A Newsletter from the Kavli Institute for Theoretical Physics at UC Santa Barbara

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Rapid Response to Supersolidity:

'Is It There or Is It Not?' May Be the Answer as Well as the Question

*"O, that this too too solid flesh would melt
Thaw and resolve itself into a dew!" (1.2)*

HERE HAMLET CONTEMPLATES a "phase transition" decades before the advent of classical thermodynamics and centuries before quantum mechanics. Shakespeare, ever the prescient observer, builds the metaphor for physical transformation by analogy with changes in a macroscopic collection of molecules he had witnessed—water which changes from solid to liquid to vapor as temperature increases.

> *'We thought a crystalline solid is something we all understand—rigid, reliable, stay-put.'*

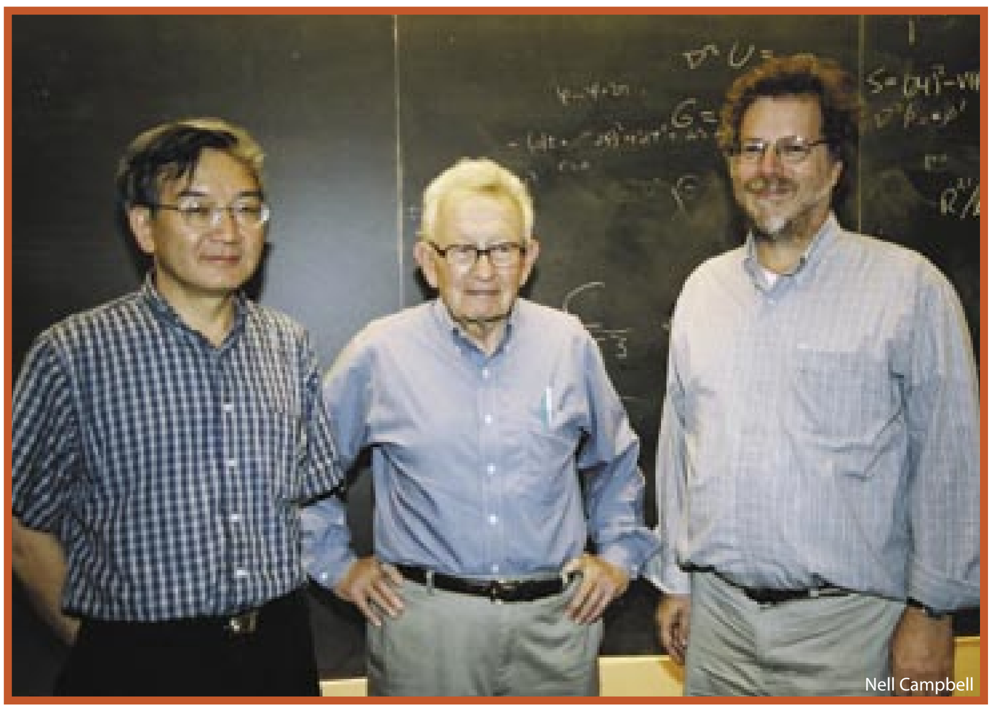
Fast forward almost exactly five hundred years since "Hamlet" was first performed at the Globe to the year 2004 and the Penn State University laboratory of physicist Moses Chan, where temperatures can be lowered to 0.2 Kelvin (0.2 above absolute zero) and pressures on a quantum crystal of helium-4 can be increased to 25 times that of earth's atmosphere at sea level. What may be emerging is a new phase of matter—a "supersolid" both crystalline and superfluid. At issue is the nature of "solid."

Said Chan, "We thought a crystalline solid is something we all understand—rigid, reliable, stay-put. Our data is indicating, 'no, not quite' if the temperature is low enough."

Theoretical solid-state physicists (Andreev, Lifshitz, Chester, and Leggett) have been envisioning supersolidity since the early 1970s.

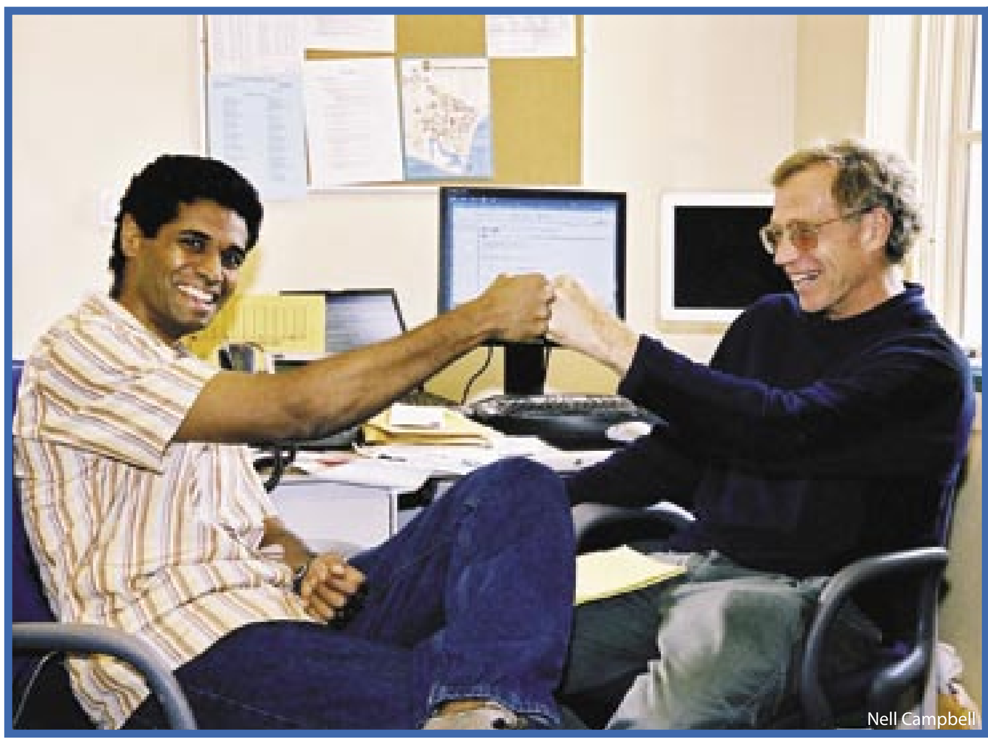
"I think theoretical physicists would say what we have seen is not impossible, but the probability of seeing a sufficiently large signature is very small. So in that sense we have exceeded the expectations of theoretical physicists," said Chan.

SEE **RAPID RESPONSE** ON PAGE 3



Nell Campbell

The KITP has instituted a singular, new kind of program—Rapid Response—to address breaking developments in science. Inaugural participants include Moses Chan (l), Phil Anderson, and David Ceperley.



Nell Campbell

Chetan Nayak (l) and Michael Freedman

Microsoft's Quantum Research Project Headed by Mathematician Takes up Temporary Residence at KITP

IN THE SPRING OF 1997, former graduate students at the University of California at San Diego invited Michael Freedman, a topologist who was awarded the Fields Medal in 1986 for his work on the Poincaré conjecture, to give a talk at Microsoft Research in Redmond, Wash. At the conclusion of that talk, an employee then there, physicist Nathan Myrvold, offered Freedman a job to work, more or less, on whatever he wanted.

Freedman's talk must have indicated to Myrvold that what Freedman wanted to work on was an idea he had in the late 1980s for possible applications of topology to computation.

Freedman accepted the job offer and assembled a small group of mathematicians and physicists to pursue the idea. That Microsoft group has taken up temporary residence at the KITP until its permanent offices are ready in the building, now under construction, that will house the California NanoSystems Institute (CNSI), located next to the side of Kohn Hall with the KITP's former main entrance.

Why locate his topnotch research group in Santa Barbara? Said Freedman, "The KITP is the center of the world for theoretical physics, I think. I wanted our group either to be in KITP or an easy stone's throw away. And that's the way it's working out. Here at Santa Barbara I am in this new growing place plus there is this physics institute, which is cycling through programs that bring everyone I would ever want to talk to right to me."

SEE **MICROSOFT'S QUANTUM PROJECT** PAGE 6

High School Teachers Need Physics Now

SOME 70 TEACHERS of physics came from throughout the United States to the KITP's fifth conference for high school teachers—this one on "Nanoscience and Quantum Computing."

David Awschalom, an experimentalist who directs the Center for Spintronics and Quantum Computing at UC Santa Barbara, put together the program for the March 24 KITP Teachers Conference in conjunction with his role as an organizer of the KITP "Spintronics" conference and program for physicists (March 13 to June 23).

The spring programming for physicists at the KITP determines the topic for the annual Teachers Conference. Not only can attendees of the physics programs be tapped as speakers, but also, even more importantly, the tie-in to current KITP programming ensures that what the teachers hear is what is happening in physics now.

As one teacher commented, "At the high school level we are largely concerned with 16th century physics (mechanics, *etc.*). It's great to get to hear research being done on some really exciting physics."

