Duke Physics

Annual Newsletter
2003

Department Happenings

—from the Chair, Prof. Harold U. Baranger

I am pleased to say that we have had a very active and productive year in terms of both research and education here at Duke Physics. This is my first year as Chair, as many of you know, and it was a year of challenges and learning for me personally. Certainly the most interesting things I learned came from finding out what my colleagues in other subfields are doing; this broad view – from biophysics to particle physics, from optics to gamma rays, from teaching introductory physics to advising graduate students – has deepened my appreciation for our department. Six of the more significant research achievements are highlighted in this newsletter. News about undergraduate and graduate education are covered in their respective sections. Here I want to highlight some general news about the department and faculty:

Bricks and Mortar:

Planning for a new sciences building within the School of Arts and Sciences proceeded rapidly this year. The functionality of the building has been described in detail, and a broad-brush design was presented by the architects; we are now starting the detailed design phase. The building is currently expected to be 160,000 net square feet in size with occupation in summer 2006. It will connect to the back of both the Bio Sci and Physics buildings; a terrace extending between the two buildings will cover a floor of teaching laboratories. The main impact on our department will be (1) new high-quality lab space for nanophyiscs, biophysics, and nuclear physics, and (2) completely renovated space for the advanced laboratory course.

The new engineering building is about half way to completion. Called the Center for Interdisciplinary Engineering, Medical, and Applied Sciences (CIEMAS), it is located where Science Dr. used to go, just beyond the Physics Building. The two elements of CIEMAS most relevant to our department are the Photonics Center in which several of our faculty participate and the joint instrumentation facility for materials science and engineering.

I am pleased to report that the loan taken out for the Duke Free Electron Laser Lab (DFELL, Prof. Glenn Edwards, Director) has been fully paid off this year. The fact that this was done entirely with overhead recovery from DFELL grants is a testament to the fund-raising abilities of past and present directors of the DFELL, the exciting science possible with the DFELL machines, and the vision of those who set out to build an FEL lab here at Duke 15 years ago. I'm sure all associates of the DFELL will appreciate having attained this milestone!

Faculty Honors:

A number of faculty won fellowships, awards, or other kinds of honors this year. First, two of our Assistant Professors in nuclear and particle theory, **Steffen Bass** and **Shailesh Chandrasekharan**, won Outstanding Junior Investigator awards from the DOE. It is unusual, and so particularly gratifying, for two researchers from the same institution to win this award in the same year. The topic of Prof. Bass's award proposal is "Modeling and Analysis of Ultra-Relativistic Heavy-Ion Collisions" while that of Prof. Chandrasekharan's is "Toward the Chiral Limit in QCD".

Gleb Finkelstein, Assistant Professor in experimental nanophysics, won a CAREER award from the NSF, the Foundation's most prestigious award for new

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faculty members. The topic of his award is "Local Probing of Electron-Electron Interactions in Nanostructures".

Anna Lin, Assistant Professor studying chemical and biological nonlinear dynamics, won an award from Duke's Smith Faculty Enrichment Fund. These awards fund a one semester leave to enable faculty to fully engage in learning a new field of endeavor. Physics faculty interested in biological systems have been adept at winning these awards and using them to learn biology; Profs. Gauthier, Socolar, and Greenside are past recipients. Prof. Lin follows in this tradition; she will use her leave to start a new experimental program in the physics of neurodynamics.

Bill McNairy, Lecturer specializing in introductory physics and demonstrations, will be a Fellow of Duke's Center for Instructional Technology during the next year. He will be working on the project titled "Bringing CIT Resources into the Introductory Courses for Non-Majors" this year, and be the department's point person on instructional technology.

Finally, **Dan Gauthier**, Associate Professor working in experimental optical physics, was elected Fellow of the American Physical Society this year.

Leadership Changes:

The department initiates the position of Associate Chair this year, with Ronen Plesser being the first to tackle the job. I became convinced that an additional leadership position is necessary in order to give teaching issues the time and attention they deserve. Thus, the Associate Chair has responsibility for overseeing the teaching mission of the department.

The Director of Undergraduate Studies (DUS) changes this year, from Joshua Socolar to Calvin Howell. As the first DUS under the new administrative structure, Prof. Howell will have the opportunity to redefine the DUS position. We anticipate that the DUS will now have more time to act as an advisor and advocate for undergraduates.

May 2003 marked the end of Lawrence Evans' four-year tenure as Director of Introductory Physics. As Professor Emeritus, Prof. Evans designed and implemented important changes in the structure and curriculum of the large survey courses, those primarily for engineers, premeds, and other science majors. In particular, this enabled a unified presentation of the material to all the students. My colleagues and I salute Prof. Evans for his invaluable service to the department.

Graduate News

— from the President of the GSO, John Wambaugh

Graduate Student Seminar

This summer, graduate students Matthew Prior and Ilarion Melnikov started a weekly graduate student seminar. Every Friday at noon, roughly thirty graduate students and post-docs gather for a presentation of a student's research. Informal questions abound during the talk, and everyone enjoys the pizza provided by the department. With the current schedule already running into October (see grad webpage for listing), the Friday seminar has a bright future.

