QUANTUMSTATES

THE QUARTERLY NEWSLETTER FROM QUANTUM DESIGN AND QUANTUM MAGNETICS WINTER, 1994

4th ISSUE

This issue of *Quantum States* is full of both technical information and insight about progress and directions in superconductivity research. I think all of our readers will particularly appreciate the thoughtful comments on the current state of HTS by Professor John Clem, Science Editor of *High-T_c Update* since 1987.

For this fourth issue, we welcome the remarks of a group at Universität zu Lübeck concerning the extraction of small-amplitude magnetic moments from sample holder backgrounds. I believe many users will benefit from the technique suggested by Dr. Butzlaff and his colleagues, and we continue to encourage similar contributions for future editions.

For our many customers in Japan, it is my distinct pleasure to introduce our new sales and service representative in that country, INDECO, Inc. INDECO's experienced staff, under the direction of president Mr.Tohru Maruyama, is committed to providing its customers a high level of value and service. I look forward to a long and productive relationship with our new partner in Japan.

Because I am short on space, I wish you good reading. Let us hear from you.

Regards,

BARRY LINDGREN
PRESIDENT, QUANTUM DESIGN ■

QD APPOINTS NEW JAPANESE DISTRIBUTOR

Quantum Design has negotiated an agreement with INDECO, Inc. to serve as authorized sales and service representative for QD's product line in Japan. INDECO was established in 1990 to distribute products manufactured in the United States and Europe into the Japanese marketplace. The company represents several manufacturers of lasers and optoelectronic equipment, including Burleigh Instruments, Lightwave Electronics, New Focus, and Coherent Auburn Group. Led by its president Mr.Tohru Maruyama, it employs 29 people at its main office in Tokyo and its branch offices in Osaka and Tsukuba. The name INDECO stands for Independence and Cooperation, symbolizing the spirit of partnership which defines the company's business relationships.

Mr. Kuni Tomita, manager of the INDECO sales group responsible for the MPMS and PPMS product lines, said, "We are excited about our new agreement with Quantum Design. QD's products are well-engineered and reliable. Four of our salesmen and two of our service representatives are receiving training at Quantum Design's headquarters in San Diego. We expect that large markets for the PPMS will develop in Japan among universities, government research labs, and large corporations."

Mr. Tomita can be reached at INDECO's headquarters, 1-11-14, Kasuga, Bunkyo-ku, Tokyo 112, Japan,
PHONE (03) 3818-4011,
FAX (03) 3818-4015. ■

IN THIS ISSUE

CROSSTALK

SUBTRACTING THE SAMPLE HOLDER BACKGROUND FROM DILUTED SAMPLES

CH. BUTZLAFF

INSTITUT FÜR PHYSIK, MEDIZINISCHE UNIVERSITÄT ZU LÜBECK, 23538 LÜBECK, GERMANY

The normal technique for measuring the magnetization of a sample with the MPMS device is first to measure the sample, which is filled into a sample holder, afterwards the measured data are fitted by Equation 1. The amplitude, corrected for the sensitivity region and multiplied by the appropriate calibration factor, gives the magnetization of the sample. This procedure has to be repeated with the empty (diamagnetic) sample holder. The two magnetizations are subtracted from each other thus yielding the magnetization of the sample alone.

For magnetically dilute samples, which is usually the case with biological material and model compounds, this procedure fails, because the response curve of the sample often does not have the ideal pattern. This is due to the fact, that the paramagnetic response of the sample and the diamagnetic response of the sample holder are of the same order of magnitude, nearly canceling each other and that there is a small spatial offset between the two response curves along the axis of the magnet. This offset significantly depends on the sample volume used. Since diamagnetism is temperature independent this problem can also occur for a paramagnetic sample, even when the response looks good at one temperature [1].

Figure 1, which represents measurements of $C_{30}H_{52}N_6S_2O_{15}CL_2Fe_2^{III}$ at 85K in a field of 1T, demonstrates this behavior. The uncorrected data (squares) cannot be described by Equation 1. Though the amount of material used for this measurement was 54.1mg, the paramagnetic response of the sample at 85K is of the same order of magnitude as the diamagnetic contribution of the empty sample holder; this is due to strong 'antiparallel' exchange interaction of the two ferric high spin ($S={}^5/_2$) iron sites.

Data correction

We have developed a procedure which solves the above described problem by appropriate data correction [2]. First, the sample and the empty sample holder must be measured under identical conditions. Especially, it has to be taken care that the sample holder is mounted at the same position in both cases. Then the program converts the datapoints for both cases to the same sensitivity region, using the sensitivity calibration factors given in Table 1.

In general, the sensitivity regions of the two measurements are not the same. First, the data are converted for both cases to the same sensitivity region. Then, in contrast to the MPMS standard software, the program subtracts the data, *point per point* for each sample position, yielding the corrected data (circles in Figure 1). This procedure applies for each temperature or applied field. Obviously the correct data now have a pattern, corresponding to Figure 1 and are ready for a fit using the response curve[1].

EQUATION 1

$$f(Z)=x(1) + x(2) * Z + \frac{x(3)}{R} * \{2[R^2 + (Z+ x(4))^2]^{-3/2} - [R^2 + (\Lambda + (Z + x(4)))^2]^{-3/2} - [R^2 + (- \Lambda + (Z + x(4)))^2]^{-3/2}\}$$

Where Lambda (Λ) is the coil separation

The fit parameters x(1) and x(2) are taking into account a linear electronic drift and x(4) a shift of the sample along the axis of the magnet. The magnetic moment of the sample can be calculated from amplitude x(3) by multiplying with the device-dependent calibration and dividing by the sensitivity calibration factor from Table 1.

We emphasize that this procedure permits the use of any sample holder. Therefore it is possible to measure a sample in a sample holder suitable for different kinds of spectroscopy.

The solid line in Figure 1 shows the corresponding fit result with the derived magnetization being $5.78 * 10^{-4}$ emu.

---

[1] *The standard Quantum Design software uses the same response function with x (3) divided by R, while a strict theoretical calculation would yield x (3) multiplied by R, as given in the manual [4]. However, this causes no problem, because the arising difference with respect to the given response function is a fixed factor, which can be lumped together with the calibration factor. For using the original MPMS calibration factor we took the former version, too.*

Figure 1

Response of 54.1mg $C_{30}H_{52}N_6S_2O_{15}CL_2Fe_2^{III}$ at 85K. The applied field was 1T. The squares represent the uncorrected, the circles the corrected data. The Range and Gain codes are 0 and 1 respectively. Using Table 1 this leads to a sensitivity calibration factor of 2. The solid line is given by the fit using Equation 1 with x(1) =3.47V x(2) = 0.50V/cm, x(3) = 4.49V, x(4) = -0.078cm.