According to another teacher, "This type of conference is the most valuable in-service I have attended in 18 years of teaching. We are starved for information on cutting-edge science. To hear it from the top researchers in the world is a great treat."

The top researchers who entranced the teachers are Robert Buhrman of Cornell, James Eisenstein and John Preskill of Caltech, Stephan von Molnar of Florida State University, and Stuart Wolf of the University of Virginia.

"I wanted speakers," said Awschalom, "who could communicate effectively to both the public and to high school teachers and were also leaders in their field, so that *de facto* they are excited by what they are doing."

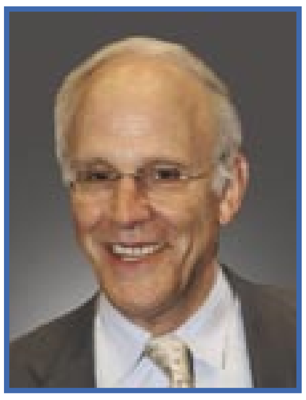
The presenters' enthusiasm for their research was contagious, as the responses of the following four teachers indicate:

- *"Only my second time to attend, but this has been the most valuable workshop I've ever attended in the way it affected me personally. I was revitalized."*
- *"This type of conference rejuvenates our interest in Modern Physics. Thank you for inviting us teachers."*

SEE **TEACHERS** ON PAGE 2

INSIDE…

From the Director


Tony Mastres

This spring we have run two programs that get to the heart of quantum mechanics. One is "Spintronics," which is centered on the attempt to use quantum spin of the electron to convey information and control devices. The other is "Topological Phases and Quantum Computing," an attempt to use a quantum mechanical system to construct an incredibly powerful computer that could out-perform existing classical computers by a wide margin.

These programs illustrate to me how central quantum mechanics is in modern physics, clearly at the atomic and of course subatomic scales. In conjunction with the programs, we held a conference for high school teachers on "Nanoscience and Quantum Computing," that led me to think about quantum mechanics in terms of education.

Many—probably all—physicists still feel a bit uncomfortable with quantum mechanics, shaped as we are in our education by classical notions of determinism and reality. Yet quantum mechanics works so well that no one has come up with an alternative picture though many, from Einstein onward, have tried.

Some of my colleagues believe that eventually quantum mechanics will have to be replaced by something more "real." I myself regard this eventuality as unlikely. If there are conceptual revolutions in the future, they are only going to make things worse not better—less classical, stranger than ever.

I have an idea that the reason we find quantum mechanics so difficult is due to our poor training. Quantum mechanics is only 70 years old—that's a short time in the history of physics for dramatic new concepts to sink into the consciousness of the field. And we are only learning, as we go along, to teach quantum mechanics better and better to our younger students, who understand it much better than the inventors did. Thus I think eventually—maybe 100 years from now, when quantum mechanics is taught in high schools (and we don't first teach classical physics and then tell the students, "That's all wrong, think quantum mechanically"), then and finally then—we will feel comfortable with quantum mechanics.

Of course by then we might have (probably will have) new conceptual revolutions that will make things appear mysterious and confusing once again.

Endowment Fund

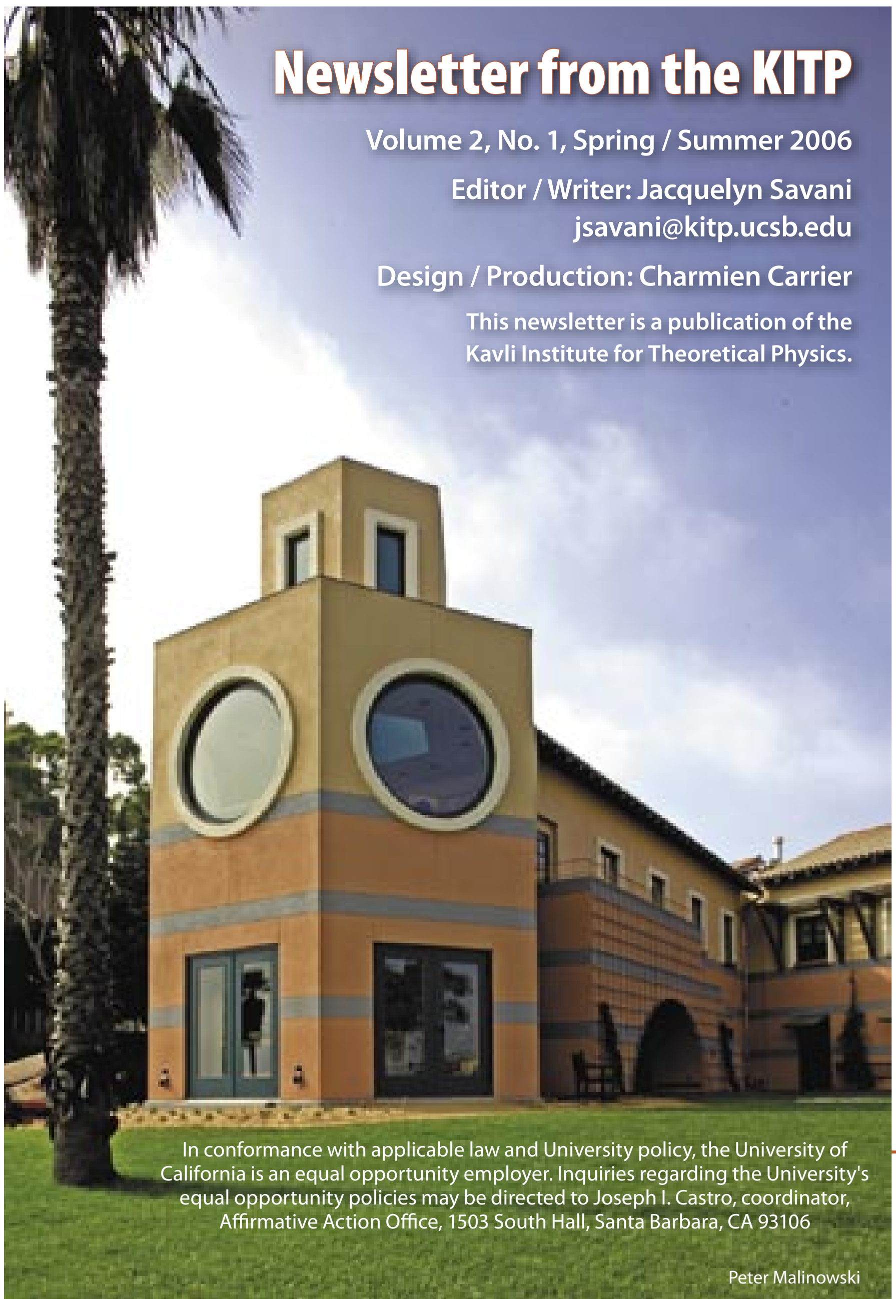
You will have noticed that this second issue of the "KITP Newsletter" contains a remittance envelope to encourage readers—our dear friends and colleagues around the world—to contribute to the KITP endowment fund. Its purpose is twofold: to enable the KITP to initiate new and exciting programming efforts—to experiment!—and to buffer us against the vicissitudes of federal funding. Please take a moment to consider and, we hope, to respond.

Director's Council

The Director's Council has seen a shift in leadership. Fred Gluck and Joe Alibrandi, who are the founding co-chairs of the Council, have given over that role to John Mackall, who has replaced them as chair. We welcome a new member, Simon Raab.

Finally, we all mourn the loss of Eli Luria, a good friend of the KITP, who served on the Director's Council till his passing in March.

David Gross



Newsletter from the KITP

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Peter Malinowski


Nell Campbell


Nell Campbell

Above, Teacher Conference participants, dressed casually in reds for the Santa Barbara event, Jon Anderson (l) from Minnesota, Randall Dunkin from Ohio, and Mark Toney from Washington (state) with conference organizer David Awschalom

Left, teachers Ed Kunitz (l) from Illinois, Patricia Spackman from Pennsylvania, and Steve Buster from Kansas.

Below, teachers Wayne Hild and Dan Stewart from California


Nell Campbell

Teachers

CONTINUED FROM PAGE 1

- *"I can use some of the info in class. But I love being brought up to date. This is energizing to me."*
- *"Re-energized my passion for physics."*

Other teachers noted the benefits to their young students:

- *"These types of conferences are very unique and most informative in regard to 'frontiers of science.' I find them most helpful. My students always look forward to my return to tell them about what I have discovered and learned in science."*
- *"This is the best part of my year. I bring back excitement and knowledge, which I cannot get elsewhere."*
- *"I teach locally and have attended 3 of these conferences. I have incorporated certain topics into my teaching (e.g., brief coverage of string theory when covering make-up of matter and energy). Plus each conference inspires me to a higher level of excitement in my own continuing study of physics."*
- *"Both of the conferences I have attended have reinvigorated my teaching."*
- *"This series of conferences has been the best I've ever attended. I have used almost every presentation in my classes."*
- *"Many good ideas for bringing modern topics to the classroom were discussed. More so, the talks were of great personal interest."*

Of the 70 teachers attending, 44 put their responses to the March 24 experience in writing. Their overriding message was one of gratitude for being revitalized and connected with physics as a live, rather than a dead, enterprise.