Graduate Student Organization

The Duke Physics Graduate Student Organization (GSO) had a good year. The first ever graduate student potluck was attended by 28 students and spouses. It was quite a feast. Afterwards many stuck around to watch Top Gun in a lecture hall. Also in the fall, the GSO presented the results of its first survey of graduate students in a Faculty Meeting. Many of the faculty responded with great interest in helping further identify and

address issues concerning graduate students in the department. In the spring the GSO held an International Potluck Dinner and Games Night during which we played cultural-awareness raising games with a representative of the International House, as well as card games. Qiang Ye (Alan), Brad Marts, Emily Longhi, Matthew Prior, Michael Stenner, Bob Hartley, Stacey Hemmer and Brian Tighe all served as representatives for 2002-2003. John Wambaugh, Brian Bunton and D.J. Cecile were president, vice-president and secretary, respectively. Josh Tuttle served as GPSC representative and Staci Hemmer also served as Ombudsperson.

Rob Saunders, GPSC President

Third-year graduate student Rob Saunders was re-elected President of the campus-wide Graduate and Professional Student Council (GPSC). He has been able to convey directly to Duke's administration the concerns of not just Duke graduate and professional students in general, but the particular perspective of a physics student. In addition to tackling health insurance and parking office policies, Rob has represented the graduate student body at many events, both ceremonial and fun — convocations, graduations, and even the women's basketball team's showing in this year's NCAA Final Four.

Campout

Every year, season passes to Men's Basketball Games are allocated to graduate students by lottery. Entering the lottery requires camping in a field on campus for roughly thirty-six hours one weekend in the fall. Because even this level of dedication does not guarantee winning, for several years physics graduate students have camped together and shared the passes. Students from first- to seventh-year experience both good times and the whims of nature together. Though the physics encampment amused other students by working hard through the daylight hours, once the sun fell the physics grads more than made up for lost time. This year there were fifteen campers and they won eight passes.

Undergraduate News

— from the DUS, Prof. Joshua Socolar

Physics Majors:

In May, 17 students graduated whose first major was physics — 7 AB degrees and 10 BS degrees — plus 3 students for whom physics was a second major. These numbers are significantly larger than in recent years, and it appears that the next few years will be similar to this one.

The department now offers more opportunities for undergraduate research in a wider variety of subfields than ever before. The number of students doing independent research projects was very high this year — 12 students in the spring — and we expect to sustain such high rates of participation as the first class governed by the Curriculum 2000 guidelines reaches its senior year in 2003-04.

This past year, four students graduated with distinction, having completed impressive research projects and senior theses:

Mark Ammons: "Characterization of a Rotational Shear Interferometer for Astronomical Purposes" (supervised by Henry Everitt);

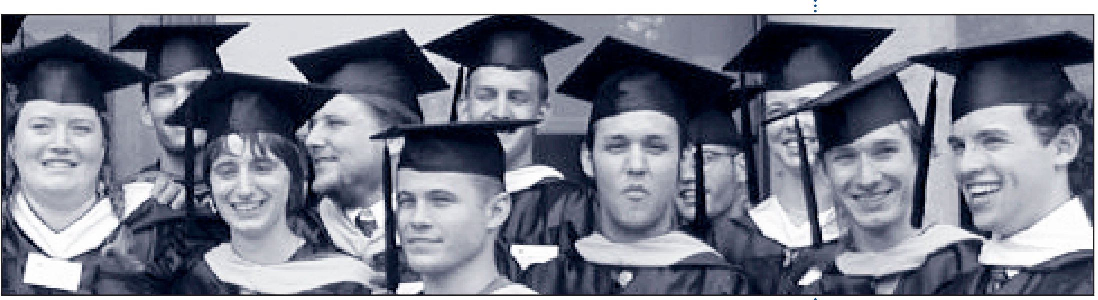
Jacob Foster: "Physics with Two Time Dimensions" (supervised by Berndt Müller);

Margaret Harris: "Design and Construction of an Improved Zeeman Slower" (supervised by John Thomas);

Michael Miller: "Statistics of Disordered Wave Functions with Applications to Coulomb Blockade Peak Spacing" (supervised by Harold Baranger).

The senior theses can be viewed online at http://www.phy.duke.edu/ugrad/senior_thesis.ptml .

In addition, physics major Jacob Foster was named a Duke Faculty Scholar and awarded a Rhodes Scholarship, which he will use to study twistor theory with Roger Penrose at Oxford next year.



Undergraduate Curriculum Development:

A particularly exciting development this year has been the construction of an observational astronomy facility in the Duke Forest, which provides relatively dark sky conditions. The Duke Teaching Observatory currently fields five 10" Schmidt-Cassegrain telescopes equipped with GPS and GO-TO capabilities. These modern instruments make it possible for students to conduct independent observations after only minimal training, introducing a lab component into our introductory astronomy class (PHY55). In addition, the facility is used in a growing outreach program aimed at Durham Public School students. Further campus outreach programs are planned, as well as undergraduate research opportunities. Prof. Ronen Plesser spearheaded the effort to assemble the observatory which was funded by the Provost's office, Arts and Sciences, and the department.