FIGURE 1

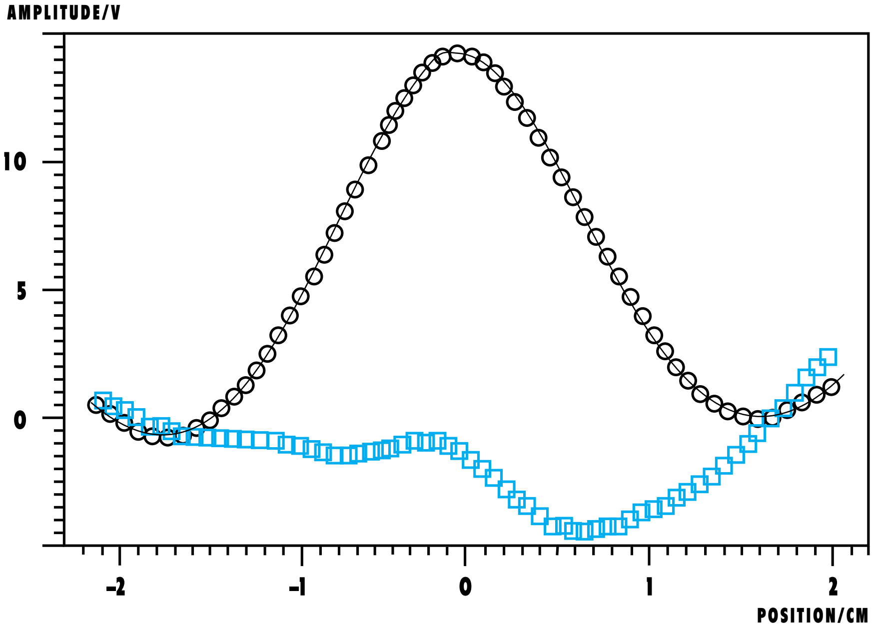


Table 1:

Parameters of the MPMS-SQUID from Quantum Design. Range and Gain Code are numbers given in the MPMS dataset for the different Range and Gain values. In our case the device dependent calibration factor is $2.569 * 10^{4}$emu/ϕ_o, with ϕ_o being the flux quantum. The amplitude of the response curve, divided by the sensitivity calibration factor and multiplied by the device dependent calibration factor yields the magnetic moment of the sample in emu.

TABLE 1

SENSITIVITY (EMU)	RANGE CODE	RANGE	GAIN CODE	GAIN	SENSITIVITY CALIBRATION FACTOR [VOLTS/Φμ]
.000125	0	1x	3	10x	10.00x
.000250	0	1x	2	5x	5.00x
.000625	0	1x	1	2x	2.00x[a]
.001250	0	1x	0	1x	1.00x
.002500	1	10x	2	5x	0.50x
.006250	1	10x	1	2x	0.20x[a]
.012500	1	10x	0	1x	0.10x
.025000	2	100x	2	5x	0.05x
.062500	2	100x	1	2x	0.02x[a]
.125000	2	100x	0	1x	0.01x
.250000	3	1000x	2	5x	0.005x
.625000	3	1000x	1	2x	0.002x[a]
1.25000	3	1000x	0	1x	0.001x

[a] *Note that the values for Gain Code 1 differ from the values given in the manual of Quantum Design [3], as those values reported in the manual for a Gain of 2x are incorrect, as verified by the factory.*

References

[1] Mike McElfresh, *Application Note #1*
Quantum Design Inc., 1992.

[2] Ch. Butzlaff, A.X. Trautwein, H. Winkler. Magnetic Susceptibility. In J.F. Riordan and B.L. Vallee, editors, *Methods in Enzymology Metallobiochemistry C.* Academic Press Inc., 1993, Vol. 227, p. 412.

[3] Quantum Design Inc., San Diego. *Magnetic Property Measurement System, Manual*, 1990.

[4] Quantum Design Inc., San Diego, *Regression Package Description*, March 30, 1988.

INTRODUCING:

HORIZONTAL SAMPLE ROTATOR FOR MPMS

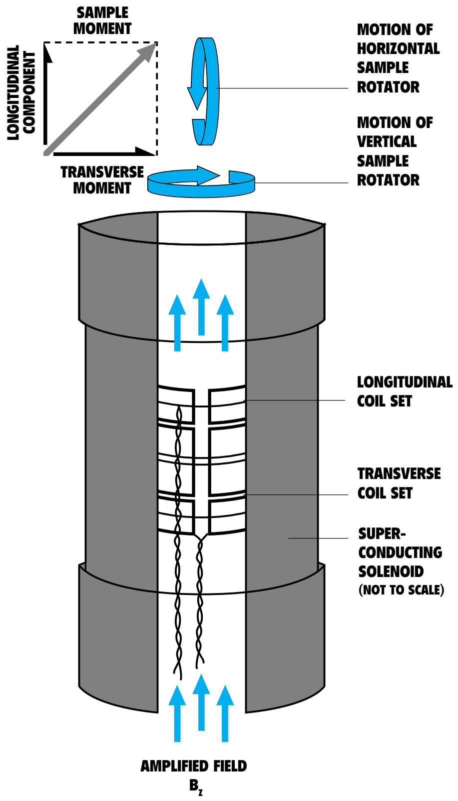
Quantum Design is now offering an accessory for the Magnetic Property Measurement System which makes it possible to measure the angular dependence of the magnetic moment of thin films or other small samples. This accessory, known as the Horizontal Sample Rotator (Option M101C), rotates the sample along an axis perpendicular to the magnetic field. It is compatible with all four MPMS models over the standard ranges of temperature and magnetic field.

Ron Sager, designer of the Horizontal Sample Rotator, said, "The sample holder is a horizontally mounted platform with a tiny pulley on one end. A spring-tensioned wire wraps around the pulley and connects to a stepping motor at the top of the magnetometer. The stepping motor pulls on the wire, which turns the pulley, causing the sample holder to rotate about a horizontal axis." The system can rotate the sample 360˚ in 2˚ steps with an accuracy of ± 0.25˚. It is made from Quantalloy, a high-purity, low-moment silicon-copper alloy; it has a magnetic moment of 10^{-5} emu.

Several of Quantum Design's customers have designed and built similar devices to study the anisotropic magnetic properties of high-temperature superconductors. Ulrich Welp and colleagues at Argonne National Laboratory measured the angular dependence of the magnetization of $YBa_2Cu_3O_{7-\partial}$ single crystals to determine the anisotropy of the upper critical field.[1] D.C. Cronemeyer and colleagues at IBM Yorktown Heights measured the angular-dependent remanent magnetization of YBCO single crystals to determine the anisotropy of the critical current density.[2]

Two groups have built sample rotators to study the angular dependence of magnetic relaxation in high-temperature superconductors. Both groups found surprising results. The first group (Tuominen and Goldman at the University of Minnesota, Chang and Jiang at Argonne National Laboratory) studied single crystals of $Bi_2Sr_2CaCu_2O_y$ and learned that when an applied field is turned off, the remanent magnetic moment quickly aligns with the c axis.[3] At high angles and low temperatures, the c axis magnetization increases with time. The second group (Zech and colleagues at Physik-Institute der Universität Zürich, Kaldis and colleagues at ETH in Zürich) studied single crystals of $YBa_2Cu_4O_8$. They found that the angle between the remanent magnetization and the c axis decreased with time at 30K but increased with time at 60K.[4]

Dave Christen's group at Oak Ridge National Laboratory has recently built a sample rotator for their MPMS. "We often measure the magnetic properties of single crystals of anisotropic materials. We built a sample rotator because we wanted to determine the effects of aligning the field in different directions and to control the orientation of our samples *in situ*," Christen said. "We're interested in studying single crystals of high-temperature superconductors that have been irradiated to create columnar defects. The way these defects pin magnetic flux vortices depends on the angle between the columns and the vortices. The vortices are like rubber bands that have varying degrees of stiffness in different materials. They're least stiff in the highly anisotropic materials, where two-dimensional pancake vortices can slide around relative to each other; that situation corresponds to a weak rubber band. Where the rubber bands are stiffer, they have to be more parallel to the columnar defects before you get significant pinning. But where the rubber bands are weak or sloppy, the pinning won't be so strongly dependent on orientation. Studies of this type are important for fundamental physics and also for technology, because they tell you about the intrinsic limits of HTS conductors."



