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ANNUAL NEWSLETTER 2008

## WHAT'S INSIDE



Editors:
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Special thanks to Yingyi Zhang for several photos.

Cover image courtesy of Professor Gleb Finkelstein, www.phy.duke.edu/~gleb/.

# Department Happenings

*—from the Chair, Daniel Gauthier*

The Department of Physics had a fantastic year in 2007–2008! Faculty were appointed, promoted, or received honors, externally funded research increased during a difficult climate, a large number of students graduated from our educational program, interdisciplinary research activities have flourished, a new undergraduate major is in the works, our faculty are ranked near the top with regards to productivity, and we continually hear good news from our alums. In this note, I'll summarize a few of these activities, while other topics are discussed in full-length articles in this issue of our newsletter. If you are reading this from afar, I encourage you to visit the Department to see the broad range of our activities!

### Faculty News

It is a great pleasure to report that Dr. Anton Tonchev accepted a position as an Assistant Research Professor of Physics, where he will continue his research on heavy nuclei and nuclear astrophysics with applications to national security and energy. The appointment is for three years and began Dec. 17, 2007. Previously, he was a Senior Research Scientist with the Triangle Universities Nuclear Laboratory.

I am also very excited by recent faculty promotions. Dr. Gleb Finkelstein was promoted to Associate Professor of Physics and Dr. Haiyan Gao was promoted to Professor of Physics, both effective July 1, 2008. Congratulations to both!

On the faculty recruiting front, the Department continues to search for an outstanding experimental condensed matter physicist to fill an endowed professorship at the Full Professor level, created by an anonymous gift to the University.

On a sad note, Dr. Anna Lin has resigned her faculty position to pursue other interests. While this is a blow to our efforts in nonlinear dynamics, statistical physics, and biological physics, I am very happy that Dr. Lin is moving in exciting new directions and we wish her great future success.

Members of our experimental high energy physics faculty continue to take on leadership positions. Associate Professor Ashutosh Kotwal was elected to serve on the Fermilab Users Executive Committee, which represents the Fermilab user community to the lab management, DoE and the government, including Congress. Fermilab is the US Department of Energy Laboratory near Chicago, which operates the current highest-energy particle accelerator in the world. Congratulations on landing such a high profile position in the HEP community!

There have been several faculty awards: Professor Mueller was chosen by the Southeastern Section of the American Physical Society (SESAPS) for the 2007 Jesse W. Beams Award. This award has been given in recognition of his extensive theoretical nuclear physics research record and his leadership in bringing international awareness to the strength of nuclear physics programs in the Southeast. The Award was presented at the Annual Meeting of the SESAPS on November 9, 2007 in Nashville, TN.

Three faculty members were named Fellows of the American Physical Society! This is a great honor; election to Fellowship in the APS is limited to no more than one half of one percent of the membership, recognizing outstanding contribution to physics. Professor Haiyan Gao is cited for: “For her extensive contributions to understanding the quark/hadron transition region and for determinations of the nucleon electromagnetic form factors.” Professor Harold Baranger is cited for: “For contributions to mesoscopic and nanoscale physics, especially the manifestations of classical chaos in quantum properties and the interplay of quantum interference and electron-electron interactions.” Professor Ashutosh Kotwal is cited for: “For his precision measurements of the mass of the W boson at the Te-vatron.”

On January 17, Professor Calvin Howell was selected to receive a coveted “Sammie” award from the Samuel DuBois Cook Society. The Cook Society was founded to be an instrument of social engagement and change. The Sammie award recognizes members of the Duke community who, though often unheralded, reflect in their work or in their academic pursuits, the objectives to which Dr. Cook dedicated his professional life: to translate the promise and potential of African Americans into fulfillment and actuality, and to seek to improve relations among persons of all backgrounds. Congratulations!

On May 12, 2008, Professor Arlie Petters was named one of the twenty-five greatest scientists of African ancestry of all time by Human Relations Associates. To read more about the richly deserved recognition, see: (http://hrassoc.net/blog/modules/news/article.php?storyid=17).

### “Physics”

The American Physical Society has created a new online source of research news and discussion, called “Physics.” (http://physics.aps.org/). This site describes exceptional papers from the Physical Review family of journals and is a great way to keep up with the latest research in an accessible format. Even though the online publication recently started, two Duke results have been highlighted. One was the work by Dr. Xu Du—together with recent graduates Dr. Le Luo and Dr. Bason Clancy—and Professor John Thomas on their observation of anomalous spin segregation in a trapped Fermi gas (http://physics.aps.org/articles/v1/27). The other was the work by Mr. Bryon Neufeld, together with Professor Mueller and former Duke post-doc Dr. Joerg Ruppert, on sonic Mach cones induced by fast partons in a perturbative quark-gluon plasma (http://physics.aps.org/articles/v1/29).

### Postdoc News

Dr. Naho Tanimoto, a former post-doc in the neutrino group, has started a new position as a researcher at the University of Tokyo. Dr. Tanimoto spent almost three years at Duke working on the Super-K and T2K experiments and will continue to work on these experiments in her new position. Everyone in the Duke group looks forward to continuing to work with her!

### Staff News

Mr. Derek Leadbetter and Mr. Ken McKenzie have accepted positions as Laboratory Administrators. They will be working with us to develop and run our Laboratories for Introductory Physics. Mr. Leadbetter has a wide range of experiences and has been associated with Duke for many years, including jobs in Special Events and as an undergraduate in the Duke Electrical and Computer Engineering Department. He has also done extensive work in the electronics industry at some of the chip companies in the Research Triangle Park. For more on Mr. McKenzie, please see the article later in this newsletter. They have already made their mark on our Introductory Physics program!

In addition, Mr. Florin Damian has joined the Department as the support person for the Director of Undergraduate Studies. He has extensive experience in computer science as well as management in local area businesses.

### Introductory Physics

The Department of Physics and the Pratt School of Engineering have been recognized in the April 2008 issue of the “Prism” magazine of the American Society for Engineering Education. The article lauds Duke for re-envisioning the Introductory Physics sequence to better suit the needs of the students. There is demonstrated evidence that the students are better prepared for the upper level courses than before our curricular changes. In an e-mail to me, the new Dean of the Pratt School, Professor Tom Katsouleas, says: “It was great to read a featured story about your successful revamp of physics for engineers at Duke. Congratulations to all who contributed—both on your success and on the terrific publicity it generated. Just what we want—the engineering world looking to see “What is Duke-Pratt doing?” Well done.

Special thanks goes to Profs. Socolar and Teitsworth who did much of the initial planning and have been following through with the plan over the past few years to make it the success it has become. Also thanks to all the other faculty, graduate students, and staff who make these complex courses a success! It is a lot of work for all involved, but it is a major part of our mission. This press is a good indication we are on the right track!

# Undergraduate News

*—by Director of Undergraduate Studies, Seog Oh*

With another academic year behind us, it is again a time for reflection and to plan to move forward. We had twenty students graduated with degrees in physics last May. Twelve students were primary majors, six were secondary majors and two were minors. Of the primary majors, four will enter graduate school in the fall (Christina Herring, Chris Lester, David Staub, Tutanon Sinthuprasith), two (Alejandro Caceres and Mike Sori) are planning to attend after a break. Alex Frank has a ROTC commitment. Simpson Reid will teach at a high school in Raleigh. Adam Lanka and Dan Fox have travel plans before jumping into the workforce. Sepehr Sadighpour will work at a Catholic ministry as a business manager for a year. I'll certainly try to find out more about their lives after Duke for next year's newsletter.

One of our majors, Konrad Dudziak, is back after taking off a year to focus, train, and compete for a spot on the United States Olympic Wrestling Team. He qualified for the Olympic trials but did not make it to Beijing. He is determined to try again in four years.

The department continues to look for ways to provide the best education for our students to prepare for the changing world. We continue to strengthen our core courses and electives while strongly encouraging students to participate in independent research, which provides the best mechanism to develop independent and critical thinking. The number of students taking independent study and writing senior theses has increased substantially the last few years. Faculty participation has increased as well. The annual poster session at the end of the spring semester was a success in terms of the number of participants and the quality of the posters. Eleven undergraduates participated with a wide range of topics. In order to prepare students for independent research, the department has created a research skills course (Phy115), where students learn the basic tools for research.