Each of the comments quoted in this article is from a different respondent to the question "Do you feel this type of conference is of value to your teaching?" Here are four more:

- *"It is of extreme value to physics teachers. This is one of the best connections between high school teachers and the science and technology of the day."*
- *"It is very important to bring current topics into your teaching."*
- *"One of the top (perhaps the best) ways of communicating state-of-art science (both content and methodology) to teachers."*
- *"Science teachers need to be with scientists as part of our regular routine."*
- *"Definitely one of the best opportunities I've had to expand my content knowledge in physics."*

In addition to being available for the first time as a Podcast, the whole Teachers Conference in audio only or in audio-visual format can be accessed via the KITP web site at www.kitp.ucsb.edu by following the links from (far right list) "Talks on Line."

Since the teachers' comments indicate that a little effort does, in some cases, go such a long way, please consider alerting high school physics teachers to this resource.

KITP Director's Council

The Director's Council is made up of leaders in fields other than physics, but with an interest in physics, who meet several times a year to provide the KITP leadership with invaluable support and advice. Chaired by John Mackall, the Council also includes Joe Alibrandi, David L. Brown, Virginia Castagnola-Hunter, K.C. Cole, Michael Ditmore, Fred Gluck, Gus Gurley, Stuart Mabon, Simon Raab, and Derek Westen. For profiles go to: http://www.kitp.ucsb.edu/community/director.html.

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Rapid Response to Supersolidity

David Ceperley, a theoretical solid-state physicist at the University of Illinois at Urbanna, said, “We thought the probability was low because in a solid we think of atoms as localized at the sites. Push on one side of a lattice of atoms in a solid and the atoms should just stay where they are and not move. But then there were these theories that a supersolid phase should exist. There have been searches since the ‘70s that till 2004 have come up with nothing.”

Chan did not find supersolidity by chance. He said, “A colleague at UCSD [University of California at San Diego], John Goodkind, had done some ultrasound measurements over the years, and he saw something rather unusual. The signature he found, while complicated, suggested a phase transition takes place in solid helium near 0.2 Kelvin. John Goodkind’s findings said to me, ‘There’s something funny here; maybe we should take a look.’ ”

Chan decided to employ a technique developed by his PhD mentor, Cornell University physicist John Reppy, in the 1970s. That approach enabled Chan to measure directly the non-classical rotational inertia (signature of a supersolid) that Ceperely’s Illinois colleague and 2003 Physics Nobel laureate Tony Leggett had specifically calculated.

‘Large defects in the crystal seem to be important to the phenomenon.’

What the experiments say about supersolidity and what the theorists thought are not, however, in complete agreement.

Such a confusing picture proved perfect for initiating a new kind of effort at the Kavli Institute for Theoretical Physics at the University of California at Santa Barbara—Rapid Response. Initially supported through Kavli Institute funding, the Rapid Response program aims to address breakthroughs such as Chan’s in a timescale of months instead of the customary one to two years.

Address how? By bringing together from around the globe, some 30 aficionados of supersolidity to tackle intensely the issues associated with “The Supersolid State of Matter” (Feb. 6 to 17, 2006). Chan and Ceperley orchestrated the Rapid Response.

The first exciting development of the two-week mini-program—and there were at least two developments that have, according to Ceperley, “changed the nature of the discussion”—was the announcement of confirmation by three other experimental groups of Chan’s discovery. All three groups were represented at the Rapid Response program: John Reppy from Cornell University; Keiya Shirahama of Keio University, Japan; and Minoru Kubota of the University of Tokyo. That was an important milestone for supersolidity because it dispelled for theorists the specter of experimental non-reproducibility and therefore hesitancy about pursuit of theoretical understanding.

The fact of the KITP Rapid Response seems to have speeded up the process of experimental confirmation because the experimentalists pushed to complete confirming experiments in order to report and discuss their findings at the KITP mini-program that brought together a more exotic type of attendee to KITP programs—experimentalists—with the staple participant—theorists.

Take that old fixture of ‘50s house parties, the Lazy Susan tray, and load it with perfectly smooth ball bearings instead of nuts or mints. Now put a saucer on top of the ball bearings and rotate the Lazy Susan. If the ball bearings and saucer were to behave like a supersolid, the saucer despite the moving Susan would not move.

So what is supersolidity? A deep physics, as opposed to a visually analogous explanation (via Lazy Susan laden with ball bearings topped by a plate) requires understanding of the difference between two overriding types of quantum entities—the boson and the fermion (See box below).

A supersolid refers to a different phase of matter exemplified in Chan’s experiments by a system of helium-4 atoms. The operative word here may be “system” because it looks like a very small amount of something else—leading to defects in the perfect crystalline structure of a solid’s lattice—may be key.

In helium-4 the atoms are bosons in contrast to helium-3 in which the atoms are fermions. The nucleus of helium-4, about 99.99986% of the helium on earth, contains two protons and two neutrons. Cooled to below 2.17 Kelvin, helium-4 becomes a superfluid, whose properties differ from those of an ordinary liquid. When, for instance, cooled helium-4 is kept in an open vessel, a thin film climbs the vessel’s sides and flows over the vessel lip. Because of the lack of viscosity (friction between the atoms of the vessel and the atoms of the fluid), a superfluid set in motion in the vessel will rotate forever.

What Chan did in his lab was to take liquid helium-4 into its solid state by increasing the pressure in order to get within the solid component of the system superfluid behavior. Essentially the solid contains a superfluid and that combination is the new state of matter—supersolidity.

The main outlines of the theory for supersolidity before the Chan experiments and the Rapid Response to them hypothesize that, within the solid, holes or vacancies—places where atoms aren’t—would behave like a gas of particles, which itself could form a condensate and behave like a superfluid. But the simple picture sketched by those theoretical speculations doesn’t quite stack up with Chan’s experimental results.

To begin with, said Ceperley, “Moses measured the heat capacity of solid helium much more accurately.” Chan’s experiments going on at Penn State, while the Rapid Responders were meeting in Santa Barbara, revealed an unusual measurement of thermodynamic response.

“Whenever there is some new phenomenon happening,” said Chan, “physicists usually like to think about how it corresponds to the energetics of the situation. We put a certain amount of heat into the system to see how much the temperature will rise. If the system can absorb a lot of energy without raising the temperature, then the system has a large heat capacity. Over the history of physics, we have learned how to use this information to tell us what is going on in the system. If solid helium were to behave like a typical solid, then the heat capacity would increase as the third power of the temperature. But,” said Chan, “we are seeing at the very low temperature, where we see the superfluid response, a deviation from the third power dependence on temperature below 0.2 Kelvin.”


Nell Campbell

In the new KITP auditorium, William Mullin (l), Mark Robbins, and John Toner participate in the Rapid Response workshop on supersolidity.

The big question is whether a phase transition to supersolidity is occurring around 0.2 Kelvin. During the Rapid Response program, findings issuing from Chan’s lab failed to detect a peak or bump in the heat capacity curve that would signal the transition. The findings mystified Ceperley and led at least one prominent theorist participating in the Rapid Response program, Princeton Nobel laureate Phil Anderson, to speculate that the transition occurs at absolute zero.

Written soon after the Rapid Response program ended, the first draft of this article reported no bump. Six weeks later, the bump expected by theorists may be emerging from the ongoing experiments in Chan’s lab. “We are doing more measurements to nail this down,” he said.

In addition to experimental confirmation for the phenomenon of supersolidity, the other key development emerging from the Rapid Responders’ consideration of the experimental evidence for supersolidity is that how the crystal is grown appears to be important.

According to Ceperley, “Large defects in the crystal seem to be important to the phenomenon. This thing is at more than 25 atmospheres pressure, and the holes—voids in the crystal which we had theorized would give rise to supersolidty—would have collapsed under that pressure.”

Since, the Rapid Responders reason, there are strong theoretical hints that supersolidity cannot happen in a perfect crystal, there is a very strong likelihood that defects are key. So what kinds of defects might be in play if defects understood as “holes,” very roughly analogous to “holes” in the conventional semiconductor paradigm, can’t withstand the pressure?

Well, there is something called “zero point vacancy” or quantum mechanical vacancy. Ultimately related to the uncertainty principle, zero point vacancy means that, to a very minute extent, since a thing’s location cannot be pinpointed, it may not be there. The probability that a thing is not completely there depends on several things, but especially mass, so that the lighter a thing (an atom of helium is quite light), the more likely it isn’t there. Theoretically, this vacancy can go around and form a big loop such that when the system containing it is measured, it would appear that its mass is not there. And that mass that is both there and not may be the signature of the supersolid’s superfluidity.