Quantum Design's Horizontal Sample Rotator (Option M101C) makes it easier to do these types of experiments.

For more information, call Chris Gardner at (619) 481-4400 or a Quantum Design distributor.

References:

1) U. Welp et al., *Physical Review B*, Volume 40, Number 7, 1 September 1989, p. 5263.

2) D.C. Cronemeyer et al., *Proceedings from International Conference on Transport Properties of Superconductors*, R. Nicolsky, editor, World Scientific, Singapore, 1990, p. 11.

3) M. Tuominen et al., *Physical Review B*, Volume 42, Number 13, 1 November 1990, p. 8740.

4) D. Zech et al., *Physical Review B*, Volume 48, Number 9, 1 September 1993, p. 6533.

PROFILE

INTERVIEW WITH:

JOHN CLEM

**PROFESSOR OF PHYSICS,
IOWA STATE UNIVERSITY**

**SCIENCE EDITOR,
"HIGH–T_c UPDATE"**

John R. Clem is Professor of Physics and Distinguished Professor in Liberal Arts and Sciences at Iowa State University, where his research concerns the electrodynamic behavior of current-carrying superconductors in magnetic fields. Dr. Clem is a Fellow of the American Physical Society and also Science Editor of "High-T_c Update."

What have been the most important milestones in high-T_c superconductor research?

The discoveries of new materials. The pioneering discovery of copper-oxide superconductors by Bednorz and Müller inaugurated this era. Even that work would not have been so exciting, were it not for the discovery of materials with T_c in the range of 90 to 95K. Another milestone was the discovery of bismuth compounds with T_c near 110K — most people credit NRIM in Japan with discovery of the bismuth superconductor, but some claim researchers at Hoechst in Germany found it earlier and kept it secret. Then came the thallium compound, discovered at the University of Arkansas. I remember when Paul Grant stepped up to the microphone at the 1988 M^2S/HTSC conference in Interlaken and reported that his group at IBM Almaden had seen zero resistance at 125K in the TlBaCaCuO system. It was the most thrilling moment in my scientific life; the hair stood straight up on the back of my neck.

More recently, A. Schilling and colleagues at ETH reported a T_c of 133K in mercury-based copper oxides. The most exciting development of the past year has been the observation that if you squeeze on this compound — that is, apply pressures of a few hundred thousand atmospheres — you can boost T_c to over 150K. Several groups have confirmed that result, and Paul Chu's group at TCSUH has now reported a T_c of 164K at high pressures. This work suggests the possibility of raising T_c to 164K at ambient pressure by some clever substitution of chemical elements that simulates the effect of high pressure.

We've heard reports of T_c in the range of 170 to 180 K in the so-called infinite layer compound, $(Sr,Ca)CuO_2$, where each unit cell contains one CuO_2 layer, but these reports have not been confirmed.

T_c is not so high in neodymium cerium copper oxide and related materials, but they reflect an interesting symmetry because they're electron doped rather than hole doped.

Buckyballs doped with alkali atoms are superconducting — rubidium- and cesium-doped C_{60} have a T_c around 33K. A group at SUNY Buffalo recently published a report in *Solid State Communications* claiming a T_c of about 60K in iodine–chlorine doped C_{60}, but I haven't heard any confirmation. It reminds me of a report from Japan two years ago describing a T_c of 57K in iodine-doped C_{60}, but the authors withdrew that paper because nobody could reproduce the work.

How high can T_c go?

Since there's no widely accepted theory of high–temperature superconductors, there's no reasonable way to place an upper limit. In my opinion, that's cause for optimism.

Apart from their transition temperatures, what is the most interesting property of these materials?

Their strong anisotropy. In isotropic superconductors, we used to think of vortices as nearly straight strands of cooked spaghetti running all the way through the material. But in high-temperature superconductors, especially the more anisotropic bismuth and thallium compounds, the vortices look more like two-dimensional pancake vortices in the copper-oxygen planes. These pancake vortices are linked to vortices in adjacent planes by "Josephson strings," supercurrents of paired electrons tunneling through the insulating layers.

What are the most important scientific issues?

I'm keenly interested in the role of thermal fluctuations. Abrikosov, in his original work on type II superconductors, described the vortex structure as a solid; he didn't consider the agitated motion of vortices dancing away from their equilibrium positions because of thermal excitations. That made sense because conventional superconductors were superconducting only at low temperatures — Boltzmann's constant times the temperature was small, so thermal energies couldn't do much.

But in materials with a higher T_c, we have to take thermal fluctuations into account. In the absence of pinning, there's a question of what happens in the region of the field-temperature phase diagram above H_{c1} and below H_{c2}. We previously called that entire regime the "mixed state;" the Russians called it the "Shubnikov phase." We thought of it as a perfect triangular lattice of vortices. We now know that portion of the phase diagram is more complicated. Through the work of David Nelson at Harvard and others, we have learned that a melting line exists — at a fixed field well above H_{c1}, we have a vortex solid at low temperatures, then a melting transition into a vortex liquid at higher temperatures.

David Bishop and Peter Gammel of AT&T Bell Labs demonstrated this transition with a controversial experiment in which they glued a superconducting sample onto a quartz oscillator. Below the melting transition, the rigidity of the vortices added to the rigidity of the quartz, making it stiffer and giving it a higher oscillation frequency. Above

Continued on page 6

Continued from page 5

the melting transition, the vortices slop around and no longer add to the rigidity of the quartz, so the oscillator frequency drops. The Q of the resonance becomes very low at the melting transition.

This claim of melting in the flux lattice is controversial; some people prefer to think of the phenomenon as simply depinning rather than a melting transition. For example, a group in Bayreuth led by Pablo Esquinazi has done many experiments with superconductors glued to vibrating reeds. Their interpretation is that the transition is a depinning line. The debate isn't over; we really don't have an ironclad proof of the exact nature of the phase transitions in the field–temperature phase diagram.

What's the difference between a melting transition and a depinning line?

Clearly the vortices become depinned at high temperatures; the debate is about whether a model based on the concept of melting is useful. Physicists developed a model called the "Lindemann melting equation" to predict the melting temperature in ordinary solids. You start with a single crystal in which the atoms have certain masses and the lattice has a certain stiffness, then turn up the temperature. The atoms start to move around, and when their root-mean-square displacement reaches about 20% of the lattice spacing, the crystal starts to melt. That approximation allows us to estimate the melting temperature for ordinary metals. We have no detailed description of the melting transition, because the way a material melts is very complicated. But the Lindemann criterion often allows us to sweep our ignorance under the rug.

Some people have taken a similar approach to the melting of the flux-line lattice. You can calculate the displacement of the pancake vortices from their equilibrium position at low temperatures and say when the root-mean-square displacement becomes 20% of the vortex lattice spacing, the lattice ought to melt. People have derived the melting line on the basis of such a calculation.

Is the melting line the same as the irreversibility line?

The melting line concept is appropriate only in the absence of pinning. For a small amount of disorder, it's useful to think of the melting line as being shifted upward slightly because of the disorder.