During the poster session, eight students were inducted into the Duke chapter of ΣΠΣ, the national physics honor society. Professor William McNairy, the faculty adviser, conducted the ceremony. The new members are: Kevin Brown, Ariana Minot, Aaron Pollack, Forest Sheldon, Pantana Tor-ngerm, Alexander Tuna, Barry Wright, and Eric Yff. Congratulations to all.

We also worked on broadening undergraduate curricular opportunities. The department has been working hard to create a major in biophysics with the Biology department. Biological science and biophysics has emerged over the past decade as an important field that deals with systems and problems of biological interest. There is little doubt that physicists with strong problem solving ability should do well in this field. Another area is astronomy. With the cooperation of UNC's physics and astronomy department, we now have a more coherent way to accommodate students interested in astronomy. The astronomy and astrophysics fields are growing, with better telescopes and detectors on the ground and in orbit and these continue to capture students' imagination.

One area we have started but have not made enough progress in is to foster a greater sense of community among the undergraduates and faculty. The idea is to have one or two faculty meet students over lunch or dinner provided by the department to discuss not only their research interests but also any topics remotely related to physics informally every month. This is especially useful for freshmen and sophomores to start thinking about the physics majors and independent research. From time to time, a guest speaker is invited to talk about careers with a physics degree other than the traditional path involving physics graduate school.

I believe that the department is doing a fine job in undergraduate education but there is always room for improvement. It is important that the faculty does not lose sight of the fact that one of our prime missions is education. We must be proactive in thinking about how to improve our teaching and our courses, as well as better interact with students and provide interesting research opportunities.


***2008 Graduates with faculty.*** *From left to right: Professor John Thomas, Professor Kate Scholberg, Professor Richard Palmer, David Staub, Professor Haiyan Gao, Professor Dan Gauthier, Sepher Sadighpour, Alexander Frank, Sebastian Liska, Adam Lanka, Tutanon Sinthuprasith, Daniel Fox, Christina Herring, Reid Simpson, Christopher Lester, Fareed Qureshi, Professor Ashutosh Kotwal, Professor Seog Oh (DUS).*

# Graduate News

*—by Director Richard Palmer and Assistant to Director of Graduate Studies, Donna Ruger*

Summer 2007 thru Summer 2008 the following students received their Ph.D.'s:

1. **Matthew Allen Blackston**
   **Advisor:** Henry Weller
   **Employment:** Postdoc at Oak Ridge National Laboratory, Oak Ridge, TN
2. **Ted Brian Bunton**
   **Advisor:** Roxanne Springer
   **Employment:** Assistant Professor at Coastal Carolina University in Conway, SC
3. **Danny James Cecile**
   **Advisor:** Shailesh Chandrasekharan
   **Employment:** Working for his family owned business
4. **Soojeong Choi**
   **Advisor:** Henry Everitt and April Brown
   **Employment:** Postdoc with April Brown, Engineering, Duke University
5. **Bason Eric Clancy**
   **Advisor:** John Thomas
   **Employment:** Postdoc at Stanford in the biophysics group of Steve Block
6. **Andrew McCutcheon Dawes**
   **Advisor:** Dan Gauthier
   **Employment:** Assistant Professor of Physics at Pacific University
7. **Jianrong Deng**
   **Advisor:** Alfred Goshaw
   **Employment:** Postdoc in High Energy Physics at UC Irvine, based at CERN
8. **Hana Dobrovolny**
   **Advisor:** Daniel Gauthier
   **Employment:** A new mother, will seek employment later
9. **Anthony Hutcheson**
   **Advisor:** Werner Tornow
   **Employment:** US Naval Research Laboratory, Chesapeake Bay
10. **Matthew Kiser**
    **Advisor:** Calvin Howell
    **Employment:** Senior Scientist at National Security Technologies, Washington, DC
11. **Le Luo**
    **Advisor:** John Thomas
    **Employment:** Postdoc at the University of MD, in the quantum information group of Chris Monroe
12. **Shomeek Mukhopadhyay**
    **Advisor:** Robert Behringer
    **Employment:** Postdoc City College of NY
13. **Qiang (Alan) Ye**
    **Advisor:** Haiyan Gao
    **Employment:** Postdoc at Duke in Physics
14. **Peidong Yu**
    **Advisor:** Robert Behringer
    **Employment:** Postdoc DLR, Cologne Germany (DLR is the German equivalent of NASA)

*We would like to congratulate these students and their advisors, and look forward to hearing great things from all of you in the future.*

Wei Chen, Joel Greenberg, Seth Henshaw, Adam Sokolow, Wenzong Wu, Yu Zeng and Nan Zheng passed their Preliminary exams last academic year. Congratulations to them on becoming candidates for the Physics Ph.D. Kristine Callan earned an MS (with thesis) degree.

In January and May 2008 fourteen graduate students successfully passed their qualifier exam requirement.

We are proud to announce that several of our students received special awards 2007–2008:

- Kristine Callan: the Mary Creason Memorial Award;
- Johannes Norrell: the Graduate Teaching Fellows Award;
- Bason Clancy, Le Luo and James Joseph: the Fritz London Graduate Fellowship;
- James Esterline and Qiang (Alan) Ye: the Henry W. Newson Fellowship;
- Kristine Callan, Willie Ong, Mark Steadman and Yunhui (Rena) Zhu: the Department of Physics Outstanding Teaching Assistant Award;
- Joel Greenberg and James Joseph: the John T. Chambers Fellowship;
- Abhijit Mehta: the University Scholar Program Award.

The graduate student mentors, last academic year, were very supportive to our Fall 2007 incoming graduate class. They felt welcomed and very comfortable in their new environment. Thank you for your efforts Kristine Callen, Chenglin Cao, Joel Greenberg, Sam Gong, Mary Kidd, Hans Norrell, Changchun Sun, Shengying Wang, Huidong Xu and Wangzhi Zhang.

Thank you to the Physics Graduate Student Organization ( GSO) for again marshalling the considerable talent and enthusiasm of our graduate students to help with recruiting during our prospective student visitations. Educating our applicants about what life is like at Duke, is not possible without our graduate students to showcase their ongoing research here.

Our Fall 2008 incoming class consists of 11 students. They originate from China, Greece, UK and the United States. We will also host one exchange student, Martin Heinrich, from Germany.

Professor Haiyan Gao, Associate Chair, has added an "Extended Orientation" for the incoming International students. She and the GSO arranged a beach trip, a tour of the Nasher Museum, a tour through the Sarah P. Duke Gardens and many more activities to familiarize them with the American culture. Some of the other graduate students heard how much fun it was and now they are interested in joining next time. A very helpful ingredient of the "Extended Orientation" were the two classes, conducted by a professional speech instructor, for the non-english speaking students.

In addition to all of the things the GSO provides for our students, they host 2 Annual Socials (one in the Fall and one in the Spring) for the entire department. This has been very successful and instrumental in making our department a friendlier place in which to work. Another social event the GSO host's, as well as Professor Haiyan Gao and Professor Richard Palmer, is their annual Thanksgiving dinner for students who cannot go home.

Last, but not least, our second year graduate students host the Annual Department Picnic, right after the new class arrives. There is a great turnout to his event as everyone is invited to bring their family and friends, the food is delicious and the games are fun!

While our Graduate Lounge isn't upgraded to our expectations, we began the renovations this fall with a new refrigerator and a nicely restored sofa. As the year progresses, we hope to continue to make more improvements. We certainly want their lounge to be a comfortable and relaxing environment for our graduate students to kick back, take a break and relax.

We would like to encourage you to visit our newly renovated and much improved graduate website: http://www.phy.duke.edu/graduate/. We have added graphics, pictures, tables and a little humor. A very important feature to assist applicants and prospective applicants with their questions regarding the application process is the Frequently Asked Questions (FAQ) section. We hope this will be a helpful recruiting tool.

On the Careers and Jobs webpage http://www.phy.duke.edu/graduate/careers/ the graduate students, as well as post-docs will find much more information than before. The Physics Department has a close connection with the Duke Career Center, which is beneficial for our students.