Said Ceperley, “If supersolidity turns out to have something to do with defects, then helium-4 will provide a simple system to understand how quantum defects work because there are defects in things like metals such as copper, which are really complicated because they have all sorts of impurities. So there is possible long-term impact of this research on metallurgy.”

Said Chan, “Another very curious thing we have seen in our experiments is that when we mix a very little helium-3 (a fraction of a part per million) into helium-4, it has a very great deal of influence on what we see. There is some indication that the supersolid response becomes very small the less the helium-3 (less than one part per billion). Our theoretical friends say, ‘Well, maybe helium-3 as impurity is the source for causing the defect in the system or that this impurity has a great deal of influence on the phenomenon.'

“This work may have materials science implications,” said Chan, “but perhaps most importantly when we try to understand this phenomenon that is very counterintuitive—such that a fraction of a solid can flow with no friction—then we will understand what we mean by a solid because all the things we talk about in terms of defects are in all other solids.”

The NSF has provided funding for Chan’s research since 1979. Ceperley, an expert at numerical simulations, is also affiliated with the National Supercomputing Center at Illinois.

How to Tell a Fermion From a Boson

***ALL PARTICLES IN THREE-DIMENSIONAL SPACE** are either bosons or fermions. What distinguishes one from the other is not a simple matter: essentially it’s whether the particle’s spin is integer (e.g., 0, 1, and so forth) or half integer (e.g., 1/2, 3/2, and so forth). These two classes of particles are distinguished behaviorally by different statistics, which refer to the way physicists count the number of possible states in collections of different particles.*

A main new insight of quantum mechanics is that the same fundamental entities, whether the same elementary particles or the same atoms, are indistinguishable.

Let’s say we have two boxes and two identical entities, which are indistinguishable. The problem is to count the states of that system because the number of states determines the probabilities of the entity being located in a given state. In terms of quantum mechanics, there are three possibilities or states: both entities can go into one box or both into the other box or one can go into each box.

A perspicacious child might ask whether each of the entities could also be put in the other box, so that the number of possible states would be four. Classically, yes, but quantum mechanically, no, because the entities are indistinguishable, and there is no way to make the differentiation that allows for the possibility of putting each in one or the other box.

In the case of atoms, the boxes are akin to the positions of the atoms in a crystal. The number of ways of putting the atoms at positions in the crystal can be “counted” and gives rise to different “statistics” that are different for atoms that are bosons and for atoms that are fermions.

Fermions that are indistinguishable can’t be in the same state. Two electrons of the same spin can’t be put on top of each other (the Pauli exclusion principle). So in the case of two spin up electrons and two boxes, there is only one possible state—each box contains one spin up electron.

In relativistic quantum mechanics, there is a deep connection between the spin of a particle and its statistics (the spin statistics theorem).

If the spin is one-half integer like the spin of the electron or the quark, then the particle is a fermion. If the spin is integer such as zero or one or two, then the particle is a boson.

An atom consists of a nucleus and orbiting electrons. Since a nucleus, except for the simplest hydrogen atom, is made out of protons and neutrons, both of which have spin one half, putting them together results in either a nucleus (and an atom) of integer spin for an even number of nucleons or a nucleus (and an atom) of half integer spin for an odd number of nucleons. Helium-4 with two protons and two neutrons has an even number of nuclei and is a boson. Helium-3 with two protons and one neutron has an odd number of nuclei so that atom is a fermion. Though both atoms contain two electrons, the number of nuclear constituents determines that one is a boson and that the other is a fermion.

Interestingly, the properties of a fermionic gas are very different from the properties of a bosonic gas. In the fermionic helium-3 gas, electrons tend to repel each other. Bosons, on the other hand, like to be in the same state, which helps to account for the phenomenon of Bose/Einstein condensation or superfluidity.

Solid-State Physics: Quantum Choreography

Fisher Frames History of Field for Focus on Strongly Correlated Electrons

"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy." (1.5)

SO HAMLET, having just conversed with a Ghost, informs his friend, Horatio, incredulous, apparently, because well schooled in Stoic philosophy, Horatio is a rationalist. Engagement with the implications of quantum mechanics is like talking to a Ghost; the experience shakes up notions of reality, and things "un-dreamt" become possible when possibility is itself understood in terms of probability.

The difference between Hamlet's ghost and quantum mechanics is one of consensus. Maybe one or two physicists believe in the possibility of ghosts, but almost all physicists believe in quantum mechanics. After 100 years of unpacking its implications, physical reality on a deep level has turned out to be much stranger than a 19th-century physicist could have dreamed.

KITP permanent member and solid-state theorist Matthew Fisher believes—counter to the prevailing view in his field—that our everyday world contains aspects which may be far stranger than we can currently envisage or even imagine. "The correlated motion of electrons inside some crystalline materials provides the platform where such exotica might be lurking, largely uncharted," he said.

In a culture where "thinking outside the box" has become a cliché for creativity, Fisher sees his approach to solid state physics as—quite literally—thinking from the outside about what is going on inside the "box," which, in his case, is the ordered array of atoms in the crystalline lattice of a solid. His preferred metaphor for this box is a dance hall, in which electrons of spin up and spin down move through the lattice like couples of men and women. Fisher's task, as he sees it, is trying to discern from outside the dance hall the dancing patterns being performed by the swirl of electrons; he is trying, in other words, to guess nature's quantum choreography.

Though his endeavors may seem abstruse to laymen, Fisher's box contains not hypothetical dust from an Andromeda moon, but earth rocks—materials which are magnetic and paramagnetic and ferromagnetic and conducting and semiconducting and superconducting.

This is the physics variously described as "solid state" or "condensed matter," from which all of our high technology of computer chips and light emitting diodes and lasers has come. This is preeminently the physics for applications and usefulness. Most current high technology is sliced from what Fisher characterizes as the paradigm of solid-state physics. In this standard paradigm, the dance hall is the setting for an orderly, well-understood behavior, in which the dancing electrons are, in the terms of his metaphor, "ultimately rather lonely and disinterested in one another."

The Paradigm

"Even," said Fisher, "if a material is cooled to very low temperatures where normally in the classical picture everything stops moving, electrons are so light that quantum mechanics keeps them fluctuating and moving around. Even at the lowest temperature, inside every piece of crystalline material, there is this miraculous electronic world with billions of electrons moving around.

"In the real world crystals are not perfect, and their inhomogeneities affect the motion of electrons. But by and large, the field of strongly correlated electrons is focusing on the simplest problem of the idealized perfect crystal. If we can't understand that, we are not going to understand the more complicated, imperfect, real world," he said.

"What we have in crystalline solids are atoms arranged in an orderly way. Cooling the crystal slows the kinetic energy of its constituent atoms. As an atom's momentum gets smaller, its wavelength gets comparatively larger, and once the wavelength becomes comparable to the distance between atoms and the size of atoms, the atoms behave like waves. The atom is too massive to manifest that waviness at room temperature. Not so the electrons."

Treating the nuclei as a set of points, a solid can be viewed as a collection of electrons. "I'm interested," said Fisher, "in what the electrons are doing because they are so light that even at room temperature they are behaving quantum mechanically. The electron particles are also behaving as waves. The wavelength is the length over which the wave oscillates, and is inversely proportional to the electron's momentum." At room temperature the electron's wavelength is typically very long—much longer than the distance between atoms. So electrons can look wavy and quantum mechanical at room temperature, and they do.

"If," said Fisher, "one is interested in understanding the behavior of crystalline solids under ordinary conditions here on earth, it is ultimately necessary to understand the quantum mechanical motion of the electrons around every single atom."

By and large the electrons are in orbits around the nuclei of atoms. And they are arranged in shells, which fill up in the order of distance away from the nucleus.

"Take a piece of copper," said Fisher. "Each copper atom is relatively inert with one extra electron sitting in the outermost shell. That electron can easily move from the sphere of influence of one copper atom to another. So," said Fisher, "in the background of these billiard balls [the copper atoms with their filled electron shells], you can easily get this fluid of electrons moving around; that is a quantum mechanical fluid called a 'Fermi liquid.' The remarkable thing about a Fermi liquid, even though it is a quantum mechanical fluid, is that its behavior can be simply understood mathematically."

Before quantum mechanics people didn't understand the behavior, including the low electrical resistance, of metals because they were thinking of the electrons as billiard balls. But an electron moving in this "periodic potential" (array of atoms) will, according to Fisher, "go into a very nice wave where it can move through the periodic background of atoms as if the atoms are not there." Felix Bloch (awarded a Nobel Prize in 1952 for first demonstrating and explaining the phenomenon of nuclear magnetic resonance [NMR] in 1946) figured this out in the 1930s soon after the advent of quantum mechanics.

Add another electron and ask what happens. Can it, for instance, collide with the original electron? The Pauli exclusion principle says that electrons, being fermions, cannot do the exact same thing as one another. More precisely, a spin up electron cannot be in the same state as another spin up electron. In addition, any two electrons because they are both negatively charged repel one another—that's the "Coulomb interaction."