When you have strong pinning centers in the material, you think instead of an irreversibility line. At low fields and temperatures, you have a pinned state with hysteretic properties of the vortex structure. Above the irreversibility line, the vortex structure becomes quite reversible, as if it were a liquid. For high-field, high-current applications, it's important that the irreversibility line be as high as possible — you want the vortices to stay put so the material can carry large supercurrents at high temperatures and fields.

What's the significance of columnar defects?

Following the pioneering experiments by Leonardo Civale and his colleagues, many people have shown that you can raise the irreversibility line by producing columnar defects in the material. As a practical strategy for producing high–T_c wires, I don't think this technique has a future because it requires high-energy ions, and even they don't penetrate much deeper than about 50 microns. But the experiments are important because they show how well the material can perform if it contains good pinning centers.

Terry Hwa and coworkers recently predicted that the columnar defects would pin flux more effectively if they were splayed out in a variety of directions, rather than aligned parallel. One way to create splayed columnar defects would be to dope the material with atoms that undergo a nuclear reaction when bombarded with neutrons. The host nuclei would emit high-speed particles that would create columnar defects in all orientations.

David Nelson of Harvard and Valerii Vinokur of Argonne National Laboratory have done some interesting theoretical work on columnar defects. They applied sophisticated theoretical models and computer routines developed for another problem, namely the properties of a two-dimensional system of bosons in a dirty two-dimensional film. They adapted this powerful apparatus to calculate and predict the behavior of vortices in high-T_c superconductors with columnar defects. In their adaptation, the c axis of the superconductors corresponds to the time axis in the two-dimensional boson problem. At zero temperature, the vortices prefer to line up parallel to the columnar defects. At higher temperatures, the thermal fluctuations kick the vortices out, and the vortices spend some time making loops and contortions outside these potential wells — they may even wander from one columnar defect to another. The Nelson-Vinokur theory gives a reasonable description of these processes. Experimentalists are testing its predictions with flux creep experiments.

What are the most interesting magnetic properties of high-temperature superconductors?

If you plot the magnetization of a high-temperature superconductor as a function of temperature for various fields, all those curves cross at one point, at the same temperature T^* and magnetization M^*. Experimentalists observed that surprising phenomenon, then theorists explained why it occurs. Abrikosov, in his pioneering work, ignored the entropy term that contributes to the free energy. Lev Bulaevskii, Marko Ledvij, and Vladimir Kogan at Iowa State were the first to incorporate the entropy term, then use the resultant free energy expression to calculate the important thermodynamic quantities, such as magnetization as a function of field and temperature. The competition between the entropy term and the Abrikosov term gives rise to the crossover at T* and M*.

What recent developments are particularly interesting to you?

Techniques for visualizing vortices. In the early 1970's, small-angle neutron scattering was used with great success to look at the structure of vortices in niobium. This technique has been more difficult with high-temperature superconductors because they have larger penetration depths, and the scattering is inversely proportional to the 4th power of the penetration depth. But several recent experiments have succeeded — a paper in a recent issue of Nature claims to show the melting transition of the vortex lattice by the scattering of neutrons from vortices in bismuth-2212.

Akira Tonomura at Hitachi has developed an electron holography technique for imaging individual vortices in superconducting thin films. He uses an electron microscope to sense the interference produced by the vortices' magnetic field. It's a dynamic technique; you can see vortices move in real time.

Other people are studying vortices with scanning SQUID microscopy, magneto-optical techniques, Hall probe arrays, and tiny scanning Hall probes. Several years ago, Harold Hess at Bell Labs visualized the cores of individual vortices in niobium diselenide with a scanning tunneling microscope. Although nobody has done this yet with HTS materials, that would be a worthwhile challenge.

What are the most important remaining questions?

The big question is the mechanism for superconductivity in these materials. Many people think it's d-wave superconductivity, which implies an electronically or magnetically based (rather than electron-phonon based) mechanism with a specific symmetry of the order parameter. David Pines of the University of Illinois is an advocate of d-wave superconductivity deriving from antiferromagnetic spin fluctuations. The materials are close to being antiferromagnets — in fact, if you don't dope them enough, they're antiferromagnetic insulators; the spins on the copper atoms alternate spin up, spin down, etc. Many people have believed for a long time that the proximity to a magnetic system is no accident, that there's a strong connection between antiferromagnetism and superconductivity. Pines and Doug Scalapino of UCSB and others are telling us that antiferromagnetism gives rise to d-wave superconductivity.

What are the prospects for applications of high-temperature superconductors?

We're seeing rapid advances in thin film applications. The major players in thin film applications are Conductus and STI. I wish them well; the success of companies like this will be critical to further development of the field. Conductus just won an R&D 100 Award for Mr. SQUID, a superconducting quantum interference device designed to demonstrate quantum effects of superconductors to undergraduate students. I expect they will sell a large number of those units to colleges and universities.

High-frequency applications such as satellite communications are particularly promising. The Navy is leading a project called HTSSE, the High Temperature Superconductor Space Experiment — they will launch modules produced by several groups into space on a satellite to test the superconducting devices.

I think hybrid semiconducting and superconducting electronic circuits will be important for future technology. Some semiconductor systems will be designed to operate at 77K for higher speed. These systems might as well take advantage of the properties of superconductivity. In the first generation of hybrid circuits, the superconducting components will be passive devices such as interconnects, transmission lines, antennas, and filters. Eventually hybrid circuits may contain active superconducting devices.

For bulk applications, the major players are American Superconductor Corporation and IGC / Intermagnetics General Corporation. They're concentrating on the bismuth compound. It's delightful that the BSCCO materials can carry large currents at 77K, even if only in low fields. It may be possible to make ac power transmission cables out of these materials; EPRI is funding some work in this direction.

At lower temperatures, in the range of 30 to 40K, these same materials can carry high currents in high magnetic fields. I recently heard a presentation by Jack Crow, Director of the National High Magnetic Field Laboratory at Florida State in Tallahassee. He talked about combining copper magnets and BSCCO magnets to create hybrid magnets which generate very high magnetic fields. He said, "At low temperatures, the superconducting materials carry plenty of current — if they had a higher critical current density, we wouldn't know what to do with it." Hybrid magnets represent a specialized niche application, but they will satisfy an important need.

American Superconductor Corporation has developed an advanced acoustic transducer which should provide superior sonar capabilities in shallow ocean waters. It's the acoustic equivalent of a radar transmitter. It contains a single crystal of an anisotropic magnetic material with a strong magneto-acoustic response: when you apply a magnetic field, the crystal expands along one axis and makes a pinging sound. To drive it you need a solenoid — in this case, a BSCCO coil.

My biggest disappointment is that it hasn't been possible to develop YBCO for large-scale application. That material has enormous potential to carry high currents in strong fields at high temperatures, but nobody has succeeded in making long lengths of it with the desired properties because of the weak link problem.

Continued on page 8

INTERVIEW WITH JOHN CLEM
Continued from page 7

On the other hand, a process known as melt texturing produces bulk samples of YBCO which are almost single crystals. The samples grow slowly, about one millimeter per hour, and the largest ones are only a few centimeters long. But they carry high currents in strong fields, and they find interesting applications in magnetic bearings and flywheels. The University of Houston is conducting work in this area. A well-known advocate of melt texturing is Masato Murakami at ISTEC in Tokyo. You may have seen the photograph of Professor Tanaka, director of the ISTEC lab, standing on a magnetic disk that was levitated over an array of Murakami's samples. Murakami told me that a Japanese company that puts on weddings wants to offer couples the opportunity to recite their vows while standing on a levitated platform. I guess that's another specialized niche application.