The development of introductory physics labs and lecture demonstrations for all levels continues apace, thanks to the efforts of Dr. Mary Creason and Dr. Bill McNairy, respectively. In addition, the Advanced Laboratory is being prepared for a major renovation associated with the construction of the new sciences building. The emphasis on research in Curriculum 2000 highlights the importance of this course. As the instructor for Advanced Laboratory, Prof. Seog Oh will work with Dr. Creason to guide the renovation efforts.

Reflections of a Convert: On a Physics Conference and Becoming a Physics Junkie

It was with great pleasure that I attended the annual conference of the National Society of Black Physicists in Atlanta this year. I must confess that I am not a traditional physics major; I took the Physics 51/52 sequence and my first major is Public Policy Studies. Nevertheless, I love physics with an acute passion, and engaging with outstanding physicists from across the world was nothing short of spectacular. I expected to meet a number of quirky scientists, but what I did not expect was to be thrilled by the richness of perspective in the physics community. Not only did I meet professors whose lectures opened my mind to new ways of thinking about the universe, but also I interacted with teachers working to reform physics education in the public schools and journalists striving to make physics accessible to the general populace.

I had once naively looked at physics as the most sterile natural science. It is an image of physics that dies hard among students, even those like myself who know that physics is the primary purveyor of scientific innovation. Neil de Grasse Tyson, a keynote speaker at the conference, made a significant impact in changing my mind about what physics means to society. Tyson, who received his PhD in astrophysics, reminisced about watching an interview he did for a local news station: "It was an out-of-body experience for me. And I finally realized what it was—for the first time I was watching a black person in the media portrayed as an authority in something that had nothing to do with race whatsoever." In order for Americans to ever escape the subtleties of racism, they must be able to visualize blacks achieving alongside their white peers—particularly in a field like physics, whose rank-and-file members are often ascribed unusually high levels of intelligence. Seeing more black physicists, who currently constitute less than 1% of all physicists, can thus be a superficial way to help Americans start conceptualizing blacks outside the disadvantaged box.

I applaud what the physics department has done in supporting the Bachelor of Arts and minor tracks in physics, but I would argue that the department could go further, particularly if one of its goals is to recruit students who did not come into Duke knowing 100% that they wanted to major in physics. From my experience as a student and tutor, in the 51/52 sequences there is such a strong focus on covering material that the big ideas are lost on the vast majority of students. As a result, many walk away not only frustrated with physics but also failing to see its profound significance to their future scientific work. They also walk away uncaptivated by what is surely the most fundamental and arguably the most elegant of all the natural sciences. For example, the department might consider dropping the thermodynamics portion of 51 and the special relativity section of 52, but professors could then increase time spent on the nuances of the conservation laws or Maxwell's equations. In addition, professors could do more to change the current environment in recitation and lecture where questions are looked down upon and illuminating debate is often stifled, chiefly because of general fears in the physics classroom of looking stupid.

Maybe as a reformed physics major I am too trusting of the often-lazy Duke student population. But I am a firm believer that if students can be taught the big ideas of what physics strives to do, then they will be hooked to it like a drug. As Brian Greene puts it: "It seemed that if one could gain a deep familiarity with the questions, a real profound understanding of them — why is there space, why is there time, why is there a universe — then at least that would be the first step towards coming to answers about the purpose of our existence. And physics is the field that has these questions as its real central motivating force."

If the physics department can convey that intensity and wisdom to the ranks of physics students coming through its doors, then it will have a host of new converts more prepared for the challenges and problems of our future.

—contributed by Philip Kurian, Undergraduate Physics Major

International Meetings Hosted by TUNL

—from the Director of TUNL, Prof. Werner Tornow

TUNL hosted the 17th International Conference on Few-Body Problems in Physics (FB17) this summer. A total of 235 scientists from 33 nations gathered at Duke from June 5-10 to discuss the newest developments in "Few-Body Physics", where "few" refers to the number of fundamental particles whose complex interactions are studied. This series of conferences began more than 40 years ago. While the early conferences concentrated on few-nucleon systems (the constituents of atomic nuclei), it did not take long for the later conferences to develop into a major gathering of scientists working in the very broad field of few-body systems, ranging from subatomic to atomic and molecular systems. At Duke, a total of 180 talks and more than 50 posters were presented. FB17 followed the 2000 conference held at Taipei, Taiwan, and it will be followed by the 2006 conference scheduled to take place in Sao Paulo, Brazil. FB17 was sponsored by the TUNL universities, the International Union of Pure and Applied Physics (IUPAP), the U.S. Department of Energy, the U.S. National Science Foundation, and a number of U.S. National Laboratories and universities.

In parallel to FB17, TUNL hosted the annual meeting of the Nuclear Physics Commission of IUPAP, bringing the crème de la crème in nuclear physics from around the world to Duke University.