"Let's imagine," suggests Fisher, "that we just turn off the Coulomb interaction; nevertheless two up spin electrons have an exclusion interaction; they cannot sit on top of one another. You might think," said Fisher, "it would be a very complicated problem to solve for 10^{23} electrons moving around as waves that can't—as particles—sit on top of one another. Miraculously one can solve that problem exactly because these wavelike states each have different momenta, beginning with low and running to high."

The filled set of momentum states from lowest to highest is called the "Fermi sea." The filled Fermi sea provides an exact description of the electrons' dynamics in the absence of Coulomb interactions.

"Even more amazing," said Fisher, "when you add Coulomb interactions in many important materials such as copper, silicon, iron, and gold, the qualitative behavior of the collective of electrons remains the same. It is as if interactions between electrons do not matter."

The assumption that it is legitimate to ignore the interactions between the electrons constitutes the backbone of the quantum theory of solids—the standard paradigm of solid-state physics with roots stretching back some 75 years.

It starts with a zero-order description where electrons do not interact at all and then adds in the (presumed) weak effects of interactions. When two electrons within the Fermi sea interact weakly with one another, there are relatively few empty states available to scatter into, and the number of such accessible states diminishes rapidly upon cooling. In the 1950s Lev Landau, the famous Russian physicist, developed the requisite mathematical description of this picture. This "Landau Fermi liquid theory" basically takes into account the residual interactions between low energy electrons without changing their qualitative behavior.

But Landau Fermi liquid theory does not always work, asserts Fisher. "In some materials the interactions between electrons can be so strong that their behavior changes qualitatively. You cannot even think in terms of momentum states; the Fermi sea does not have any sharp meaning."

First with the quantum Hall effect and then the fractional quantum Hall effect (both efforts netting Nobel Prizes, in 1985 and 1998, respectively) and then even more dramatically in 1986 with the discovery of the high temperature superconductors, physicists began to realize that collections of electrons can be much, much more interesting and complicated than described by Landau Fermi liquid theory.

The quantum Hall effect represented the first well-understood example of electrons behaving in a manner qualitatively different from the standard paradigm. "We understand what the electrons are doing," said Fisher, "and they are doing something amazingly interesting simply because they are doing something other than ignoring one another. Though the quantum Hall effect occurs only in special circumstances, our understanding of it has convinced us that qualitatively different behavior is possible."

Divining the Dance

"Imagine a town hall with a dance going on, but to which no physicists are admitted though couples enter and music is audible," said Fisher. "The problem for the physicists is to guess the dance pattern inside.

"One way—one experiment—would be to start pushing people in the front door and see how quickly people come out the back door. That way you could tell how crowded the hall is. Or you could push in women, and see how quickly men come out or women; that way you could get some idea how tightly bound the men and women are (This method of probing is called 'electical transport').

"Another thing you might want to do is listen to the vibrations of the music—akin to observing scattered neutrons to infer the 'vibrations' of the electrons' spin.

"Or, perhaps you climb on the roof of the dance hall and drop people in through a skylight and listen to the commotion below when they land on the floor amidst the dancers. This might give one some idea of how crowded the room is with dancers. This tactic is analogous to tunneling electrons from a metallic tip into a solid, in order to determine the behavior of the electrons inside the solid," said Fisher.

Within the standard Fermi liquid paradigm, how would one describe the dancing within the hall? "People walk straight through the room, bump into a wall, and bounce off," said Fisher, describing people moving like zombies in a low-budget horror film. "Most condensed matter theorists today," said Fisher, "do not believe that thinking in terms of more exotic quantum choreography will be productive; 95 percent of the practitioners


Nell Campbell

Chalk Talks, a program of the Friends of KITP, enables audience members to ask questions of presenting scientists in a relaxed and casual setting.

Inside Crystals

Illustrated by Peter Allen

prefer contemplating adding bells and whistles to the true and tested Fermi liquid approach.

"Phil Anderson [Princeton physicist and 1977 Nobel laureate] was perhaps the first physicist who clearly envisioned that there was much more out there than such bells and whistles. Motivated by a particular class of materials, he made a guess in the 1970s that intuited what is, in the hindsight of my present thinking, quantum choreography. It was a stroke of genius. He saw a kind of dance pattern although at the time he did not understand it fully in mathematical terms. As soon as high temperature superconductivity was discovered over a decade later, he resurrected this quantum dance and suggested that it should underlie the strange electronic behavior of these materials. His insight was initially well received, but has since largely fallen out of favor. A few diehards, though, have continued to refine, develop and generalize the original quantum choreography. In the past five years there has been a good deal of progress in exploring toy models, which can be shown to manifest Anderson's very first quantum dance proposed over 30 years earlier."

What about high temperature superconductivity? The researchers who discovered it in 1986 got a Nobel Prize in 1987. In the meantime 20 years have passed, and over 100,000 experiments have been conducted. Is it understood yet?

Replied Fisher, "We have not yet been sufficiently creative; I don't believe that we have yet guessed the right choreography."

Quantum choreography is not easy. Even Fisher's examples of how one might go about guessing quantum choreography in terms, not of mathematics, but square dancing are not easy.

"Just like the docey-doe in square dancing, where a couple pairs together and dances about one another, electrons sometimes like pairing. A quantum docey-doe of two electrons is often akin to a 'valence bond.' But sometimes, just like men and women who tire of dancing with the same partner," said Fisher, "electrons become 'swingers' switching between different partners. The 'resonating valence bond state' proposed by Anderson in the 1970s is a quantum analog of square dancing's 'grand right and left' in which everybody dances with everyone of the opposite sex on the dance floor.

"If the dance floor is disturbed appropriately," said Fisher, "a pair of dancers can become separated. The lone man (an up spin electron) will quickly impose upon another—stealing his partner—only to leave another lonesome 'gent.' Similarly, for the woman (the spin down electron). The net effect is that at any time there will be an unpaired male and female traversing about the dance floor. Each loner will carry the electron's spin (spin one-half) and has been christened a 'spinon.'

"The electrons' charge, which is simply determined by the total number of people irrespective of sex, will be uniform throughout the dance floor, so that the spinons are effectively electrically neutral with respect to the background density of dancers. In particle physics the spin and charge of an electron are enslaved, always moving together. But in this strange hall filled with twirling dancers, the electron's spin is effectively separated from its charge—a phenomena called 'spin-charge' separation."

Fisher often prefers visualizing such intricate quantum choreography in terms of "vortices," places on the dance floor around which dancers are twirling. "Particles are waves and waves have phases, they can swirl around in a current called a 'vortex.' I can describe various dance patterns by focusing on the quantum motion of the places where they are rotating rather than looking at individual electrons."

There is much quantum choreography to divine. Spinning vortices and triangular (instead of square) lattice dance halls, where (perhaps strangest of all) critical spin liquids can take the floor.

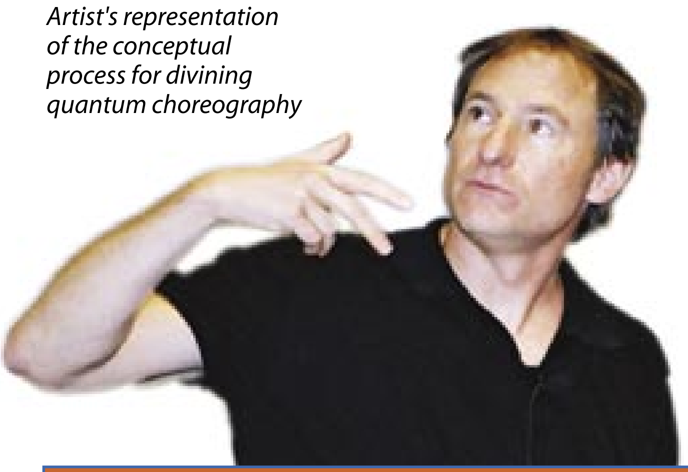
In such critical spin liquids, a female dancer can be paired, or entangled, with a male clear across the dance floor. Dancing pairs come in all sizes, intertwined with one another. And partners are continuously being swapped. Moreover, the "spinon"—the unpaired male or female dancer—moves across the dance floor in a very complex manner, due to partner swapping between well-separated pairs. "It is impossible to describe the motion of this spinon as a quantum mechanical particle," said Fisher. "It doesn't behave like a boson; it doesn't behave like a fermion. It doesn't behave like a free particle at all. It is," said Fisher, "an element of a strongly interacting theory."

Such exotic quantum choreography is possible largely due to the "frustration" inherent in the triangular lattice, according to Fisher. "I am very excited by the quantum antiferromagnet on the triangular lattice and other frustrated lattices," said Fisher. "It's a situation where men and women like to be next to one another, but can't all be, so they all can't be happy. This leads to interesting collective behavior, driven by compromises, much as in complex human societies." On triangular lattices there are presently two experimental materials, which are good candidates for being critical spin liquids.