When I took this new position as DGS, I moved into the office beside Donna Ruger the DGSA. Now both of us are located in the front hall making accessibility to each of us or to both of us at the same time, more convenient to the department.

This year the Graduate Curriculum Committee, consisting of some Faculty and some Graduate Students, put in many hours to complete our Mission Statement (see box).

We are proud of our Graduate Program. The time and effort put in by so many people has successfully made a friendlier, more cohesive department.

The Duke graduate program in physics equips promising students from all over the world with the skills and experience to perform cutting-edge scientific research in physics. Our students go on to become the next generation of leading teachers, scholars, researchers and professionals.

Graduate education at Duke is designed to solidify students' command of the concepts and methods of the discipline through course work and research. Students participate in state-of-the-art research early in their tenure, working closely with a faculty member, to gain personal research experience and a deep understanding of a particular subfield. The education culminates in the completion of a Ph.D. dissertation based on an original piece of research.

Faculty, students and staff within the department maintain a professional environment with a welcoming culture and a truly international climate so that all students can fully develop their talents and the joy of doing science pervades everyone's experience.


***First Year Graduate Students:***
*Front Row: Hannah Guilbert, Yu Song, Min Huang*
*Back Row: Ben Cerio, Yuan Lin, Qiujian Ye, Georgios Laskaris, Huaixiu Zheng, Chris Coleman-Smith, Martin Heinrich (Exchange Student), Abe Clark*

*Taritree Wongjirad also joins the incoming class of 2008.*

# Alumnus Profile: Harry Weller

*Harry Weller*

Harry Weller graduated from Duke with a bachelor's degree in Physics in the early 1990's. Since that time, he served as an officer in the U.S. Navy, before attending Harvard Business School where he received his MBA. Harry is currently a general partner at New Enterprise Associates, the world's largest venture capital firm. He focuses on technology investments and NEA's activities in China. Harry also serves on the board of the Mid-Atlantic Venture Association (MAVA), is a past Chairman of MAVA Capital Connection, and co-founded the Young Mid-Atlantic Venture Association (YAVA). Network Magazine named Harry one of the 50 Most Powerful People in Networking. Harry has been honored numerous times in Forbes magazine's "Midas List" as one of the most successful venture capitalists in America.

Prior to joining NEA, Harry was a Partner at FBR Technology Venture Partners where he worked with several successful startup teams in the software area. Early in his career, Harry managed strategy and technology initiatives in the financial, energy and telecommunications industries for the Boston Consulting Group and Deloitte & Touche Management Consulting.

Harry's undergraduate physics training has provided him with important insights for a number of projects that he has been involved with in the venture capital world. 1) Working on new solar cell technology that was spun out of GA Tech's DOE Center of Excellence for Photovoltaics. Harry recalls that "I had to remember a great deal of our studies on how photons work!" Additionally, Harry has been working on a Wind Turbine company whose power electronics system is its prime differentiator. The understanding of electronics was hugely helpful in understanding how these systems can better connect with the grid versus the standard approaches.

Interestingly, Harry points out that his studies of classical physics has helped him gain a great deal of credibility in the computer gaming space. Traditional Newtonian physics is utilized extensively in video games that simulate human scale events. Harry comments: "that knowledge impressed video game designer Dave Jones, creator of Grand Theft Auto—I was able to banter with him about it. I ended up investing in his company, Realtime Worlds."

More generally, Harry finds that "The interplay between scientific discovery and commercializing an actual product is a wonderful thing to watch happen. It is tricky and there are few people who can do it well. At the end of the day, an innovation can be commercialized if the market is large enough. Everyone has to understand the roles they play in that process and egos must be put aside to increase the probability of something working. Innovation must go hand-in-hand with management and capital to increase the probability of success."

# Kenneth McKenzie

*Kenneth McKenzie, Co-Manager, Introductory Undergraduate Laboratories*

Ken joined the staff of the Duke Physics department in November 2007 as co-manager of the Introductory Undergraduate Laboratories, together with Derek Leadbetter. In this role, he and Derek are responsible for ensuring the smooth operation of labs for the Physics 4x, 5x, and 6x course sequences, and taking care of the demonstrations. They also create new lab activities, often in collaboration with course instructors. He credits the late Dr. Mary Creason for awakening his interest in physics education. “She had a contagious enthusiasm for teaching,” he recalls, “I’m certain I caught it.”

Ken lives in Raleigh with his wife Hannah, a project manager for Maurer Architecture. They are currently working to expand their vegetable patch, and to plan a wildlife-friendly garden in their back yard. “The idea is to use North Carolina native plants,” he explains, “because native wildflowers attract butterflies, and native bushes provide cover for nesting birds.” The two also enjoy camping and hiking, most recently at Doughton Park along the Blue Ridge. Ken rides the TTA to work every day, and uses his time on the bus to gobble up books.

# Science outreach with Bob Behringer: granular dynamics at the Museum of Science and Industry in Chicago

Professor Bob Behringer recently designed and developed a new interactive demonstration for the Museum of Science and Industry in Chicago, in collaboration with workers at the museum, and at Evidence Design, based in New York. The basic design is made so that it is possible to rotate the apparatus, and then see the evolution of the force chain structures between the granular elements which, in this case are photoelastic disks. These disks were fabricated at Duke. The technique involves, as noted, photoelastic particles, which become birefringent under stress/strain. Where forces on a particle are large, the image appears bright (the child standing next to the exhibit gives a sense of scale.) This particular exhibit is part of a larger show indended to give a sense of forces in nature and to inspire a new generation of scientists. Note that the point of the exhibit is to show how inhomogeneously forces are carried in granular systems.


*Stress chains exhibit as it will appear in the museum.*

# Recording the History of the Duke Physics Department

*—by Maxine Stern and Horst Meyer*

Physics Chair Daniel Gauthier and J. Horst Meyer, Fritz London Professor Emeritus of Physics, felt that it was important for current members of the department to have a sense of the history of the department, particularly of the main actors who were responsible for the development and evolution of the Duke Physics Department. Horst Meyer wrote nine essays on important physicists, now deceased, who were in the Physics Department from the 1930's to the 1990's. These essays, accompanied by photographs, are now displayed on the Physics Department website: http://www.phy.duke.edu/history/.

Not wanting to lose the opportunity to record information from other retired faculty members and those who have been department chairs and directors of laboratories, Professor Gauthier asked Maxine Stern who was retiring from the position of Administrative Manager, to undertake this project. Maxine decided to videotape the interviews and have them edited so that current students and other department members, as well as our undergraduate and graduate alumni could view the edited interviews on our website. To date, fifteen faculty members have been interviewed. Discussions have touched on topics such as how they made the decision to come to Duke, what the department's environment was like while they were on the faculty, their research and teaching experiences. From them, we gain insight into the evolution of Duke University, race relations, and changes in the city of Durham and the Research Triangle in the second half of the twentieth century.

Eleven of these interviews now appear on the website. Four others are still in the edit phase, and will follow shortly. This project is on-going and will be expanded to include additional interviews and other items which shed light on other aspects of departmental history.

*Dr. Maxine Stern, who recently retired from her position as Administrative Manager in the Physics Department and Professor Emeritus, Horst Meyer.*

# Graduate Student Organization Activities

*—by Joel Greenberg*

### Rock Climbing

A new addition to Duke this year, the rock climbing wall provides more than a mechanism to strengthen one's forearms—the warm, social atmosphere and impressive number of physicist climbers of all levels has practically made this a physics hangout spot.

### Basketball/Campout

'Campout,' an annual graduate physics tradition, is the three-day trial that graduate students must go through in order to be ELIGIBLE to get season tickets to Duke men's basketball games. This year, eight students officially participated in campout, but even more stopped by to enjoy the festivities. Whether you are in it for the sport or play, campout is a lot of fun.

### Volleyball

Between the spring and fall (weather permitting), a weekly game of volleyball is played on the sand courts behind the Gross Chemistry building. What began with a small group of physics graduate students has grown to include several different departments. The games are friendly and non-competitive, and are played Thursdays at 6pm (until it is too cold to walk around barefoot!).

### GSO socials

This year, the GSO organized informal fall and spring socials in order to promote socializing outside of the physics building. The events were held in the new French Family Science Center, and were well-attended by the entire physics community. We are looking forward to keeping this tradition going in future years!