Biophysics of Tissue Dynamics

—adapted from an article by Dennis Meredith, Duke Office of News & Communications

An interdisciplinary team of physicists, biologists, and mathematicians has snipped their way to a new understanding of a key process in a fruit fly's embryonic development. The process, called dorsal closure, is the complex mechanism by which the embryonic skin of the fruit fly Drosophila knits itself together to protect its innards from the outside world.

The researchers' achievements were reported in April [Science 300, 145-149 (2003)] and two reviews have appeared in print [Science 300, 63-64 (2003); Current Biology 13, R494-495 (2003)]. It was this broad collaboration, said the scientists, that enabled them to refine the laser microbeam, to perform the microsurgery on the fly tissue, and to model the forces involved in key developmental machinery.

"Dorsal closure is a good system for studying these processes because it's tractable," said Shane Hutson, a postdoctoral fellow in the FEL Laboratory. "We only have to deal with a few different kinds of cells that are arranged in a planar fashion." The mystery, said Hutson, was precisely how these different tissues, and the forces they exert, work together to effect dorsal closure. "There are lots of ways you could build a model such that closure would occur," said Hutson. "And so, we wanted to systematically investigate the forces in the system to figure out which of these processes were really contributing to closure, and which were simply following along."

To attack the problem, the team needed to be able to selectively dissect the force-producing tissues, and to simultaneously observe the result through a confocal microscope. Thus, they designed an optical and steering system for the microbeam that was implemented and refined by physics graduate students Yoichiro Tokutake and Ming-Shien Chang. The resulting system can produce and guide a laser beam as small as a half-micron in diameter — roughly a hundredth the diameter of a human hair.

Said FEL Director and physicist Glenn Edwards, "These four forces are working in concert, so in essence we are trying to understand the 'symphony' of dorsal closure — how these forces are coordinated in space and time." The dissection of the symphony produced surprises, said Hutson. "For example, we found that the system was very resilient," he said. "When we perturbed only one or another of the tissues, the process kept right on going. "We were surprised by this finding because we thought we'd find that at least one of these processes was absolutely essential," he said. "But it does make sense in the end that you'd want a system where, if something's not quite right in one process, you can compensate and still complete dorsal closure."

Key to the rigorous understanding of this intricate system was the physical reasoning inherent in creating a quantitative model describing the process — the result of a team effort led by Edwards, Hutson, Duke biologist Dan Kiehart and Duke mathematician Stephanos Venakides.

One of the next goals of the collaboration, according to Dan Kiehart, will be to use the same kind of modeling to study wound-healing. "We may begin with Drosophila, but then progress to studying vertebrate cell cultures, fish or mice, where genetic studies may be of more direct interest to physicians." However, emphasized Kiehart — an expert on the molecular machinery of such contractile processes as dorsal closure — Drosophila remains an attractive research model because the flies can be genetically manipulated so easily.

Other major questions include how the multiple forces involved in dorsal closure are synchronized, and how the system initially launches the process. Said Venakides, "One way this system might work is like the unwinding of a clock, with the closure proceeding on its own initial energy. Another analogy might be the driving of a car, where a steady force is being guided."

More broadly, said Kiehart, such studies "are going to provide a model not only for dorsal closure and wound-healing, but for studying any such developmental process that involves tissue migration and closure." Essential for these scientific advances, said Edwards, is the value of interdisciplinary collaboration. "The FEL Lab is an interdisciplinary think tank, and in this environment my group, Dan's group, and Stephanos came together to work on this problem at the interface of traditional disciplines. And we've made a lot of progress towards cracking it!"

—Glenn Edwards is Director of the FEL Lab and Professor of Physics

Ultracold Gas Shows "Lopsided" Properties

—adapted from an article by Monte Basgall, Duke Office of News & Communication

Duke University researchers have created an ultracold gas that has the startling property of bursting outward in a preferred direction when released. According to the researchers, studying the properties of the "lopsided" gas will yield fundamental insights into how matter holds itself together at the subatomic level. Also, the research team leader said their data suggests the possibility that the gas is exhibiting a never-before-seen kind of superfluidity. However, the researchers emphasized that they cannot rule out other mechanisms.

The findings, by a research team led by Duke physicist John Thomas, were posted online Nov. 7, 2002, on Science Express. In their experiments, Thomas and his colleagues used a "bowl" of laser light to confine a cloud of lithium-6 atoms to a cigar-shape between three and four millionths of a meter in diameter — and then cooled the cloud to 50 billionths of a degree above absolute zero.

Ordinarily, a gas cloud — even a cigar-shaped one — behaves in a predictable way when released in a vacuum. "It expands and quickly becomes spherical because it moves at equal speeds in all directions," said Thomas. "This new gas does something radically different," Thomas said in an interview. "In the direction that it was initially tightly confined the gas explodes rapidly outwardly. And in the other direction it doesn't move at all."

As reported in Science Express, Thomas's group explains this behavior as a sign that the lithium atoms are both cold enough and sufficiently strongly attractive to become what is known as a "strongly interacting, highly degenerate Fermi gas" — the first time such a gas has been produced, they said.

