara as a powerful source of high-frequency radiation.



OLEKSIY SVITELSKIY

Oleksiy Svitelskiy is originally from Loukhi, Karelia in northern Russia. He finished his undergraduate work at Kyiv National Shevchenko University in June 1991. After that, he worked at the Institute of Semiconductor Physics National Academy of Science of Ukraine. In 1996, he entered Graduate School at Lehigh University (Pennsylvania). He completed his Ph.D. requirements in 2002. His areas of interest are ultrasonic studies (both, pulse-echo and resonant) of various crystals, light and neutron scattering, and photoluminescence. He is working with Alexei Souslov.

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CONFERENCES & WORKSHOPS

Complex Behavior in Correlated Electron Systems
http://www.lc.leidenuniv.nl/lc/web/2005/20050801/info.php3?wsid=127
August 1-18, 2005
Leiden, The Netherlands
Contact: Vlad Dobrosavljevic
vlad@magnet.fsu.edu
850-644-5693

Physical Phenomena at High Magnetic Fields-V (PPHMF-V)
http://pphmf5.magnet.fsu.edu
August 5-9, 2005
Tallahassee, Florida
Contact: Diane Nakasone/Alice Hobbs
pphmf5@magnet.fsu.edu
850-644-9186/644-3665

24th International Conference on Low Temperature Physics (LT24)
http://www.phys.ufl.edu/~lt24/
August 10-17, 2005
Orlando, Florida
Contact: Gary Ihas
lt24@phys.ufl.edu
352-392-9244

International Conference on Ultra-Low Temperature Physics (ULT2005)
http://www.clas.ufl.edu/ULT2005/
August 11-17, 2005
University of Florida, Gainesville
Contact: Carol Binello
cbinello@clas.ufl.edu
352-392-0780

Sixth International Symposium on Crystalline Organic Metals, Superconductors, and Ferromagnets (ISCOM 2005)
http://iscom.magnet.fsu.edu
September 11-16, 2005
Key West, Florida
Contact: Jim Brooks
850-644-2836
iscom2005@magnet.fsu.edu
or Diane Nakasone
850-644-9186

8th International Symposium on Magnetic Suspension Technology
http://www.ifw-dresden.de/imw/ISMST8/
September 26-28, 2005
Dresden, Germany
Contact: Hans Schneider-Muntau
smuntau@magnet.fsu.edu
850-644-0863