### GSS

The Graduate Student Seminar is an excellent forum for graduate students to give informal presentations to their peers. Most of the talks are given by students in preparation for a conference or exam, and enable the students to get useful feedback while educating their peers about the work currently being done in the department. In addition to these talks, we had some special presentations from the career development department, a talk on public speaking from alumnus Rob Saunders (*05), and a talk on medical physics from alumnus Eric Schreiber (*94).

### Orientation/Extended orientation

One of the GSO's main charges is helping with the recruitment and integration of incoming and first year graduate students. For the first time, an extended orientation program was put in place to allow students to arrive earlier and get acquainted with Durham and Duke before starting classes and teaching. The opportunity is open to all incoming students, and involved a movie night, Q&A forum with upperclass students, and a walk along the Eno River (among other things).

### Mentoring Program

The graduate student mentoring program is designed to provide first year students with an additional network of support via tried and true graduate student wisdom. Each first year graduate student is paired up with two upperclass students, and various group and one-on-one events are held over the course of the year. This year, students went out for afternoon ice cream breaks and we had a group Thanksgiving dinner to celebrate the holiday.

*Graduate students enjoying one of their weekly volleyball games on the sand courts.*

# The Symmetry of Physics and Music

*—by Junyao Tang*

It seems that physics and music often go together. Albert Einstein was an enthusiastic violinist, and Richard Feynman was a skilled bongo drummer. The same pattern is also found in the Physics department at Duke where a number of faculty members are skilled instrumentalists, vocalists, and musical enthusiasts.

Here, I would like to highlight two of our own grad students who are also talented musicians: Joshua Albert and James Esterline.

Joshua Albert is a 3rd-year graduate student who works in the neutrino group. He is also a tuba player in the Duke Wind Symphony. When talking about the role of music plays in his life, Joshua told me that it was more like a hobby and through this activity he got to know a lot of people outside physics which makes his hobby a social pastime. “When I play music, I never think about physics,” Josh said,” but I still admit there are some common points between music and physics. They both prove the beauty of nature. Music has a set of beautiful notes and a lot of more natural rules. Quantum Physics also has a beautiful symmetry built inside.”

James Esterline is a 6th-year grad student who works in TUNL and is also a talented concert pianist. He notes that when he plays music, there is only the music itself and he never thinks about the acoustics involved. However, James observes how the origin of the classical 5-note pentatonic, 7-note diatonic, and the 12-note chromatic scales can be related to number theory: “If notes with frequencies that differ by a factor of two (this interval being called an octave) can be identified with each other, then to express the range of frequencies within an octave, one comes up with a scale. Choosing which frequencies make up the notes of the scale can be tricky, though. For instance, Pythagoras came up with a system of tuning derived from the harmonic series, in which the frequencies of notes in a scale are related by powers of three divided by powers of two (related to the musical interval called the perfect fifth)—so the white-key scale on the piano, C-D-E-F-G-A-B-C, would have frequencies of 1, 9/8, 81/64, etc. times the frequency of the lower C. This doesn’t exactly work (otherwise, the upper C would have a relative frequency of 2.136 instead of the desired value of two), but comes close enough for music.”

“But I do find a difference between learning physics and learning music,” James comments. Then, he adds, “for physics problems, I do not need to do it again and again once I understand it. However, for music, you need to repeatedly practice and you typically enjoy practicing the same music. More importantly, you never know how many new things you can explore from playing the same piece.”

Well, those are some observations from our own musicians. While the detailed connection between music and physics may not be so clear, we can still take great enjoyment in the performances of our musical grad students.

*Joshua Albert, third year graduate student, plays tuba in the Duke Wind Symphony: “Music has a set of beautiful notes … Quantum Physics also has a beautiful symmetry built inside.”*

*James Esterline, sixth year graduate student and accomplished pianist: “When I play music, there is only the music itself; I never think about the acoustics.”*

# Searching for Perfect Fluidity in a Fermi Gas

—by John E. Thomas

Atomic Fermi gases provide a new paradigm for exploring the latest theories of exotic matter in nature. Confined in an optical trap at an appropriate bias magnetic field, a cloud containing a mixture of spin ½ up and spin ½ down atoms becomes the most strongly interacting non-relativistic system known. These Fermi gases offer unprecedented opportunities to test theoretical techniques that cross interdisciplinary boundaries, spanning fields from the very practical, such as super-high temperature superconductors, to the very fundamental, such as neutron matter and the quark-gluon plasma of the Big Bang. All of these systems share the common trait of having very strong interactions between spin-up and spin-down fermions.

We create a strongly interacting Fermi gas on a tabletop in an optical trap made of a $CO_2$ laser beam that is focused tightly into a high vacuum chamber, Fig. 1. Spin-up and spin-down $^6$Li atoms are attracted to the focal point and form a cigar-shaped cloud. Using a bias magnetic field to tune near a collisional (Feshbach) resonance, the gas is strongly interacting. In just a few seconds, the atoms are cooled by evaporation to a temperature of a few billionths of a degree above absolute zero, near the quantum ground state.

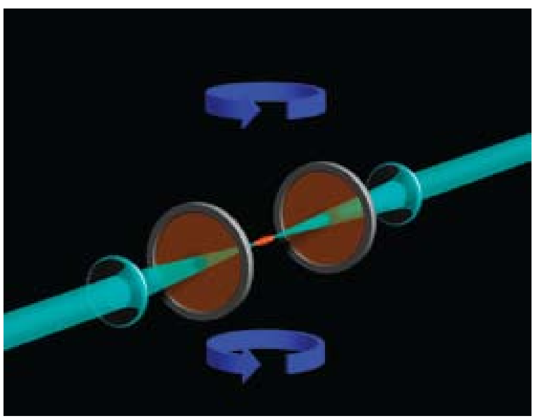


**Figure 1:** *$CO_2$ laser beam trap. Atoms are attracted to the focal point, forming a cigar-shaped cloud. Bias magnetic field coils (blue) tune the cloud to a collisional resonance.*

Remarkably, this ultracold Fermi gas at shares a common feature with the trillion-degree cigar-shaped quark-gluon plasma recently created by physicists at RHIC by colliding gold nuclei. As first demonstrated by our group in 2002 [O'Hara et al., *Science*, 298, 2179 (2002)], a cigar-shaped strongly interacting Fermi gas expands anisotropically when released from an optical trap, Fig. 2. Incredibly, at a temperature some 19 orders of magnitude higher, a quark-gluon plasma exhibits analogous behavior, termed "elliptic flow," which is a signature of extremely low viscosity hydrodynamics.

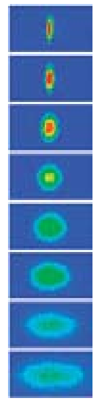
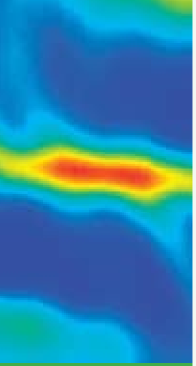


**Figure 2:** *A cigar-shaped cloud of strongly interacting Fermi atoms expands anistropically, exhibiting "elliptic" flow. Top, 100 μs after release from the trap. Bottom, 2 ms after release.*

Currently, this extremely low "quantum" viscosity of the Fermi gas is of great interest in the context of a recent conjecture from the string theory community. The conjecture is that there exists a universal lower bound for the ratio of shear viscosity $\eta$ to entropy density $s$ in strongly interacting systems. Our measurements of the thermodynamic and hydrodynamic properties of the gas show that $\eta/s$ is close to the lower bound, suggesting that our Fermi gas is a nearly perfect fluid.