A Fermi gas is one composed of "fermions," a class of atoms constrained by a quantum mechanical property from getting too close to each other. Lithium-6 is an example. That property contrasts with the other class of atoms, called "bosons," which prefer closeness. Helium-4 is an example of a boson. A Fermi gas is "degenerate" when at a very low temperature, known as the Fermi temperature, its atoms approach their closeness limits. Thomas' lab has been a leader in developing optical traps for cooling-down fermions to well below their Fermi temperature, using a carbon dioxide laser trap he likens to an "optical bowl."

To create a strongly interacting gas of fermions, the Duke team had to fill the optical bowl with lithium atoms whose subatomic constituents are in two different states of spin. Those two fermion types can be induced to approach each other unusually closely in the presence of an applied magnetic field. His group's latest achievement, chilling the trapped atoms to about 50 billionth of a degree above absolute zero, means "we're getting down to the very lowest temperatures anybody has ever seen in a Fermi system," he said.

The fact that the gas is both strongly interacting and highly degenerate means each atom's "range of interaction becomes larger than the distances between each atom," Thomas said. "There's this tremendous interaction that is reaching out to attract the atoms to one another. Some theorists have predicted that the whole gas should implode and be unstable. We suggested that's probably not the case. And our experiments show it is probably not the case."

The new atomic gas could interest scientists studying strongly interacting systems in other areas of physics, such as high-temperature superconductors in solid-state physics or quark matter in high-energy physics. The interactions in the atomic system are certainly not the same as in these other systems, but the description and calculation methods are similar. Says Thomas, "Our system provides a model for studying strongly interacting systems."

Physicists have predicted that an atomic gas of fermions could become superfluid at temperatures lower than their Fermi temperatures. And experimentalists have been trying to observe such superfluidity in a Fermi gas since about 1995, Thomas said.

There are possible signatures of superfluidity in the data obtained by the Duke group. For one thing, the experiments produced the conditions recently predicted for this type of superfluid. Furthermore, a theoretical group in Italy predicted that a fermionic gas exhibiting superfluidity should show "an anisotropic expansion of the type we're observing," Thomas added. But the researchers are reluctant to definitively conclude that they have observed superfluidity because they have identified an alternative explanation for the data. The gas may be in a new regime of collisional dynamics, Thomas said. While collisions may adequately explain the data, the Duke researchers will have to carefully address this possibility in additional experiments.

If this oddly behaving gas is a superfluid, Thomas said it is of a special type that would be an "analog of a very, very high temperature superconductor" were it in solid form.

—John E. Thomas is Professor of Physics

KamLAND Observes Anti-Neutrino Oscillations

Do neutrinos have mass? Do these subatomic particles oscillate back and forth from one "flavor" to another? What can they tell us about the workings of the Sun, the composition of the Earth, the process of star collapse, and the origin and the future of the cosmos? These are just a few of the questions being explored by TUNL researchers in the experiment known as KamLAND, the Kamioka Liquid-scintillator Anti-Neutrino Detector located in a mine cavern 1 km beneath a mountain on Japan's main island of Honshu.

The KamLAND detector was built by a collaboration of scientists from Japan and the United States. The TUNL group is the largest U.S. university group at KamLAND. It built and continues to operate the veto detector, a 3.3 ton ultra-pure water based Cherenkov detector surrounding the 18 m diameter stainless steel sphere that contains a balloon filled with 1.3 tons of liquid-scintillator fluid. The veto detector is needed to distinguish the events of interest from muon induced events that can mimic anti-neutrino events. The anti-neutrinos are produced by nuclear reactors in Japan and South Korea. The weighted average distance between the reactors and the KamLAND site is about 175 km.

When an incoming anti-neutrino collides with a proton contained in the liquid-scintillator fluid, flashes of light are emitted that are detected by about 2000 photomultiplier sensors attached to the inner surface of the stainless steel sphere. The photomultipliers convert the flashes into electric signals that are processed by electronic chips specifically designed for KamLAND, and finally analyzed at computation centers in Japan and the U.S.

The KamLAND experiment is not only the largest liquid-scintillator detector ever built, but it also needs more electric power than any other experiment performed on earth: it is based on a total of 60 GigaWatts of electric power, which corresponds to 4% of the world's man-made power or 20% of the world's nuclear power. Fortunately, all this comes for free for the KamLAND scientists.

Neutrinos are subatomic particles that interact so rarely with other matter that some of them would pass "untouched" through a wall of lead stretching from the Earth to the Moon. They are produced during nuclear fusion, the reaction that lights the Sun and other stars. In fact, our Sun produces so many that about one billion of them pass through your fingertip every second. Anti-neutrinos are created in fission reactions such as those that drive nuclear power plants. Splitting a single atomic nucleus yields smaller radioactive nuclei that emit an electron and an anti-neutrino. Since anti-matter is thought to be the mirror-image of matter in properties and behavior: to study anti-neutrinos is to study neutrinos. Both neutrinos and anti-neutrinos come in three "flavors".