What developments do you expect in the science of superconductivity within the next few years?

I think we'll see further clarification of the various phases and boundaries in the field vs. temperature phase diagram. I also expect more discoveries of new superconducting materials.

I would like to see experimental confirmation of the mechanism for high-temperature superconductivity. In low-temperature superconductors, tunneling experiments confirmed the electron-phonon mechanism described by the BCS theory and the Eliashberg equations. Bill McMillan figured out how to invert John Rowell's tunneling data to calculate the a^2F function, the square of the electron-phonon coupling constant times the density of phonon states. By plugging that parameter back into the Eliashberg equations, they could calculate the observed transition temperature. Their work gave us dramatic proof of the mechanism for superconductivity in lead and niobium.

A beautiful tunneling experiment might reveal the mechanism for high-temperature superconductors, but tunnel junctions have been difficult to make reproducibly. Tunneling experiments have generated curves with wiggles that could be interpreted as phonons, but there's a general lack of willingness to accept tunneling characteristics as evidence of an electron-phonon interaction — there may be other reasons for structure in the tunneling characteristics. On the other hand, if high-temperature superconductivity is mediated by a boson other than the phonon, its frequency may be so high that the structure it produces in the tunneling characteristics will be too small to see experimentally. If that's true, we'll need a different kind of smoking gun.

I would also like to see a theory of the Hall effect and the viscous drag coefficient for vortices in the mixed state. No microscopic theory can yet explain why the Hall angle becomes large at low temperatures.

What has the field of high-temperature superconductivity meant to you?

I've invested an enormous amount of time in preparing the "Nota Bene" section of *High-*T_c *Update.* This job has consumed about 25% of my effort since 1987. *High-*T_c *Update* has made the outside world a little more aware of the fine work done by my colleagues at Ames Laboratory and at Iowa State University; it compensates for our geographic isolation. The project has made Ames a clearing house for the preprints in the field, which are still coming in at a rate of about 50 per week.

The job of preparing "Nota Bene" has forced me to read all the papers I should have been reading anyhow. Like many scientists, I tend to be lazy about going to the library. Now I don't have to go the library so often or even send off for preprints; almost every preprint comes to me. The output of papers has remained steady over the last four years, and the overall quality has improved.

Partly because of my exposure via *High-*T_c *Update*, I've received many invitations to lecture on my favorite subject, the statics and dynamics of vortices in superconductors. This work has kept me extremely busy and put stress on my marriage, but it has enabled me to visit many interesting places and meet a lot of wonderful people. My wife Judy has been remarkably cooperative in tolerating my work schedule, and we celebrated our 33rd wedding anniversary in August.

It has been rewarding to provide a service that my colleagues around the world tell me is valuable. It gives me great pleasure when leaders in the field at the most productive labs tell me that they read our newsletter without fail. And it's particularly heartening when colleagues in developing countries where they can't afford to buy *Physical Review Letters* or *Physical Review B* tell me that *High-*T_c *Update* is their window on the world of superconductivity. I'll continue to write "Nota Bene" as long as my international colleagues tell me that it's useful and continue to send us interesting papers. My dream is that some day I'll be able to write a section of "Nota Bene" with the headline "Room Temperature Superconductivity Confirmed!" ■

SINGLE-SIDED NMR

BY LOWELL BURNETT

PRESIDENT, QUANTUM MAGNETICS

Quantum Magnetics develops innovative nuclear magnetic resonance methods and equipment for laboratory and industrial applications. In the previous issue of this newsletter, we discussed Quantum Magnetics' accomplishments in NMR with SQUID amplifiers. In this issue, we discuss the company's interest in another novel technique: "single-sided NMR".

Nuclear magnetic resonance has become a workhorse technique in chemistry and life science laboratories. A researcher typically places the sample inside a signal coil, which lies within the bore of a magnet. These geometrical considerations have restricted NMR to inspection of relatively small samples.

Quantum Magnetics is developing NMR techniques which make it possible to study one side of an object without placing it inside a cylindrical bore. Our motivation is to develop a nondestructive evaluation (NDE) technique for inspecting large objects. We have applied the technique successfully to the study of composite materials and are now applying it to solid rocket motors. We believe the technique will find a wide variety of industrial applications.

Solid Rocket Motors

NASA and the Department of Defense are interested in nondestructive evaluation of solid rocket motors used to launch the space shuttle and a variety of rockets and missiles. Structurally, a solid rocket motor consists of the following parts, starting from the outside and progressing inward:

- a hard cylindrical outer case made of either steel or a composite material,
- a thin layer of thermal insulation bonded to inside of the outer case,
- an adhesive called the "liner" that bonds the insulator to the propellant, and
- a chemical propellant, which is often polybutadiene-based.

If the adhesive liner fails, a high-pressure, high-temperature pocket of gases builds up as the propellant burns. The gases burn through the insulator and the case, and the rocket explodes. This is the most common failure mode for solid rocket motors.

To avoid these failures, the people who build solid rocket motors must make sure the adhesive liner is ready to bond before they insert the propellant. NMR is potentially valuable in this context because it can measure the chemical properties of the adhesive and determine whether the curing process has proceeded enough to ensure a good bond. The conventional NMR geometry, however, would be useless because placing a large solid rocket motor inside the bore of a magnet would be virtually impossible.

Quantum Magnetics is developing a prototype single-sided NMR instrument that can inspect the adhesive liner by a noncontact scanning technique. The instrument can measure the degree of curing which has taken place and also the thickness of the adhesive layer without introducing new sources of contamination. Our most difficult technical problem was how to conduct an NMR experiment in the presence of the steel case. Steel is strongly ferromagnetic — it distorts the field profile of nearby magnets, thereby making it difficult to create the homogeneous field required for NMR studies. We solved this problem by developing a technique for including the steel case as an integral part of the magnet design.

Composite Materials

Quantum Magnetics has also built a single-sided NMR system that measures the moisture content of high-strength composite materials in aircraft. Moisture enters these materials through microcracks, then expands the cracks during thermal cycling. When the cracks become macroscopic, the material can no longer support the load it was designed for. The NMR system can enhance safety and reduce repair costs by identifying planes in which the moisture content is approaching a critical threshold.

Moisture is also responsible for other failure mechanisms. The wings of Navy fighter planes are typically made from an aluminum or fiberglass composite covered by a thin sheet of carbon epoxy composite. In the high-humidity environment typical of an aircraft carrier, moisture which enters through microcracks in the wings can build up in the underlying honeycomb. Over time, some types of aircraft can take on over 1000 pounds of moisture in this way. The moisture can interfere with the balance and the performance of the aircraft. Catastrophic failure can occur when the wings heat up during a supersonic dive, the water boils, and the wings explode. Single-sided NMR system can help to prevent this type of failure by providing a sensitive measure of moisture content.

The composite materials in aircraft can also be damaged by heat — for example, when the jet engines of one plane on an aircraft carrier accidentally heat up an adjacent airplane. The single-sided NMR system can scan the composite, sense the chemical changes in regions that have been heat-damaged, and target those regions for repair.