Our thermodynamic measurements determine both the energy and the entropy of the gas, [Luo et al, *Phys. Rev. Lett.* **98**, 080402 (2007)]. In 2005 we proved both theoretically and experimentally that the strongly interacting gas obeys the virial theorem for an ideal gas. In a harmonic trap, the total energy E is then twice the total potential energy U. Since U is proportional to the mean square cloud size, by simply measuring the spatial profile of the trapped cloud, the energy is determined in a model-independent manner. To determine the entropy, the bias magnetic field is adiabatically swept to tune the cloud to a weakly interacting regime. The weakly interacting cloud is essentially an ideal Fermi gas in a harmonic potential, for which the entropy S is readily calculated from the cloud profile. Together, these measurements determine the energy as a function of entropy, Fig. 3, and provide stringent tests of the best current nonperturbative many-body calculations. Our estimate of the ground state energy, at $S = 0$, is in very good agreement with our previous estimate based on measurements of the sound velocity in the gas [Joseph et al., *Phys. Rev. Lett.* **98**, 170401 (2007)]. These ground state measurements test predictions for a model of the ground state of neutron matter spanning several decades, and now agree with the best current calculations within a few percent.



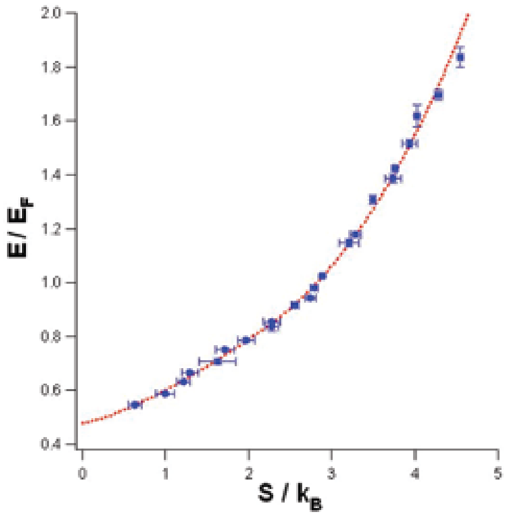



**Figure 3:** *The total energy E of the gas is measured as a function of the total entropy S. $E_F$ is the Fermi energy of an ideal gas. A superfluid-normal fluid transition occurs near E = 0.83 $E_F$.*

Our recent hydrodynamic measurements explore the expansion dynamics of a rotating Fermi gas [Clancy et al., *Phys. Rev. Lett.* **99**, 140401 (2007)]. By abruptly rotating the cigar-shaped trap through a small angle, we set up an angular oscillation in the cloud that is then released with a nonzero angular velocity. We are able to measure the angle and the aspect ratio of the principal axes of the expanding cloud, Fig. 4. When the cloud is initially cooled near the quantum ground state, it is a strongly interacting superfluid. In this regime, one expects the gas to exhibit "irrotational" flow, where the curl of the velocity field is zero, since the velocity is the gradient of the phase of a macroscopic wavefunction. Indeed, we observe expansion dynamics consistent with nearly perfect irrotational flow: The angular velocity increases rapidly as the cloud profile becomes circular, showing that the moment of inertia is decreasing dramatically to conserve angular momentum. Remarkably, nearly identical behavior is observed in the normal fluid when the gas is initially heated to well above the superfluid transition, signifying extremely low viscosity in a normal, strongly interacting Fermi gas.

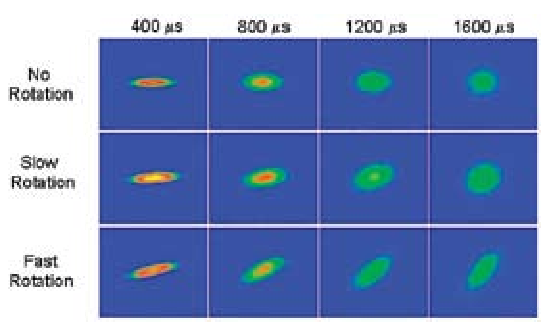



**Figure 4:** *A rotating strongly interacting Fermi gas expands according to nearly perfect irrotational hydrodynamics in both the superfluid and normal fluid regime.*

Our current measurements indicate that the ratio of the shear viscosity to the entropy density in a normal strongly interacting Fermi gas is close to the conjectured lower bound, and comparable to the lowest estimate obtained from the quark-gluon plasma community. We are continuing to refine our measurements of this fundamental ratio, which may provide a universal relationship between thermodynamics and hydrodynamics in strongly interacting many-body systems.

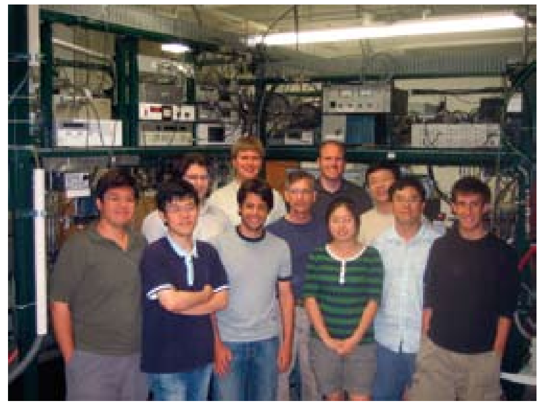


**Figure 5:** *JETLab group. Front row: Willie Ong, Chenglin Cao, James Joseph, Yingyi Zhang, Le Luo, and Dave Weisberg; Second row: Ethan Elliot, John Thomas, Xu Du; Back row: Jessie Petricka and Bason Clancy*

***John E. Thomas is the Fritz London Professor of Physics at Duke University and is a Fellow of the American Physical Society. He received his doctorate in physics from the Massachusetts Institute of Technology in 1979. The JETlab Quantum Optics group is broadly interested in the quantum physics of light-matter interactions, ultra-cold quantum gases, and optical methods for biomedical imaging. Dr. Thomas enjoys cooking, especially Chinese and Italian style, and making replicas of antique guns in his metal/wood working shop.***

# Searching for the Elusive Higgs Particle

*—by Ashutosh Kotwal*

Professor Ashutosh Kotwal's research in experimental particle physics focuses on the mechanism of "electroweak symmetry breaking," which is the theoretical way of asking the question: how do fundamental particles acquire the property of mass? When the weak interaction was first discovered many decades ago as the force that mediates certain forms of radioactivity, one of the mysteries was why this force is so much weaker than the electromagnetic force. Many other properties of the weak interaction could be derived from the principle of gauge invariance, in a manner similar to the derivation of the electromagnetic force laws. However, the critical difference was that the mediators of the weak force are very massive particles, in sharp contrast to electromagnetism where the mediating photons are strictly massless. The small effective strength of the weak interaction at low energies was explained by the large masses of the mediating particles, called W and Z bosons. This theory was spectacularly confirmed when they were directly produced and detected in high-energy collisions about 25 years ago. However, the mystery of their large masses still remains. For the theory to be self-consistent, a new mechanism to generate their masses was needed.

Such a mechanism, called the Higgs mechanism, has been invented but has not yet been confirmed. This mechanism postulates a new field, called the Higgs field, which is supposed to pervade all of space. The field is neutral, and therefore does not disturb the electromagnetic interaction, allowing the photon to remain massless. The Higgs field does experience the weak interaction, thereby breaking the symmetry between the electromagnetic and weak interactions and generating mass-like properties for the W and Z bosons, as well as all the fermions that experience the weak interaction.

Professor Kotwal pursues the evidence for the Higgs mechanism in two complementary ways. The first method exploits the uncertainty principle of quantum mechanics: a particle may couple to new particles fluctuating in and out of the vacuum, as long as the energy of these particles and the duration of the fluctuations are consistent with the uncertainty principle. If the Higgs field exists, its excitations, called Higgs bosons, can participate in these vacuum fluctuations and their effect on the mass of the W boson can be detected.

Professor Kotwal and his post-doctoral research associate Christopher Hays (now a faculty member at Oxford), working with collaborators from Univ. of Toronto, developed the techniques and the analysis of the data from the upgraded CDF detector (see Figure 1) at Fermilab, to measure the mass of the W boson with unprecedented precision. In this experiment, protons and anti-protons collide with a total energy of about 2 trillion electron volts (equivalent to a trillion batteries stacked in series), at the rate of about five million times per second.