Fisher has focused for over two decades on building up an intuition for quantum choreography. "I think that eventually we will successfully ascertain the correct quantum choreography that underlies the mysterious behavior in materials such as the high temperature superconductors and heavy fermion materials. Each class might conceivably have its own distinctive choreography." He says he doesn't have a feel for whether the classes will themselves be classifiable into an overarching pattern.

Besides high temperature superconductors, strongly correlated electron systems hold another tantalizing prospect for applications—in terms of quantum computing. "Correlation" is basically the name of the game in quantum computing.

SEE **QUANTUM CHOREOGRAPHY** ON PAGE 7



Artist's representation of the conceptual process for divining quantum choreography

Thinking About Thinking About Quantum Mechanics

Possible Good News for Aging Quantum Physicists

"OUR INTUITION IS ALL ABOUT particles and positions; it is not about quantum waves," said solid-state theorist Matthew Fisher, a permanent member of the Kavli Institute for Theoretical Physics at UC Santa Barbara. "We don't have good experimental probes that measure particle waves very well. We're good at measuring particle positions, but not the phase of waves because we ourselves are solid, and solids by nature are good at measuring the positions of things.

"What makes it so difficult for people to grasp quantum mechanics is the necessity of thinking in terms of both particles and waves at the same time—the wave/particle duality.

"If liquid helium atoms are cooled under pressure, they crystallize," he said. "In a crystal the atoms are basically behaving classically; there is some quantum motion, but more or less the atoms stay still like an atom in a solid should. But reduce the pressure a little bit, and the atoms go into a liquid, into a Bose/Einstein condensate or superfluid. Suddenly the atoms are behaving very much like waves, but the waves are kind of classical because all of the atoms are 'waving' coherently like photons in a laser.

"What's really interesting are situations when large collections of quantum mechanical degrees of freedom [lots of variables such as position, spin, and charge] are behaving in a manner which is not easy to understand in terms of either a particle or a wave picture. Both types of behavior are simultaneously manifest.

"Gaining intuition for those intrinsically quantum mechanical choreographies, in which neither wave-like nor particle-like aspects are dominating, requires thinking about both together. You really want to be thinking somehow 'in between' the two pictures."

Fisher won the prestigious Waterman Award in 1995, for demonstrating, according to the specifications for nomination of candidates, "exceptional individual achievement in scientific or engineering research of sufficient quality to place them at the forefront of their peers."

Fisher said he learned to think quantum mechanically by thinking mathematically first.

"One's intuition can with time transcend the mathematics. I would say that mathematics is to physics, what grammar and syntax are to poetry. You can't do the latter well unless you have a deep grasp of the former. You can't compose poetry without language, and once you know a language it affects how you think. When you are thinking in images, you may be operating in a mixed mode somewhere between words and vision. One's thinking is so intertwined with one's knowledge of language that having done enough mathematics it's hard to know what is physical intuition and what is mathematical because you now have an intuition for mathematics."

So physics may not just be a game for the 20 and 30 somethings, like so many of the prized behaviors of society, such as athletics and TV script writing?

"Twenty is, I think, too young, for great physics," said Fisher. "At the other end, obviously, one eventually burns out. I do notice that the leaders in string theory are not only 30-year-olds, but also 40- and 50-year-olds. With the 50- and 60-year-olds who were great successes earlier on, their success tends to generate distractions in the form of new duties. And physics, above all else, takes incredible focus."

Topological Quantum Computing:


Nell Campbell

Richard D. Eager (l) and Dan Malinow, both first year physics students at UCSB, chat with Caltech's John Preskill after his “pedagogical lecture” on “Fault Tolerant Quantum Computation.” “Pedagogical lectures” are a distinctive feature of the KITP program “Topological Phases and Quantum Computation.”

“INTERDISCIPLINARY” IS A WORD that has gotten a lot of press in the past decade's reporting on prospects for scientific discovery. The presumption is that the action is occurring not just at the boundaries of disciplines, but also at the intersections where the boundaries of two or more disciplines overlap. Such is surely the case with topological quantum computing, as the KITP program (Feb. 21 to May 19) has dramatically illustrated.

Its roughly 80 participants represent the confluence of four streams of research. There are condensed matter theorists who are experts on the fractional quantum Hall effect and other possible topological phases of matter. There are condensed matter experimentalists studying fractional quantum Hall states in gallium arsenide devices. There are also theorists studying quantum computation: some coming from an atomic physics background; others studying quantum information in the abstract. Straddling all of these groups are the proponents of topological quantum computing, a small core group which is collaborating intensely with experts from the other areas and attracting converts.

The use of topological phases represents an approach to quantum computing which is so radically different from the other approaches that the overlap between the people pursing this approach and the other approaches has indeed been small.

The sustained opportunity for sharing ideas is one reason for the dynamism and distinctiveness of the program, according to one of its organizers, condensed matter theorist Chetan Nayak, a participant in Microsoft's topological quantum computing project temporarily lodged at the KITP and scheduled to move into the new UC Santa Barbara building housing the California NanoSystems Institute (CNSI). The other two organizers are Sander Bais from the University of Amsterdam's Institute for Theoretical Physics and Caltech's John Preskill, whose May 3 public lecture “Putting Weirdness to Work: Quantum Information Science” provided a snapshot of the quantum approach.

One distinctive feature of both groups of quantum computing researchers is the overlap they represent between condensed matter physics, especially theory, and mathematics.

Said Nayak, “Many people have come here who study quantum computing abstractly and in many cases have been thinking about other realizations of quantum computers not involving topological phases.” That latter group, according to Nayak, has come to the KITP program to learn, for instance, “the connections between their kind of error correcting codes and what a topological quantum computer does.”

Perhaps the key strength of the topological approach to quantum computing is that the underlying physical system automatically corrects and protects against errors.

“These people,” said Nayak, “who have worked on the problem of error correction codes with respect to the other approaches to quantum computing based on spin states and trapped ions, see the topological approach as an exciting 'outside the box' approach. People realize the difficulties involved in building a quantum computer are great, to say the least, so as a result some people think a linear progression isn't necessarily going to get us there. We have to try something sneaky if we want to build a quantum computer, and this is such an idea.”

Genesis of Quantum Computing

Quantum computing arrived on the scene in a big way with Bell Labs' Peter Shor's 1994 discovery of an algorithm for finding the prime factors for large numbers via a hypothetical quantum computer. He said, in effect, here is what a quantum computer could do fast that a classical digital computer can't (unless it can run for decades, centuries, millennia).

Who cares about the ability to find the prime factors of large numbers? The answer is the vast national security enterprise engaged in codes and code-breaking.

Conventional computing operates in a binary mode with a bit of either 0 or 1. What is different and makes quantum computation a potentially richer computational approach is that it takes advantage of the multiplicity of quantum states to encode not just one piece of information (for instance whether the spin of a particle is up or down), but more, such as the superposition of particle spin states. (Quantum mechanically, particle spin isn't necessarily up or down, but in a state that is [classically speaking] a combination of up and down states.)

Shortly after Shor's proof of usefulness, he and others began tackling the problem of error correction. The problem is that quantum information is delicate, so one must take very seriously the problem of correcting errors. Since the error correction process can itself introduce errors, the rate of errors must be low initially for the whole enterprise to work.

The KITP hosted a four-month program in 1996 “Quantum Computing and Quantum Coherence,” which catalyzed developments in the newly emerging field of quantum information processing because it enabled the pioneers, including Shor, to get together for the first time for sustained intellectual exploration. Another program in 2001 (“Quantum Information, Entanglement, Decoherence and Chaos”) again enabled the principals to gather for a slightly longer five-month stretch.

Those two earlier programs focused on approaches to quantum computing other than topological phases because that approach had yet to coalesce into a set of ideas to ground a program. A key difference between the earlier programs and the current one reveals a key difference between the approaches. The earlier programs, especially the first one, focused on, in effect, software issues, especially error correction, while the latter program is focused essentially on hardware.

The titles of both early programs underscore what was emerging as perhaps the principal stumbling block to the other approaches to quantum computing: “decoherence,” the seemingly insurmountable problem of sustaining evanescent coherent states of a collective of quantum “particles,” especially when trying to scale up to a real computer. Quantum systems generally decohere very rapidly; consequently, it is difficult to keep the rate for this type of error low.

Other approaches to quantum computing have essentially analogized digital computing. Since the spin of an electron understood classically as up or down is understood quantum mechanically as any possible superposition of up/down, particle spin has, for instance, by analogy been envisioned as a candidate for the qubit. And a collection of spin qubits could encode vastly more information than a collection of classical bits. In contrast, with a topological phase, the qubit is not a single electron, but rather a collective excitation of the whole system, which is inherently stable because of its topology.