To repair a composite material on the outside of an aircraft, the typical procedure is to cut out the damaged area, build it up again with layers of cloth and epoxy, then apply a heat blanket to cure the epoxy. The single-sided NMR system can then scan the repaired region to confirm that the epoxy cured properly — or locate regions that didn't cure properly because of improper mixing or insufficient heat.

Other Applications

We think this single-sided NMR technology will prove its value in a broad range of industrial NDE applications, to inspect either a chemical substance near a ferromagnetic material or a product made from composites. Since NMR is the only NDE technique that is sensitive to chemical variations in composites, we expect that a broad range of manufacturers will view it as an indispensable tool in the future.

OPERATING THE MPMS BELOW 4.2 K

HOW TO OPTIMIZE MEASUREMENT TIME

BY ADO UMEZAWA AND RON SAGER

Many users of the Quantum Design Magnetic Property Measurement System (MPMS) have commented to us that one of its most notable features is its fully automated temperature control system. Indeed, the ability of the MPMS temperature control system to automatically set and maintain any temperature within its operating range is a key element in its ability to operate completely unattended after the user has set up his desired measurement sequence. Critical elements of the Quantum Design temperature control system are protected under U.S. Patent 4,791,788.

The purpose of this article is to discuss how the system operates at temperatures below 4.4K, and to provide some hints for extending the time over which you can make measurements in this temperature regime. Because the MPMS control system uses a helium reservoir of limited volume to control the temperature in this regime, it can only operate below 4.4K for a limited period of time, typically about 40 to 50 minutes when one is making measurements at its lowest temperature (about 1.9K).

To state our conclusion at the beginning, it is much more efficient to start a measurement sequence at 4.4K making measurements in order of decreasing temperature, than to cool immediately to 2.0K and make measurements while warming up. Furthermore, if one needs to operate only between 4.0K and 4.2K, the helium reservoir can last for several hours. We realize that experimental constraints may sometimes require that measurements be made in order of increasing temperature, but when possible, performing measurements in order of decreasing temperature can increase your operating time below 4.4K by as much as a factor of two, depending on the specific sequence of measurements you are doing.

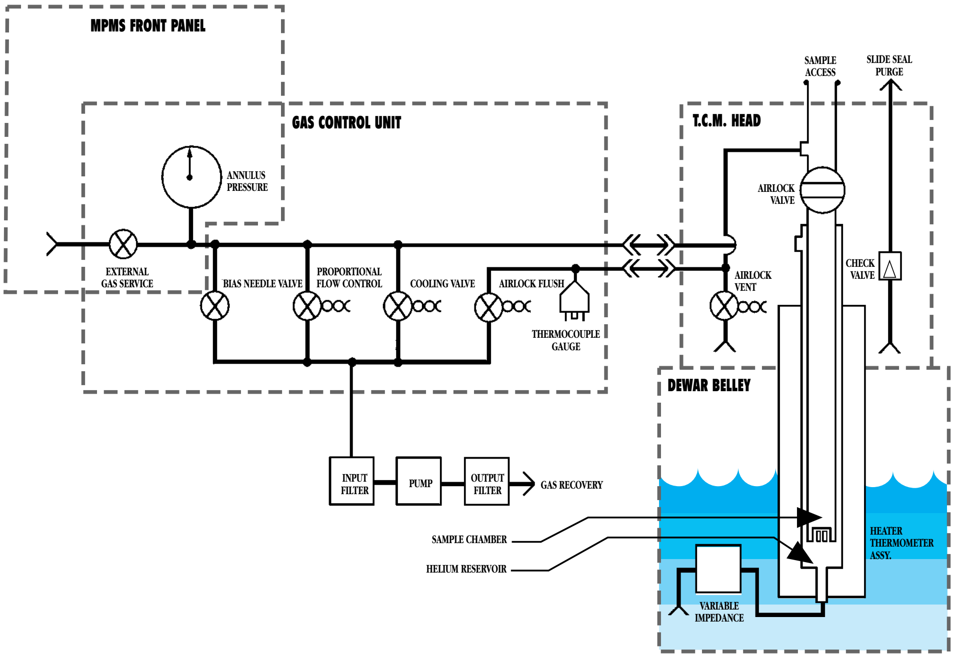
The Hardware and Principle of Operation

The schematic diagram below (taken from Figure 7 on page 45 of the MPMS Hardware Manual) shows the principal components of the temperature control system: the liquid helium dewar in which the MPMS probe is installed and immersed in liquid helium, the Variable Impedance assembly, the Temperature Control Module (TCM), the Proportional Flow Control (PFC) valve, and the vacuum pump. As shown in the schematic diagram, the impedance assembly is connected to the TCM by a small tube, and the TCM is connected to the Gas Control Unit and vacuum pump by a flexible pumping line. Also note the space inside the TCM, but outside the sample chamber, which we have labelled as the helium reservoir.

While the control system for operating the MPMS at temperatures below 4.4K is rather complex, the principle of operation is very simple. When one specifies a temperature below 4.4K, the system adjusts the PFC valve to establish a lower pressure in the helium reservoir such that liquid helium will flow through the impedance assembly and into the helium reservoir via the connecting tube. Maintaining this condition for a short period of time (typically 10 to 15 minutes) will result in the accumulation of 10 to 20 cubic centimeters (cc) of liquid helium in the reservoir.

After the desired volume of helium is collected, the impedance heater is turned on and the impedance warms up to a temperature above 200K. This is made possible by a small vacuum sleeve which surrounds the impedance tube to thermally isolate the impedance from the liquid helium bath. Since the impedance itself is a short piece of tiny tubing, warming it up (and warming up the helium gas inside the impedance vacuum sleeve), causes a dramatic reduction in the flow of helium through the impedance. So turning on the heater is essentially equivalent to closing a mechanical valve, although in the case of the warm impedance, there is still a small residual gas flow after the heater is turned on.

Once the impedance has warmed up we have essentially isolated the helium reservoir from the main helium dewar, and we can now use the PFC valve to adjust the pressure inside the helium reservoir, thereby controlling the temperature. The system cools down by opening the PFC valve to lower the pressure in the helium reservoir, and warms up by closing the PFC valve and turning on a heater to boil off a small amount of liquid,



thereby raising the pressure in the reservoir. This action can continue until all the liquid in the reservoir has been depleted. When this occurs the control system turns off the impedance heater allowing the impedance to cool down, re-initiates the filling process to draw more liquid into the reservoir, warms up the impedance, and reestablishes control at the desired temperature.

Heat Load on the Liquid Helium Reservoir

When the MPMS is controlling at a stable temperature with liquid in the reservoir, the helium loss rate is determined by heat leaking into the reservoir. This becomes clear when one notes that the evaporating helium is removing heat from the reservoir at a rate given by the product of its latent heat of vaporization and the rate of evaporation. When the temperature of the bath and sample chamber are not changing, the heat being absorbed must be entering the reservoir from external sources.

Once the reservoir is filled with liquid helium and the impedance is hot, the dominant heat load on the reservoir is the heat introduced by the residual gas flow coming through the impedance. The next largest heat leak is thermal conduction down the stainless steel tubes that form the walls of the reservoir, but the heat load from this source is much smaller than the heat load from the residual impedance flow. Furthermore, the thermal conduction down the walls from room temperature changes by less than 1% over the temperature range of 1.9K to 4.4K, so the conduction heat load is essentially independent of temperature in this regime.