According to the predictions of the Standard Model of Particle Physics, which has successfully explained subatomic physics since the 1970's, neutrinos/anti-neutrinos are massless. Contrary to this, over the past two years, solar neutrino experiments at the Sudbury Neutrino Observatory in Canada and at Super-Kamiokande located adjacent to the KamLAND cavern implied that the ghostlike snippets of matter possess mass. This enables them to change flavor over a distance, often referred to as neutrino oscillations. However, solar neutrinos might have interacted in an unexpected way with the Sun's magnetic field en route to the detector on Earth. KamLAND is the first experiment to observe the neutrino properties responsible for solar neutrino flavor changes from a terrestrial source – the reactors in nuclear power plants. It's an amazing coincidence that KamLAND just happens to be the right distance from Japan's nuclear reactors to be sensitive to the anti-neutrino oscillations that are expected from the solar experiments.

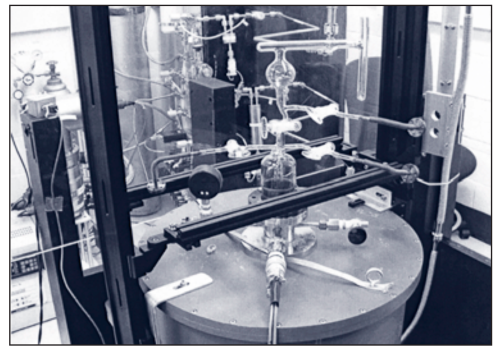
In a January 2003 paper in Physical Review Letters, the 92 physicists who make up the KamLAND collaboration reported that over a period of 145 days of operation, they recorded 54 anti-neutrino events as opposed to the approximately 86 events predicted by the Standard Model. The researchers at KamLAND are seeing a deficit of antineutrinos that is compatible with the deficit that has been observed for solar neutrino experiments.

This result means that neutrinos have mass. Although their mass is very small, neutrinos contribute more to the mass of our universe than all visible stars.

—contributed by Werner Tornow, Director of TUNL and Professor of Physics

A New Search for the Neutron Electric Dipole Moment

Precision measurements of the properties of the neutron present an opportunity to search for violations of fundamental symmetries and to make critical tests of the validity of the standard model of electroweak interactions. Recently, a new experiment was proposed to search for the neutron electric dipole moment (EDM) with unprecedented sensitivity; the team consists of physicists from the U.S., Canada, France, Germany, and the Netherlands, including Professor Haiyan Gao's group at Duke. The proposed search will improve the neutron EDM limit by about two orders of magnitude.



A non-zero neutron EDM would be a direct indication of time-reversal symmetry (T) violation. That in turn would indicate violation of the symmetry CP (charge conjugation C and parity P) because of CPT invariance. The Standard Model (SM) prediction for the neutron EDM is below the current bound by six orders of magnitude. However, many proposed models of electroweak interactions, which are extensions beyond the SM, predict much larger values for the neutron EDM. By reducing the acceptable range for predictions by two orders of magnitude, the proposed experiment may provide a significant challenge to these SM extensions as well as pointing toward New Physics Beyond the SM. Furthermore, if sources of CP violation beyond the SM mechanism are present in nature and are relevant to hadronic systems, this experiment offers an intriguing opportunity to measure a non-zero value of the neutron EDM.

The current understanding of the origins of baryons provides one reason for thinking that new sources of CP violation might exist in nature. To explain the baryon number asymmetry in the universe (many more baryons than anti-baryons) through a grand unified theory or electroweak baryogenesis, substantial New Physics involving CP violation is required.

The proposed experiment is based on the nuclear magnetic resonance technique. The strategy is to form a three-component fluid of ultra-cold neutrons (UCN) and ^{3}He atoms dissolved in a bath of superfluid ^{4}He at 300 mK. When placed in an external magnetic field (about 1 mGauss), both the neutron and ^{3}He magnetic dipoles will precess about the direction of the field. The measurement of the neutron electric dipole moment comes from the shift in the precession frequency of the neutrons when a strong electric field (50 KV/cm) is turned on (see Figure). Because the magnitude of the shift due to the interaction of the neutron EDM with the electric field is extremely small, it is imperative to measure the overall precession frequency with great precision.

The required precision will be obtained by comparing the UCN precession frequency to that of ^{3}He. The comparison makes use of the spin dependence of the nuclear absorption cross section:

$$n + {}^3\text{He} \longrightarrow p + t + 764\ \text{keV}\ ;$$

it is strongly suppressed when the spins of the neutron and ^{3}He nucleus are aligned parallel to each other. The neutron absorption rate can be measured by monitoring the scintillation light generated in superfluid

^{4}He by the reaction products. The polarized ^{3}He nucleus also acts as a magnetometer – knowledge of the magnetic field environment of the trapped neutrons is a crucial issue in the analysis of systematic errors.