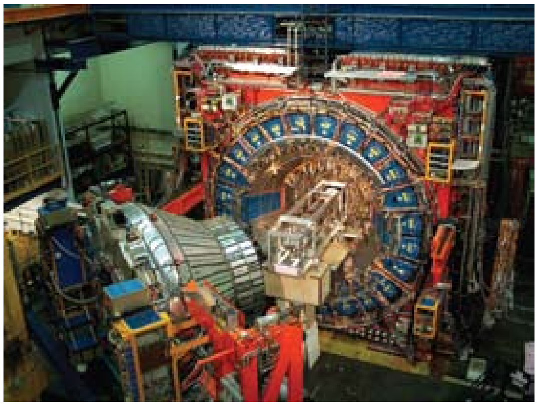


***Figure 1.*** *Picture of the CDF detector, as it was getting upgraded for the current run. The picture shows the new silicon vertex detector being installed inside the new drift chamber, both of which track charged particles. One of the new endplug calorimeters has been moved out to install the silicon detector.*

About once in ten million collisions, one of the constituent quarks and anti-quarks in the colliding proton and anti-proton annihilate to produce a W boson. When the W boson decays to an electron or a muon and an accompanying neutrino, the W boson mass can be extracted quite precisely. Professor Kotwal's group recently published the world's best single measurement of the W boson mass, which has had a significant impact on the indirect constraint on the Higgs boson mass via the calculated quantum corrections in the Standard Model theory. Professor Kotwal and his post-doctoral research associate Bodhitha Jayatilaka and student Yu Zeng have initiated the effort to perform an even more precise measurement of the W boson mass.

The top quark was discovered at Fermilab through its direct production and decay about 13 years ago. Since then, the upgraded Tevatron accelerator and the CDF and D0 experiments have collected much larger data samples, making a precise measurement of the top quark mass possible. Professor Kotwal and Bodhitha Jayatilaka, along with collaborators from Univ. of California, Irvine, have made the world's most precise measurements of the top quark mass using its decays to a lepton, a b quark and a neutrino.

The relationship between the measurements of the W boson mass, the top quark mass and possible values of the Higgs boson mass is shown in Figure 2. The ellipse shows the measurements, and bands labeled SM show the expected relationship in the Standard Model theory of particle physics, for various choices of the Higgs boson mass. Within the standard model context, the data show a clear preference for a relatively light Higgs boson. At the same time, the experiments that ran at the Large Electron-Positron Collider at the CERN Laboratory in Geneva, in the last decade searched for evidence of direct production of light Higgs bosons, but did not find it. Putting these pieces of information together is creating a very interesting puzzle, which we hope to solve soon at Fermilab's Tevatron accelerator and at the Large Hadron Collider, which is starting up at CERN. Figure 2 also shows the relationship between these observables in another theory called the Supersymmetric Extension of the Standard Model. This theory predicts an additional quantum dimension for each of our space-time dimensions, and a new supersymmetric particle to partner with each of the fundamental particles in the Standard Model. Constraints on the properties of supersymmetric particles have already been derived, using the precision measurements of the W boson and top quark masses by Professor Kotwal and others.

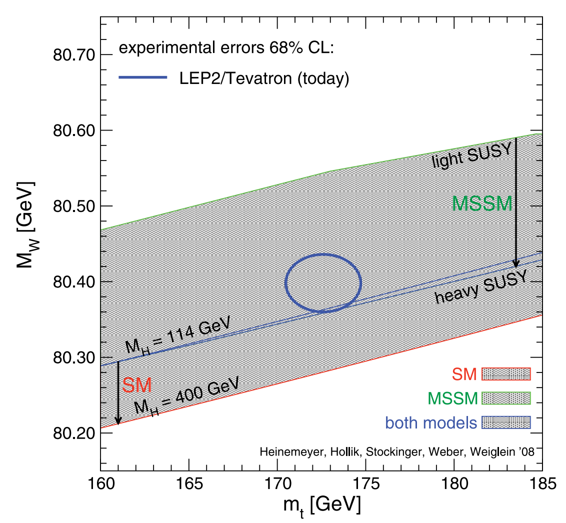



***Figure 2.** The 68% confidence level 2D contour for the W boson mass and the top quark mass, compared to the predictions of the standard model (SM) and the minimal supersymmetric extension of the standard model (MSSM). Direct searches for the SM Higgs boson have already excluded its mass below 114 GeV.*

Apart from making precision measurements to gain insights into new physics, Professor Kotwal is also engaged in direct searches for new particle production in the CDF data. He is working on a search for Higgs boson production with his post-doc Bodhitha Jayatilaka and student Ravi Shekhar, along with collaborators from Irvine, Wayne State and Fermilab. The expected signal is rather small, with large backgrounds. Professor Kotwal's group has applied advanced statistical methods and pattern recognition techniques based on artificial neural-networks, to create a very sensitive search for this long sought-after particle.

Professor Kotwal will be shifting his research from Fermilab to the newly commissioned Large Hadron Collider (LHC) at CERN, which takes a big leap in energy by a factor of seven. The LHC will open up a new frontier with the potential to discover fundamental symmetries beyond the standard model. Professor Kotwal has published searches for exotic fermions and has recently completed searches for heavy neutral gauge bosons and massive gravitons that are predicted by theories of force unification. The LHC data will provide very exciting opportunities for such research.

***Ashustosh Kotwal graduated from the University of Pennsylvania's Management and Technology program with Bachelor's degrees in Electronics and Finance. His undergraduate research experiences in physics convinced him to pursue a research career in physics. He received his Ph.D. in particle physics from Harvard University, and was a post-doctoral researcher at Columbia University before coming to Duke. He enjoys reading, travelling and watching episodes of "Man vs. Wild" on the Discovery Channel with his son.***

# The Search for Color Transparency and the Neutron Electric Dipole Moment

*—by Haiyan Gao*

Quantum Chromodynamics (QCD) is the theory of strong interaction, one of the four fundamental forces in nature. While it has been tested extremely well in the very high energy regime, known as the perturbative QCD (pQCD) regime, little is known about the non-perturbative regime where ordinary matter exists. Therefore, understanding the nucleon structure, and quark confinement in terms of the underlying degrees of freedom of QCD is becoming increasingly important. The study of fundamental symmetries at low energies is essential because of its sensitivities to new physics beyond the Standard Model. Currently, a new search is underway for the neutron electric dipole moment (nEDM) aiming at a two orders of magnitude improvement over the current limit. Such sensitivity will be extremely important for the study of charge conjugation and parity (CP) violation, and may help to understand the baryon number asymmetry of the universe.

In addition to myself, the Medium Energy Physics Group at Duke consists of Adjunct Professor Dipangkar Dutta, postdocs Drs. Yi Qiang, Qiang Ye and Xiaofeng Zhu, four graduate students (Wei Chen, Xin Qian, Wangzhi Zheng, and Xing Zong), and two Duke undergraduate students: Poy Torngern and Sebastian Liska [1].

In this newsletter, I will highlight two of our research accomplishments in the last year: the observation of Color Transparency effect in pion electroproduction and a first study of nuclear polarized $^3$He spin relaxation time under the nEDM experimental condition.

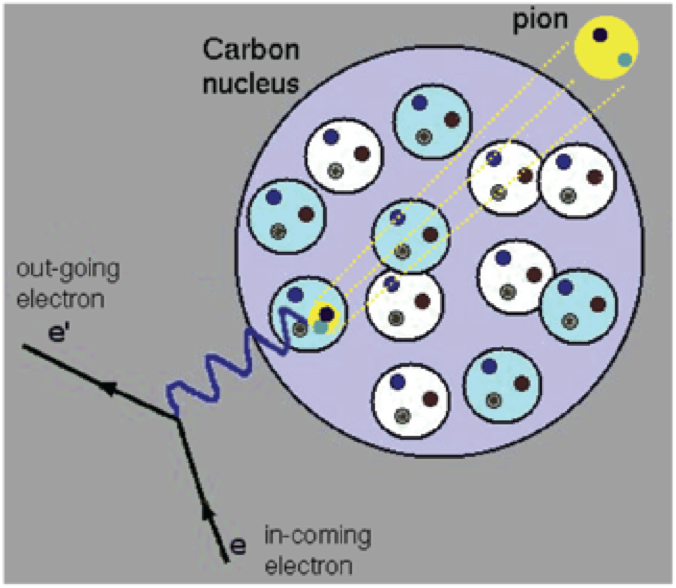
## The Search for Color Transparency—Color Coherence Effects in the Nucleus

Color Transparency (CT) is a natural consequence of QCD, and follows from the fact that as the momentum transfer Q increases, the range of the interaction decreases. Therefore, an exclusive process at large Q preferentially selects out hadrons of reduced transverse size. This reduced size, color neutral object, then passes ``undisturbed" through the nuclear medium before expanding to its equilibrium size. CT is a novel QCD phenomenon which, if observed, would be a clear manifestation of hadrons fluctuating to a small size in the nucleus—an example of color coherence phenomena in nuclear physics. Nuclear transparency, defined as the ratio of the cross section per nucleon for a process on a bound nucleon in the nucleus to the cross section for the same process on a free nucleon, is a typical quantity used in CT searches. A clear signature for the onset of CT would involve a dramatic rise in the nuclear transparency as a function of Q. A number of searches for color transparency have been carried out in the last two decades, however, no conclusive model independent evidence for CT has been observed for the three quark hadrons (baryons).