However, the heat load from the residual gas flow through the impedance, which is proportional to the volume of gas entering the reservoir, is determined by the pressure drop across the impedance. Consequently, the helium loss from this mechanism is zero at 4.2K (when the pressure in the helium reservoir is equal to the pressure in the helium dewar), and is a maximum when the reservoir pressure and temperature are at their lowest values. Keep this point in mind, as we will return to it later in the discussion.

Cooling Down

Once the helium reservoir is filled with liquid and the incoming helium flow is largely shut off by the hot impedance, the system cools down to lower temperatures simply by turning off the TCM heaters and opening the PFC valve to lower the pressure in the helium reservoir. When the PFC valve is opened, the pressure over the helium reservoir drops quickly and the helium boils vigorously. The boiling, of course, represents the rapid evaporation of helium from the reservoir which cools the remaining liquid down to the temperature determined by its vapor pressure.

When operating the MPMS in this temperature regime, it is important to realize that if one starts with a certain volume of liquid helium at 4.2K, cooling the liquid down to 2.0K will consume about 40% of the total starting volume. In other words, to cool one liter of liquid from 4.2K to 2.0K, one must begin with about 1.7 liters of liquid and boil off 0.7 liters to remove the necessary heat from the remaining liter. In the MPMS this means that if the reservoir is initially filled with 20cc's of liquid helium, and the user immediately sets a temperature of 1.9K, when the system temperature stabilizes at 1.9K there will be less then 12cc's of liquid left in the reservoir.

In steady-state operation the helium evaporation rate from the reservoir is rather low. During factory testing we have typically found that MPMS systems can remain at 2.0K for approximately 40 to 50 minutes after filling the reservoir and immediately setting the temperature to 2.0K. This means that the system can operate for 40 to 50 minutes on about 12cc's of helium, assuming that the reservoir is initially filled with about 20cc of liquid.

Warming up

When the next temperature to be set is warmer than the present temperature, the system must warm up the liquid in the reservoir by raising the pressure over the reservoir. Since the only source of helium in the reservoir with which to increase the pressure is the liquid itself, the only means of raising the pressure is to evaporate additional liquid from the reservoir. This is accomplished by turning on heaters in the TCM and evaporating enough helium to raise the pressure (and temperature) to the desired value. The significant point here is that warming the system up further depletes the liquid reservoir since some of the liquid must be evaporated to raise the reservoir pressure.

Optimizing Your Measurement Time

From the above discussion there are several points which combine to determine the length of time the MPMS system will operate below 4.4K, depending on the exact sequence of operations one has specified. If one first cools down to 1.9K, then takes measurements while warming up, the reservoir operating time is reduced because:

1. Additional liquid from the reservoir is consumed by the warming process, which is not required if one collects data in order of decreasing temperature.
2. The system must operate for a longer period of time at the lowest temperature (and pressure) so helium loss from the reservoir due to the residual gas flow through the impedance is greater.
3. When you cool down immediately following the filling operation, you have the maximum amount of liquid in the reservoir, and 40% of that volume must be used to cool the remaining liquid to 2.0K.

Conversely, if you collect data in order of decreasing temperature your operating time will be substantially increased for the following reasons.

1. There will be no loss due to the warming operation since no warming is required until your measurements in this temperature regime are completed.
2. The operating time at low temperature (and pressure) is kept as short as possible, minimizing liquid loss from the residual gas flow through the impedance.

3. While making measurements at the higher temperatures, the system is continually consuming helium from the reservoir, so that the amount of helium which must eventually be cooled to 2.0K is reduced. This also reduces the volume of liquid which must be evaporated to cool the remaining liquid to the lowest temperature. (The increased operating time made possible by this savings can be substantial.)

These considerations should make it clear that performing measurements in order of decreasing temperature will provide the maximum operating time in this temperature regime. The increase in operating time achieved by starting your measurements at 4.4K and taking subsequent measurements as the system cools down can be substantial.

If you are already performing measurements in order of decreasing temperature, or your experimental constraints prohibit that possibility, you may still be able to increase your operating time below 4.4K by specifying a longer "Fill Time" for the reservoir filling operation. This parameter, which specifies the filling time in seconds, appears in the "Temperature Calibrations" menu which can be found in the "Calibration Factors" menu under the "Diagnostics" menus (F7 on the Vectra keyboard). If the original factory adjustments on your system have changed so that the helium reservoir is filling more slowly than it should, you may specify a longer filling time with this parameter, allowing a greater volume of liquid helium to flow into the reservoir before the system heats up the impedance. The factory default is 650 seconds, but a larger value for the filling time may be entered. (Changing the other "Fill" parameters can cause a complete failure of the filling operation, so we do not recommend changing any parameters besides the "Fill Time").

Changing the fill time parameter is not guaranteed to improve the operation of your system, but under some conditions it can increase the operating time below 4.4K. If your system does not stay below 4.4K for a period of 40 to 50 minutes, it may not be operating correctly. If so, please feel free to contract our Customer Service group at 1-800-289-6996 for assistance.

Recent Improvements in Software Control

In our continuing efforts to improve the function and operation of the MPMS, we have recently refined the software control algorithms which set and control the temperature in the low-temperature regime. As a result of these improvements, we are now finding during factory testing that systems typically operate at 2.0K for 60 to 70 minutes after being cooled to 2.0K immediately after the reservoir has been filled. These changes have been included in our latest revision of the MPMS Operating System Software, Revisions 2.25.3, which is now being field tested and should be available soon.

Operating Continuously at 42K

Some of our customers have noted that it would be desirable to set the temperature right at 4.2K, and hold it there for many hours. This is useful, for example, when comparing sample measurements in the MPMS to previous measurements on the sample which were performed in a liquid helium bath at atmospheric pressure. In response to these requests, we have developed a technique for operating the MPMS temperature control system continuously at 4.2K.

One can initialize the system to operate in this mode in only a few steps which require no special modification of the MPMS hardware. These steps can also be placed in a sequence file to automatically initiate this mode of operation when the sequence file is executed. The sequence steps are as follows:

1. SET TEMPERATURE 10K
2. PAUSE 600 SECONDS
3. SET TEMPERATURE 4.2K
4. IMPEDANCE HEATER OFF

The first two steps are included to make sure that the sample chamber and helium reservoir are relatively cool before the system tries to fill the reservoir with liquid helium. If the sample chamber is already at or below 20K, steps 1 and 2 are not required, but when constructing a generic sequence that can be used from any starting temperature, these steps should be included. During step 3, the reservoir fills with liquid helium, the impedance is closed, the PFC valve is opened, and the temperature is controlled at 4.2K using both the PFC valve and the heater.

Once the temperature control system stabilizes the temperature at 4.2K, the fourth step turns off the impedance heater, thereby opening the flow impedance. The "Impedance Heater" command can be found under the "Gas Controls" menu in the "Diagnostics" menu (F7 on the Vectra keyboard). In this mode the reservoir is placed in a continuously-filling condition, wherein helium from the main dewar is drawn continuously into the reservoir. Furthermore, with the PFC valve and the TCM heater operating in a feedback loop to hold the temperature at 4.2K, the system will actively hold the temperature at 4.2K, even if the dewar pressure changes. Since the helium consumption does increase when operating the system in this mode, one should set the temperature back to 10K when the measurements are complete to minimize helium consumption.

We hope that this discussion has offered you some insight into the design and operation of the MPMS temperature control system, and that some of the comments and ideas discussed above may be useful in your own measurements. If you have further questions or would like assistance in setting up more complicated temperature control processes, please contact Ado Umezawa at Quantum Design at 1-800-289-6996.