Such an excitation can be useful for quantum computing when it is an “anyon,” which exists only in two-dimensional space and has strange properties, such as “fractional

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Microsoft's Quantum Project

CONTINUED FROM PAGE 1

“The people I wanted to recruit to work with me (I know them all; every single person has been a collaborator) were all coming from universities. I thought it would be very difficult to assemble this group because obviously the people you want for a project like this are people who have a lot of options in their lives. I am not the only person who realizes their brilliance. The people I wanted to bring on board would look at this opportunity and say, 'This is going to be the most vibrant place to do my work and also culturally easy, on a university campus.'”

Employees of the Microsoft group hold UCSB adjunct positions in the departments of Mathematics and Physics, “as is most appropriate depending on our training,” said Freedman. “We all expect to be close participants in the university life so we will advise graduate students, for example, and in fact we will probably support graduate students as well. We've already given a two-quarter course in the Mathematics Department that had 16 to 18 people in attendance at any given meeting. Many physicists came; Matthew Fisher and Andreas Ludwig [both UCSB faculty and theorists] and all their condensed matter students trekked over to South Hall,” where the Mathematics Department resides.

The Witten Effect

The impetus for Freedman's idea to use topological phases for quantum computing came from his engagement with the ideas for which theoretical physicist Edward Witten (a student at Princeton in the mid-1970s of KITP Director David Gross) was to win the Fields Medal in 1990.

Freedman, on leave from UC San Diego in 1988, attended a seminar in the Harvard Mathematics Department. Said Freedman, “We went through Witten's paper” on quantum field theory and the Jones polynomial. “I had the idea then that the technology of Witten's paper could potentially be used to make a new kind of computer.”

Some British mathematicians showed in 1988 that evaluating the Jones polynomial was computationally difficult. At about the same time, Freedman said, “I was working very hard in this seminar to understand Witten's paper, where he was saying, in a sense, that if you do the right kind of physical experiment, you do the Jones polynomial. So a light flashed on in my head, which said it looks stupid to calculate the Jones polynomial on an ordinary computer if there is some laboratory physics you could do to get the answer. And that must mean that there is a new kind of computer that hasn't been thought of yet.”

Freedman got very excited. “I talked to everyone I knew or could find at Harvard to ask if we could build a quantum computer this way. I wanted to know what would we need to make this physics that Witten is talking about. In a sense I was asking the question two years too early. Everyone was very negative. One source said, 'What Witten thinks of as physics is not what you learned in high school'; that, in effect, there is no material system in the world that acts the way his equations dictate.”

But there is—the fractional quantum Hall effect (FQHE). Though discovered in 1982, the FQHE systems known to physicists at the time of Freedman's quest in 1988 exhibited fractional but ordinary abelian statistics, and not the non-abelian statistics of the mathematical structures discovered by theoretical physicists Greg Moore and Nathan Seiberg in 1987, which were integral to Witten's work on the Jones polynomial and which Freedman's idea for a quantum computer required. (“Non-abelian” roughly pertains in group theory to a pair that is noncommutative, such that “*ab*” is not equivalent to “*ba*.”)

Moore, a string theorist (now at Rutgers University in New Jersey), joined his Yale colleague, condensed matter physicist Nicholas Read, in the early 1990s to search for FQHE states with non-abelian statistics. They found several.

Freedman found out about FQHE in a popular article written by UCLA physicist Steve Kivelson and published in *Scientific American* in 1996. “Then,” said Freedman, “I really got interested. I knew that there were physical systems that were governed by a Chern-Simons term that actually would be producing observations potentially that would be exactly what Witten had talked about.”

Afire with that realization, Freedman shortly thereafter accepted his former students' invitation to talk at Microsoft Research. Of course, his subject was the topological phases approach to quantum computing, whose exploration has now become the main mission of the Microsoft project.

“The possibility was out there,” said Freedman, “as a very abstract mathematical idea in Witten's paper, but Witten proposed no connection to the real world.”

In brief, it is an ironic tale of the interplay between two remarkable minds: the physicist who had the great abstract mathematical insights (via sidetracking from string theory) and the pure mathematician who intuited the relevance of those insights to condensed matter physics and the “real world” of potentially transformative technology.

The Devil is *Not* in the Details

statistics," ranging "anywhere" (thus its name) between bosonic and fermionic statistics (See box, page 3).

In 1997 Alexei Kitaev (then at the Landau Institute in Moscow and now with Microsoft's quantum project and a KITP program participant) wrote a "brilliant" paper explaining, according to Nayak, "how non-abelian anyons would have built-in error correction. I don't think," said Nayak, "that many people besides Michael Freedman [a topologist with a Fields Medal and head of the Microsoft project] realized that the Kitaev paper was a work of landmark importance. Alexei," said Nayak speaking about Kitaev's expertise in mathematics and physics, "is one of those peculiarly Russian geniuses whose conceptual insights fuse mathematics and physics."

The next important development in the direct line of topological quantum computing came in a paper by Freedman and two mathematicians from Indiana University, Zhengang Wang (a member in the Microsoft project) and Michael Larsen. Wang, like his PhD mentor Freedman, is a topologist, and Larsen is an expert on the representation theory of groups. Their papers demonstrated that a large class of non-abelian anyons have just as much computational power as ordinary qubit quantum computing. As Freedman, Kitaev, and Wang showed, a topological quantum computer has no more power than any other quantum computer; therefore, the two approaches are equally powerful computationally. The big advantage of topological quantum computing is its very low error rate.

What is a topological phase?

Said Nayak, "Topology is the study of shape irrespective of length and angle. So for a topologist the doughnut really is a coffee cup because even though the handle is small compared to the cup and a doughnut is all handle, by stretching and deforming the doughnut you can make it into a coffee cup and vice versa. Topologists are people who forget about all the details and look at the really important key features of a geometrical shape. Focusing on key features frees one from focusing on details wherein errors occur. With the storing of important physical information in topological features such as shape, small errors in the geometry [like a blip in the ceramic surface of a cup, which doesn't interfere with the cup's mission as container of liquid] don't matter."

Translated to a physical system, a topological phase is one in which the electrons organize themselves in a state such that the collective state of all the electrons doesn't care about minor details. The only example in nature (at least so far) is the fractional quantum Hall effect. However, the hunt is on for topological phases in other systems.

Discovered in the early 1980s by experimentalists Dan Tsui and Horst Stormer and explained by theorist Robert Laughlin, the fractional quantum Hall effect occurs when electrons are cooled to low temperature and put in high magnetic fields. They organize themselves in a highly correlated state in which the ground state and low-energy excitations of the system don't care about any local perturbations. The effect showed up in measurements of electrical resistance that is quantized, and the resistance doesn't depend on details of the device (fabricated out of very high quality gallium arsenide initially made by UCSB's Art Gossard, then at Bell Labs), so the effect is robust.

"It turns out," said Nayak, "that is exactly the kind of physical system one is looking for in quantum computing."

Braiding

He described computation based on such a physical system as "taking one excitation around another or around several others," which is called "braiding." Because of the system's robustness against details, said Nayak, "it doesn't really matter whether one excitation takes a perfect circular path around the other one or a wiggly path or even pauses to take a break and then completes the transit. All that matters is that it goes around the other. Therefore the error rate associated with such an operation is essentially zero."

Said Nayak, "When you have a bunch of these excitations, it turns out that there isn't a unique ground state of the system with those excitations present." Rather there exists a rich manifold of states determined by the topology of the system and the excitations. Information can be stored and manipulated in this manifold of states. In the system that is most exciting experimentally what most closely corresponds to a qubit, said Nayak, "is the presence or absence of a neutral fermionic excitation associated with a pair of electrically charged excitations.

"When the charged excitations are far apart, the fermion isn't really localized anywhere, so no local measurement you could do or that the environment can do is going to be able to tell whether it is there or not, and that's essentially where the protection is coming from. When these two excitations are far apart, the information is delocalized over the whole system. That is a miraculous thing; not only is it very beautiful mathematically and conceptually, but it may also be useful for something," said Nayak.

The charged excitations and the delocalized neutral fermion are examples of "quasiparticles" in the fractional quantum Hall effect. As a result of the neutral fermions, the charged quasiparticles are non-abelian anyons. According to Nayak, "Many of us believe that non-abelian anyons of this type exist in the 5/2 fractional quantum Hall state," discovered in 1987 by some of the drop-in experimentalists attending the program: Robert Willett of Lucent, Jim Eisenstein (now at Caltech), and Horst Stormer (now at Columbia), together with their collaborators.

KITP Gives Birth to 'Anyon'

Nayak did his PhD at Princeton University under Frank Wilczek, a particle theorist then at the Institute for Advanced Study in Princeton and now at MIT. Wilczek, who shared the 2004 Nobel Prize with his Princeton University thesis advisor, KITP director David Gross, served from 1980 to 1988 as the first permanent member at the KITP, where he first dabbled in condensed matter theory. In 1982 Wilczek coined the term "anyon" to describe quasiparticles in two-dimensional systems whose quantum states range continuously between fermionic and bosonic.

Nayak's 1996 thesis research with Wilczek focused on understanding the behavior of possible non-abelian anyon excitations in the 5/2 state. They didn't know it, but what Nayak and Wilczek were uncovering is, in today's language, the qubit structure for topological quantum computing.