We have carried out the first measurement [2] of nuclear transparency of the $\gamma n \rightarrow \pi^- p$ process on $^4$He nuclei. This experiment was performed at Jefferson Lab (JLab Experiment E94104, Haiyan Gao and Roy Holt, spokespersons), and utilized several advantages of $^4$He such as its relatively small nuclear size. The results from our experiment suggest a CT-like behavior for the first time for such processes. However, the limited statistics of our results at the highest energy prevents conclusive statements.

Lacking any conclusive evidence for CT, there is an urgent need for a systematic study of the transparency over a wide range of momentum transfers and nuclei. JLab experiment E01-107 (Spokespersons: D. Dutta, R. Ent, K. Garrow), designed to measure nuclear transparency of pions over a Q2 range of 1–5 (GeV/c)$^2$ on various nuclei completed data taking in Hall C in the end of 2004. This experiment measured the electroproduction of charged pions from nuclear targets in coincidence with scattered electrons using the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS) in Hall C. From these data we have extracted the nuclear transparency of pions by comparing charged pion production from nuclear targets to that from a hydrogen target.

Two graduate students, Ben Clasie from MIT and Xin Qian from Duke, both under the supervision of Professor Haiyan Gao carried out the data analysis. Ben Clasie analyzed the transparency data and graduated with a Ph.D. degree in August 2006. The results for the nuclear transparency have been published in 2007 [3]. The extracted nuclear transparency seem to confirm the predicted early onset of CT in mesons compared to baryons. Figure 1 is a cartoon picture showing how such a "skinny" pion expands and propagates through nuclear medium experiencing reduced interaction with nuclear medium.




Scientists have observed that the nucleus becomes invisible for "skinny" pions. Normally, pions traversing the nucleus feel the strong force of the protons and neutrons they encounter, causing a fraction of the pions to be reabsorbed by the nucleus. However, if the strong force is described in terms of the underlying quarks and gluons, such reabsorption is predicted to disappear. This vanishing act is a result of small-sized, point-like or "skinny" pions being produced in sufficiently energetic collisions between beams of particles and atomic nuclei.

**Figure 1:** *Skinny pion propagating out of a residual $^{12}C$ nucleus.*

### The Search for a possible Neutron Electric Dipole Moment—a Direct Search for Time-Reversal Symmetry Violation

A non-zero value of the neutron electric dipole moment (nEDM) would imply the violation of time reversal symmetry (T), which is a unique way of search for CP (charge conjugation C and parity P) violation because of CPT invariance. The Standard Model (SM) prediction for the neutron EDM is below the reach of the current limit of EDM measurement by six orders of magnitude! However, many proposed models of electroweak interaction which are extensions beyond the SM predict much larger values of neutron EDM. The proposed experiment has the potential to reduce the acceptable range for predictions by two orders of magnitude and to provide a significant challenge to these extensions to the SM and to search for New Physics beyond the SM. Furthermore, if new sources of CP violation are present in nature beyond the Standard Model and are relevant to hadronic systems, this experiment offers a unique opportunity to measure a non-zero value of the neutron EDM. Our understanding of the origin of baryogenesis provides one reason for thinking that other sources of CP violation might exist in nature beyond what's described in the Standard Model and beyond what have been observed so far. To explain the baryon number asymmetry in the universe through the grand unified theory or electroweak baryogenesis, substantial new physics in the CP violation sector will be required.

Currently, we are working on a new search aiming at a two orders of magnitude improvement over the current nEDM limit. This new nEDM experiment is based on the nuclear magnetic resonance technique. The overall experimental strategy is to form a three-component fluid of ultracold neutrons (UCN) and $^{3}$He atoms dissolved in a bath of superfluid $^{4}$He around T = 400 mK. When placed in an external magnetic field of on the order of 10 mGauss, both the neutron and $^{3}$He magnetic dipoles will precess in the plane perpendicular to the field. The measurement of the neutron electric dipole moment comes from a precision measurement of the difference in the precession frequencies of the neutrons as modified when a strong electric field (50 KV/cm) parallel to the magnetic field is turned on (or reversed). Because the magnitude of the precession frequency shift due to the interaction of the neutron EDM and the electric field is extremely small, it is imperative to measure this overall precession frequency with great precision. The technique adopted in this experiment is to make a comparison measurement in which the UCN precession frequency is compared to the $^{3}$He precession frequency. The technique relies on the spin dependence of the nuclear reaction: n + $^{3}$He → p + t + 764 keV. The cross section, for the two initial spin states of the reaction, is strongly spin dependent: the process is strongly suppressed when the spins of the neutron and $^{3}$He nucleus are aligned parallel to each other. The reaction rate can be measured by monitoring the scintillation light generated in superfluid $^{4}$He from the reaction products. The polarized $^{3}$He nucleus also acts as a co-magnetometer in the proposed experiment. Understanding the relaxation mechanism of polarized $^{3}$He nuclei and maintaining their polarizations under the nEDM experimental conditions is essential to the success to the entire nEDM experiment.

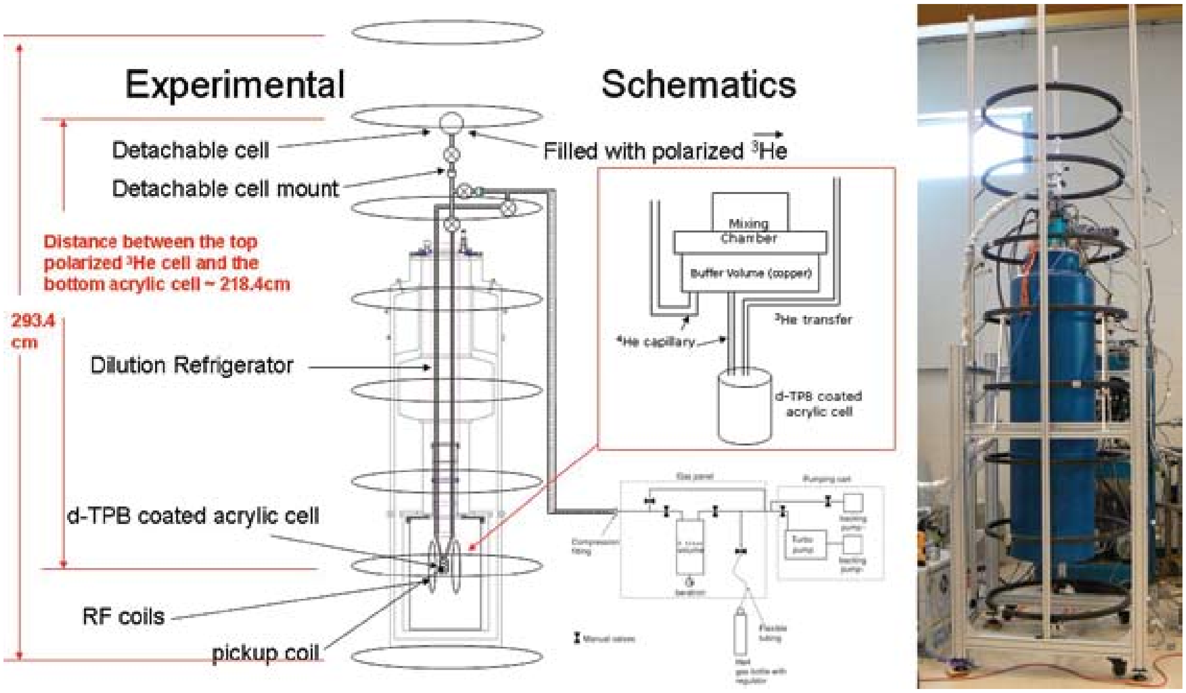



**Figure 2:** *Schematics of the below 400 mK setup in FFSC at Duke University.*

In the neutron electric dipole moment (nEDM) experiment, the neutron storage cell will be made of dTPB-dPS (wavelength shifting material) coated acrylic and filled with superfluid $^4$He. The relaxation times of polarized $^3$He in a cylindrical acrylic cell were measured for the first time by our group at 1.9 K (with the presence of superfluid $^4$He at a magnetic holding field of 21 Gauss). Most recently, we have carried out a first measurement below 400 mK (nEDM experimental temperature) using a dilution refrigerator in the TUNL assembly hall in the French Family Science Center (FFSC) building at Duke. Figure 2 shows the experimental setup and its schematics for the below 400 mK measurement.