BIBLIOGRAPHY

M. Bennahmias, A.F. Bello, D. Back, H.B. Radousky, T.J. Goodwin, P. Klavins, and **R.N. Shelton,** "Magnetic properties of polycrystalline $R_{1.5}Ce_{0.5}Sr_2Cu_2NbO_{10}$ (R = Eu,Nd and Sm) high-T_c superconducting ceramics," *Physical Review B*, Vol. 48, No. 9, 1 September 1993, p. 6252.

S.J.L. Billinge, G.H. Kwei, A.C. Lawson, J.D. Thompson, and **H. Takagi,** "Superconductivity and the Low-Temperature Orthorhombic to Tetragonal Phase Transition in $La_{2-\chi}Ba_{\chi}CuO_4$," *Physical Review Letters*, Vol. 71, No. 12, 20 September 1993, p. 1903.

M. Däumling, G. Triscone, and **R. Flükiger,** "Critical currents in $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{\chi}$ powder," *Physica C* 214 (1993) p. 403.

D. Delagnes, N. Pellerin, A.R. Fert, P. Odier, A. Mari, X. Bozec, and **J.P. Redoules,** "Critical current density and activation energy in melt-textured growth YBaCuO from magnetic measurements," *Physica C* 211 (1993) p. 355.

L. Gao, Z.J. Huang, R.L. Meng, J.G. Lin, F. Chen, L. Beauvais, Y.Y. Sun, Y.Y. Xue, and **C.W. Chu,** "Study of superconductivity in the Hg-Ba-Ca-Cu-O system," *Physica C* 213 (1993) p. 261.

K. Ghosh, S. Ramakrishnan, S.K. Malik, and **Girish Chandra,** "Resistivity and magnetic susceptibility studies in the RPd_2Al_3 (R = La, Ce, Pr, Nd and Sm) system," *Physical Review B*, Vol. 48 No. 9, 1 September 1993, p. 6249.

M. W. Grinstaff, M. B. Salamon and **K.S. Suslick,** "Magnetic properties of amorphous iron," *Physical Review B*, Vol. 48, No. 1, p. 269.

P.E. Kazin, M. Jansen, N. Wagner, Yu.D. Tretyakov, S.R. Lee, V.I. Putlayev, and **A.M. Tesker,** "Magnetic characterization of the melt processed $YBa_2Cu_3O_7$ and $Bi_{1.8}Pb_{0.2}Sr_2CaCu_2O_{\chi}$ superconductors," *Physica C* 211 (1993) p. 227.

J.A. Lewis, C.E. Platt, M. Wegmann, M. Teepe, J.L. Wagner, and **D.G. Hinks,** "Superconducting properties of grain-aligned $HgBa_2CuO_{4+\chi}$," *Physical Review B*, Vol. 48, No. 10, 1 September 1993, p. 7739.

Q. Li, M. Suenaga, T. Kimura, and **K. Kishio,** "Reversible magnetic properties of $(La_{1-\chi}Sr_{\chi})_2CuO_4$ single crystals with ($0.05 \leq x \leq 0.10$)," *Physical Review B*, Vol. 47, No. 17, 1 May 1993, p. 384.

K. Moloni and **E. D. Dahlberg,** "Remanent magnetization in single crystals of $YBa_2Cu_3O_7$," *J. Appl. Phys.* 73 (10), 15 May 1993, p. 5868.

M. Paranthaman, J.R. Thompson, Y.R. Sun, and **J. Brynestad,** "Synthesis and magnetic characterization of the High-T_c superconducting compound $HgBa_2CuO_{4+\delta}$," *Physica C* 213 (1993) p. 271.

L.M. Paulius, C.C. Almasan, and **M.B. Maple,** "Enhancement of flux pinning by Pr doping in $Y_{1-\chi}Pr_{\chi}Ba_2Cu_3O_{7-\delta}$ ($0 \leq x \leq 0.4$)," *Physical Review B*, Vol. 47, No. 17, 1 May 1993, p. 627.

T.S. Plaskett and **T.R. McGuire,** "Magnetoresistance in $(Co10\ \text{Å} / Cu10\ \text{Å})_n$ multilayer films as *n* increases," *J. Appl. Phys.* 73 (10), 15 May 1993, p. 6378.

M.F. Schmidt, N.E. Israeloff, and **A.M. Goldman**, "Applicability of high-T_c paradigms to magnetic relaxation and irreversibility in superconducting Nb," *Physical Review B*, Vol. 48, No.5, 1 August 1993, p. 3404.

K. Takanashi, H. Kurokawa, and **H. Fujimori,** "A novel hysteris loop and indirect exchange coupling in Co/Pt/Gd/Pt multilayer films," *Applied Physics Letters*, Vol. 63, No. 11, 13 September 1993, p. 1586.

F. Tsui and **C.P. Flynn,** "Magnetic Phase Diagram of Epitaxial Dysprosium," *Physical Review Letters*, Vol. 71, No. 9, 30 August 1993, p. 1462.

U. Welp, G.W. Crabtree, J.L. Wagner, D.G. Hinks, P.G. Radaelli, J.D. Jorgensen, and **J.F. Mitchell,** and **B. Dabrowski,** "The irreversibility line of $HgBa_2CuO_{4+\chi}$," *Applied Physics Letters*, Vol. 63, No. 5, 2 August 1993, p. 694.

M. Wolf and **W. Gey**, "Strong magnetic relaxation toward diamagnetism and evidence for glassy behavior in $YBa_2Cu_3O_{7-\delta}$ single crystals close to T_c," *Physical Review B*, Vol. 8, No. 9, 1 September 1993, p. 6707.

J.A. Xia, H.T. Ren, Y. Zhao, C. Andrikidis, P.R. Munroe, H.K. Liu, and **S.X. Dou,** "Critical current density and the irreversibility line in melt-textured $YBa_2Cu_3O_{\gamma}$ and $YBa_2Cu_3O_{\gamma}$/Ag superconductors," *Physica C* 215 (1993) p. 152.

X. Xu and **S.A. Shaheen,** "Structural and magnetic properties of rare-earth iron nitride $Ce_2(Fe_{1-\chi}Co_{\chi})_{17}N_{\gamma}$ series," *J. Appl. Phys.* 73 (10), 15 May 1993, p. 5896.

S.I. Yoo and **R.W. McCallum,** "Flux creep in $Nd_{1+\chi}Ba_{2-\chi}Cu_3O_{7+\delta}$ (x = 0.0 - 0.1)," *Physica C* 210 (1993) p. 157.

D. Zech, H. Keller, M. Warden, Y.H. Simmler, B. Stäuble-Pümpin, P. Zimmerman, E. Kaldis, and **J. Karpinski,** "Angle-dependent magnetic relaxation studies in single-crystal $YBa_2Cu_4O_{\delta}$," *Physical Review B*, Vol. 48, No. 9, 1 September 1993, p. 6533.

QUANTUM DESIGN'S E-MAIL ADDRESS

We welcome article contributions and comments from our readers. To request a subscription please contact the Marketing Department at (619) 481-4400, Fax: (619) 481-7410, or e-mail (Internet) INFO@QUANDSN.COM.

QUANTUM
DESIGN

QUANTUM
MAGNETICS

11578 Sorrento Valley Road
San Diego, California 92121