It turns out that the 12/5 state is an even better place to do quantum computing than 5/2, but it is also a more delicate state.

A specific scheme for how to do quantum computation in the 5/2 fractional quantum Hall state came late in 2004 in a paper Nayak co-authored with Freedman and a condensed matter theorist who operates close to experiment, Sankar Das Sarma of the University of Maryland, also a program participant. Their architecture is fairly concrete, and serious experimental efforts are underway to realize it.

In intermittent attendance at the three-month-long program and in more sustained fashion at its concluding five-day conference (May 15 to 19) are condensed matter experimentalists, including representatives of the four groups who are now engaged in friendly competition to make that device out of gallium arsenide. Another program drop-in, Loren Pfeiffer, heads the Lucent facility for making gallium arsenide devices of the quality required by the experiments.

With developments in topological quantum computing representing the now rapid convergence of many types of theoretical and experimental expertise, one of the key features of the KITP program "Topological Phases and Quantum Computation" has been the pedagogical Thursday afternoon sessions, designed to facilitate an expert in one field learning from a lecture by an expert in another field in a relaxed atmosphere that encourages attendees to ask the kind of "stupid" questions they might be wary of venturing in a more formal seminar setting.

To get up to speed on the subject, Nayak said, "You can't learn about it in a book. The only way for somebody on the outside of this game to become an insider is to talk a lot to the right people, and they are [mostly] here."

Quantum Choreography

CONTINUED FROM PAGE 5

"Some people think the solid state physics done here in Santa Barbara is simply crazy; others are more receptive," said Fisher. "There is a strong orthodoxy in the solid-state physics community [and more physicists are members of this community than any other], an orthodoxy which is amazingly powerful when it works. Expressing a strong preference for exploring what does not fit should not be taken as dismissal of the original paradigm. Quantum mechanics didn't mean Newton was a fool."

But searching for a new paradigm has been challenging, and at times dispiriting. "About five years back, together with T. Senthil, after extending some of Phil's early ideas, we proposed an experiment which could be used to unambiguously determine whether or not the simplest resonating valence bond state was responsible for the behavior observed in the underdoped cuprates. The theoretical foundations were sufficiently clear to put forward a concrete and falsifiable prediction for an eminently doable experiment. We were shortly proved wrong.

"It takes a certain personality," he said, "to push optimistically, if not blindly, into creative new directions. There is a real fear of being misguided. But until ideas are sufficiently well formulated to enable testable predictions, one should persist. Without taking the risk of being wrong, you can't have new ideas."

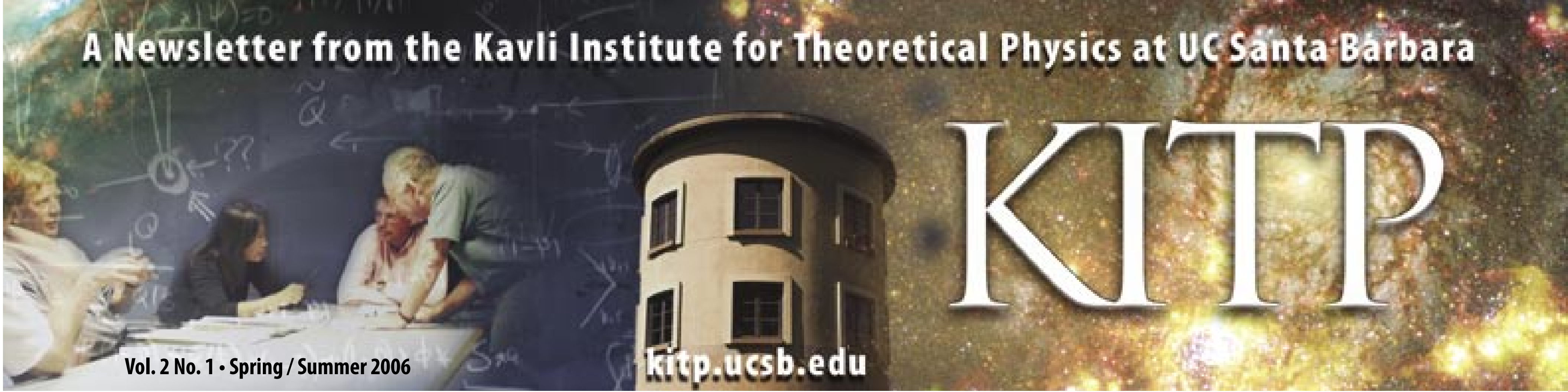

Nell Campbell


Nell Campbell


Nell Campbell

Top, Friends of KITP gather in the Kohn Hall courtyard before attending a Chalk Talk in the main auditorium by KITP permanent member Matthew Fisher (above, r), who met Friends, such as John Mackall (above, l), chair of the KITP Director's Council.

Left, Friends of KITP, Glen Mitchel (l), Dr. Eugene Ellis, Gunnar Bergman, and Samuel Fordyce



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For Physicists…

Programs

*Spintronics**
David Awschalom, Gerrit Bauer, Michael Flatte, Daniel Loss, Allan MacDonald, Dan Ralph
March 13 – June 23, 2006

Molecular and Cellular Machines
David Bensimon, Robijn Bruinsma, Philip Nelson, Adrian Parsegian
April 3 – June 30, 2006

*Physics of Galactic Nuclei**
Martin Haehnelt, Scott Hughes, David Merritt, Roeland van der Marel
May 22 – July 28, 2006

*Attosecond Science**
Andre Bandrauk, Nathaniel Fisch, Anthony Starace
July 31 – Sept. 15, 2006

*Stochastic Geometry and Field Theory**
Ilya Gruzberg, Pierre LeDoussal, Andreas Ludwig, Paul Wiegmann
Aug. 7 – Dec. 15, 2006

*String Phenomenology**
Michael Dine, Shamit Kachru, Gordon Kane, Joseph Lykken, Fernando Quevedo, Eva Silverstein
Aug. 7 – Dec. 15, 2006

*Applications of Gravitational Lensing: Unique Insights into Galaxy Formation and Evolution**
Leon Koopmans, Chung-Pei Ma, Ben Moore, Peter Schneider, Tommaso Treu
Sept. 18 – Nov. 03, 2006

Evolution of Molecular Networks
Eric Davidson, Michael Lassig, Tomoko Ohta, Nikolaus Rajewsky, Stephen Small
Jan. 15 – April 13, 2007

*Accretion and Explosion: The Astrophysics of Degenerate Stars**
Lars Bildsten, Rosanne Di Stefano, Robert Kirshner, Craig Wheeler
Jan. 29 – June 1, 2007

*Strongly Correlated Phases in Condensed Matter and Degenerate Atomic Systems**
Immanuel Bloch, Victor Gurarie, Deborah Jin, Yong B. Kim, Leo Radzihovsky, Peter Zoller
Jan. 29 – June 15, 2007

Biological Switches and Clocks
Reka Albert, Albert Goldbeter, Peter Ruoff, Jill Sible, John Tyson
July 2 – Aug. 10, 2007

*Moments and Multiplets in Mott Materials**
Leon Balents, Matthew Fisher, Daniel Khomskii, George Sawatzky, Oleg Tchernyshyov
Aug. 6 – Dec. 14, 2007

*Star Formation**
Tom Abel, Alyssa Goodman, Chris McKee, Paolo Padoan
Aug. 6 – Dec. 14, 2007

**Indicates a program-related conference was held (or is planned to be held) during the program.*

Mini-Programs

Cardiac Dynamics
Eberhard Bodenschatz, Emilia Entcheva, Robert Gilmour, Alain Karma, Valentin Krinsky
July 10 – Aug. 4, 2006

The Nature and Dynamics of the Earth's Transition Zone: A Multidisciplinary Approach
Adam M. Dziewonski, Stanley Hart, Louise Kellogg, Barbara Romanowicz
July 17 – Aug. 4, 2006

The Quantum Nature of Spacetime Singularities
Martin Bojowald, Robert H. Brandenberger, Gary T. Horowitz, Hong Liu
Jan. 8 – Jan. 26, 2007

Singular Geometries and Geometrical Singularities
L. Mahadevan, Tom Whitten, W. Zhang, Edward Spiegel
July 16 – Aug. 3, 2007

For details of programs go to our website: http://www.kitp.ucsb.edu/activities/

For Friends of KITP…

SEE WEB SITE:
www.kitp.ucsb.edu/community/friends_upcoming_events.php

Nell Campbell

Matthew Fisher (l), KITP permanent member, discusses his Chalk Talk, "Quantum Crystals, Quantum Choreography and Quantum Computing," with Derek Westen, chair of Friends of KITP.

For information about events and membership, contact Charmien Carrier at (805) 893-6349 or charmien@kitp.ucsb.edu. For other Friends queries, contact Sarah Vaughan, Director of Development and Community Relations at (805) 893-7313.