Understanding the relaxation mechanism of polarized ^{3}He nuclei and maintaining their polarization is essential to the success of the entire EDM experiment. Currently, an intense effort within the EDM collaboration (Caltech/Duke/UIUC/NIST/HMI/Simon-Fraser) focused on studying ^{3}He relaxation study is centered at Duke and is led by Prof. Haiyan Gao's Medium Energy Physics Group at TUNL. A spin-exchange optical pumping technique produces polarized ^{3}He nuclei whose relaxation is then probed using nuclear magnetic resonance (NMR) The apparatus will allow the study of ^{3}He relaxation down to a temperature of 1.5 K under the UCN storage cell conditions. Preliminary results at Duke are expected in the summer of 2003, and the final measurements from the Duke EDM apparatus will be completed by February, 2004. The ultimate test at 300 mK is anticipated to take place at the University of Illinois, Urbana-Champaign, where a low temperature facility is currently being built. Details of the EDM experiment can be found at http://p25ext.lanl.gov/edm/edm.html.

—contributed by Haiyan Gao, Associate Professor of Physics and Dipangkar Dutta, Assistant Research Professor

How Do Particles Acquire Mass?

Professor Ashutosh Kotwal's research focuses on the physics of fundamental particles and forces at high energies. One of the outstanding mysteries is the mechanism by which particles acquire mass. The theory of gauge symmetry has been very successful in describing the known fundamental forces; however, this theory is obviously incomplete because it requires all particles to be massless. Clearly we are missing a big piece of the puzzle.

Prof. Kotwal is pursuing this question experimentally using two approaches – precision measurements of fundamental parameters, and direct searches for new particles and forces. He is the convener of the Electroweak physics group in the CDF experiment at Fermilab. The experiment is collecting data from proton-antiproton collisions with a total energy of 2 trillion eV, the highest energy collider in the world. The electroweak group is engaged in precision measurements of the production, decay, and self-interactions of the W and Z bosons and the photon.

Prof. Kotwal leads the effort to measure the mass of the W boson, which is sensitive to the quantum mechanical effects of new particles or forces. He has developed a new experimental technique based on finding and using cosmic rays for precise calibrations (published in Nuclear Instrumentation and Methods this year). With the data to be collected over the next few years, the goal is to make a W mass measurement with a precision of 0.03%, a major improvement over the current state-of-the-art.

Students and a post-doc work on searches for rare, exotic signatures of new interactions. He recently published in Physical Review Letters the results of a search for a new weak force and particle substructure, which is the most sensitive search in the electron-neutrino channel. His student, Heather Gerberich, is completing her Ph.D. thesis on a search for new, electron-like particles decaying to an electron and a photon. Such states are predicted by particle hypotheses as tightly-bound states and in theories of unified forces. She presented her results at the APS Conference this year and will also be presenting them at the Lepton-Photon Conference. Dr. Kotwal is also working with an undergraduate student, Edward Daverman, to perform a similar search for massive muon-like states decaying to a muon and a photon. These heavy lepton searches are the first performed at Fermilab.

Prof. Kotwal is working with his post-doc, Christopher Hays, and another graduate student, Joshua Tuttle, to search for doubly-charged Higgs particles. These particles are predicted in theories where the weak interaction has both left-handed and right-handed couplings, as is indicated by recent data on neutrino oscillations. Furthermore, in Supersymmetric extensions which impose a fermion-boson duality, the doubly-charged Higgs particle is predicted to be light, providing exciting motivation for the search. The experimental signatures for light doubly-charged Higgs particles are rather striking: decays to two same-sign leptons, or quasi-stable tracks with large ionization signal. Chris presented these and other exotic search results at the Annual Fermilab Users Meeting this year. The cosmic ray detection technique mentioned above provides crucial input that makes these searches possible.

In addition to his experimental research, Prof. Kotwal has done theoretical work in the phenomenology of black holes in extra spatial dimensions. Extra spatial dimensions have been motivated by string theory and to explain why the gravitational force is so much weaker than the electromagnetic force at large distances. In this scenario it is possible for the gravitational force to be strong in the high energy regime of particle colliders, leading to the production of black holes. Prof. Kotwal and his post-doc published a paper in the Physical Review D last year, which analyses the production and decay of rotating black holes, and describes their experimental signatures. Prof. Kotwal has also co-authored a paper on black hole relics with colleagues from J. W. Goethe University in Frankfurt, which was published in Physics Letters B this year.

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—contributed by Ashutosh Kotwal, Assistant Professor of Physics

Controlling photons and phonons in semiconductors

Ascertaining the degree to which properties of nature once thought immutable can be altered and controlled is a key goal of physics research. In Adjunct Prof. Henry Everitt's lab, students have recently demonstrated remarkable control over both the spontaneous emission rate of photons and the amplitude of phonon oscillations in a semiconductor heterostructure. To accomplish these feats, both experiments utilized special properties of one of today's hottest semiconductor materials, the GaN family which has tremendous technological importance for the lighting, display, and detector industries.

Control of photon emission rate

The spontaneous emission rate from a semiconductor quantum well depends on the photon density of states (DoS), as predicted by Fermi's golden rule. Most semiconductor emitters couple light into free space, resulting in the familiar emission from laser diodes and light emitting diodes. However, if the surface of a semiconductor is coated with a thin metallic film and the quantum well is grown just below this surface, the emission rate can be dramatically increased. A surface plasmon, which is a collective photon-carrier excitation at the interface of the metal and semiconductor, is created into which the photons are emitted. The photon DoS of the surface plasmon is much higher than the free-space pho-

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ton DoS and is very strongly peaked near the surface plasmon resonance frequency. The quantum well therefore emits strongly at this frequency.

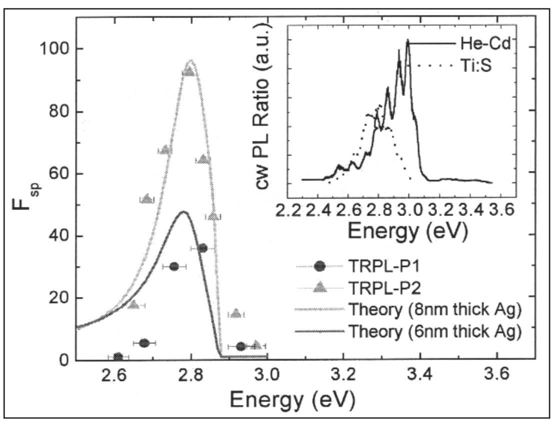

Figure 1: Measured and modeled frequency (energy) dependence of the spontaneous emission enhancement factor (Fsp) of an InGaN quantum well coupled to a silver surface plasmon. The data correspond to two different locations (P_1 and P_2) on the sample, indicating the sensitivity of the enhancement to the thickness of the silver film. Inset: An estimate of the enhancement factor from continuous wave photoluminescence (cw PL) by comparing the radio of the PL from the silvered and unsilvered sides for two different laser excitation sources (a He-Cd laser and a frequency-doubled Ti: Sapphire laser).

In this study, the spontaneous emission from an InGaN single quantum well with a nearby silver film was measured, using picosecond time-resolved photoluminescence techniques, to be as much as 92 times faster than the rate for emission into free space (Figure 1). Resonant enhancements by as much as 10,000 are predicted for slightly modified structures.

Designers of optoelectronic devices may now optimize emitter performance for the material used. This capability has many potential applications such as faster modulators and photonically coupled devices.

Control of coherent acoustic phonons

In bulk semiconductors, very low frequency acoustic phonons (gigahertz) can be observed optically through inelastic scattering of the light. High frequency (terahertz) acoustic phonons may be observed if the bulk semiconductor is replaced by a multiple quantum well (MQW) structure. This two dimensional artificial periodic structure breaks translational symmetry, making it possible to observe the so-called "zone folded" acoustic phonons.

Using sub-picosecond optical pump-probe techniques in Prof. Everitt's laboratory, students generated high frequency, zone-folded longitudinal acoustic phonons (ZFLAPs) in an InGaN multiple quantum well structure. Carriers injected near the MQW barrier band edge generated strong ZFLAP oscillations; moreover, the oscillations were coherent since screening by the photoinjected carriers suddenly and simultaneously relieved lattice strain in each of the quantum wells. Because of the long-lived coherence, these phonons could be controlled as well: two pump beams were used to generate two coherent ZFLAP oscillations whose relative timing and amplitude were controllable (Figure 2). Both enhancement and suppression of ZFLAP oscillations were demonstrated, including complete cancellation of generated acoustic phonons for the first time in any condensed matter system.

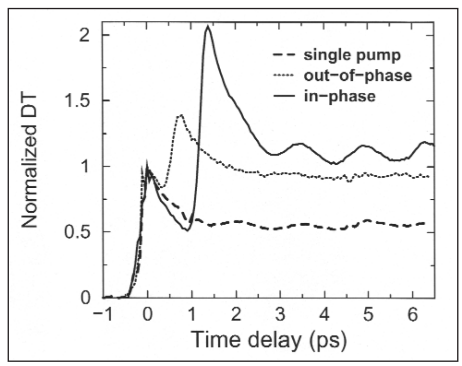

Figure 2a: Typical differential transmission data showing coherent ZFLAP oscillations. The upper curve is the raw data, and the lower curve reveals the damped ZFLAP oscillations after the bi-exponential carrier decay has been substracted.

The ability to generate and control spectrally pure, single mode acoustic phonon oscillations places researchers at the threshold of a new experimental regime never before available to the limited arsenal of the phonon physicist.

—contributed by Henry Everitt, Adjunct Professor of Physics

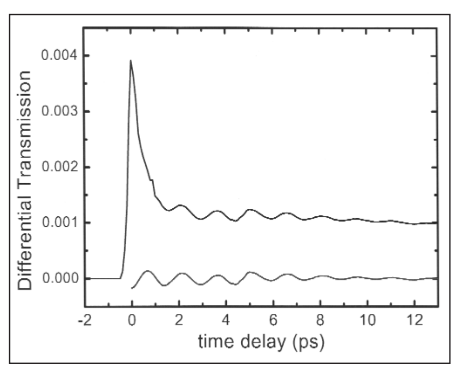

Figure 2b: Two-pump, one-probe differential transmission data demonstrating coherent enhancement and suppression of coherent ZFLAP phonons.