Our measurement with the cell full of superfluid $^4$He at 400 mK gives a $^3$He relaxation time of several thousand seconds and the corresponding $^4$He depolarization probability of the wall is below $1 \times 10^{-7}$ with the surface to volume ratio to be 2.0. The scaled relaxation time of polarized $^3$He in the nEDM cell is in excess of $10^4$ seconds. Our study shows that the currently achieved $^3$He relaxation time has achieved the goal for the success of the nEDM experiment, an extremely important result and milestone. Our group is also leading another important effort in the entire nEDM experiment which is to inject polarized $^3$He atoms from an Atomic Beam Source into a collection volume filled with superfluid $^4$He before the mixture is transported into the experimental cells. Our work has been supported by the Department of Energy.

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***Professor Haiyan Gao was born in Shanghai, China. She received her B.S. degree in 1989 from Tsinghua University and her Ph.D. degree in experimental nuclear physics from Caltech in 1994. She was a postdoctoral research associate at the University of Illinois from 1994–1996. She was on the staff at the Argonne National Laboratory briefly in 1996 to 1997 before she joined the faculty at MIT in 1997. She moved to Duke University in 2002. Currently, she is a Full Professor and Associate Chair in the Department of Physics at Duke University. She has received a number of awards including her recent election as a Fellow of the American Physical Society. In her spare time, she enjoys Chinese opera, gardening, music, stamp collection, reading and cooking.***

# Dynamics of Complex Regulatory Networks

*—by Joshua Socolar*

One of the grand challenges of modern science is to explain the characteristic properties of the biosphere. A full theory of such an extravagantly complex system would have to account for dynamics at many scales, from the interactions within and between species that determine which mutations survive, down to the organized biochemical processes that give rise to cellular functions. It is often useful to describe such complex systems as "networks," graphs in which nodes represent species or genes and directed edges represent causal interactions between them. Socolar's current research aims to discover dynamical features of network models and ascertain their relevance to real biological systems. He is also collaborating with several Duke biologists studying gene regulation networks governing cell cycles and cell differentiation.

The sequencing of full genomes and monitoring of the concentrations of thousands of molecular species within cells have given us new windows into the physical nature of life. A host of scientific questions about the roles of genes and proteins in cellular functions, development, and evolution now seem within reach, and the answers will undoubtedly yield practical benefits ranging from medical therapies to microbe-based solutions to environmental problems. Progress on these questions requires moving beyond our understanding of the physics and chemistry of biological molecules and materials to theories of the structure and dynamics of complex regulatory networks. This is simultaneously a part of the advancing frontier of biology and a problem in the physics (or applied mathematics) of systems composed of many interacting elements.

In a transcriptional regulatory network, each node represents a gene and each edge indicates that the protein produced by one gene directly influences the rate of production of the protein coded in the second gene, either acting itself as a transcription factor (by binding to the DNA near the second one and assisting or blocking recruitment of a RNA polymerase), or by binding to another transcription factor to influence its activity. The logic of the network plays a dominant role in determining which genes in a cell are expressed.

One branch of Socolar's research addresses mathematical aspects of model transcriptional networks. He considers classes of networks characterized by parameters such as the average number of links per node and the probabilities of the various ways in which a set of inputs can determine the transcription rate. By assuming that the network structure is otherwise random, one can classify the behavior of ensembles of networks—and it turns out that the results are highly nontrivial.

Socolar's work in this area began in 2001 with a sabbatical stay in Santa Fe with Stuart Kauffman, then at a company called Bios Group. Kauffman pioneered the study of random Boolean networks with numerical studies in 1969. [1] Together with Kauffman, postdoc Björn Samuelsson and graduate student Hans Norrell, Socolar has been studying the order-chaos transition in random Boolean networks and addressing the question of whether the lessons learned from Boolean systems carry over to systems where the links between genes are described by differential equations. The group has developed a complete theory of the phase transition in Boolean systems, which can be viewed as an unusual type of percolation transition. [2,3] It has also shown that critical networks provide an optimal balance between sensitivity to perturbations and reliable relaxation to stable attractors. [4] It is now focusing on the question of how well continuous systems mimic their Boolean idealizations—and finding that subtle effects can lead to the suppression or even elimination of the disordered phase. These results are relevant to the behavior of high speed operation of digitial circuits (a topic of current experimental investigation in the lab of Dan Gauthier) as well as biological networks.

In recent years, Socolar has turned to biologists at Duke for collaboration on the dynamics of real biological networks. With Steve Haase (Biology), Alex Hartemink (Computer Science) and postdoc Volkan Sevim, he is working to understand transcriptional oscillations observed in budding yeast. They are looking to characterize in greater detail the mechanisms underlying the results reported in their recent Nature article showing that cell cycle oscillations persist on schedule in mutant strains that cannot complete mitosis. [5]

With Phil Benfey (Biology), Socolar and Norrell are studying the dynamics of cell differentiation in plant roots, focusing on the issue of how the division of a single layer of cells into a double layer of cortex and endodermis occurs. Current efforts involve the collection of spatiotemporal data on many roots to determine whether there is evidence for cell-to-cell signaling in the initiation of the division and subsequent differentiation into two cell types.

With Dave McClay (Biology), Socolar and graduate students Xianrui Cheng (Computational Biology and Bioinformatics) and Sam Gong are studying the transcriptional network the underlies cell differentiation in the development of the sea urchin embryo. The embryo is remarkable for its ability to develop normally even after the micro-surgical removal of all cells of a particular type. Socolar and McClay's collaborative group is conducting experiments on the dynamics of gene expression in the transfating cells that take the place of the removed ones. They are also constructing mathematical models of the transcriptional regulatory network and signaling pathways involved.

Much of this work is supported by Duke's Center for Systems Biology, within the Institute for Genome Science and Policy. Socolar is one of 15 Co-PI's on the NIH grant that funds the Center and is enjoying the multiple opportunities afforded by the Center for learning new science from biologists, computer scientists, mathematicians, statisticians, and engineers—and for bringing insights from statistical physics and nonlinear dynamics to their efforts.

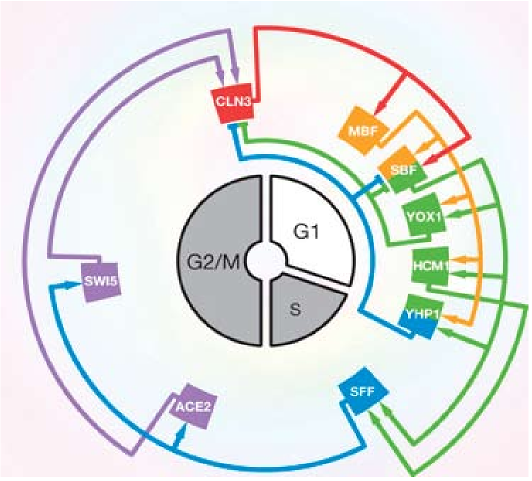


**Figure 1:** *Network structure of a synchronous Boolean model for transcriptional oscillations in yeast. Transcription factors are arranged according to times of peak measured transcript levels. Arrows indicate regulatory action: activating interactions, outer rings; repressive interactions, inner rings. Coloring indicates activity in one of five successive states. Inner annular shapes indicate phases of the cell cycle.*

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***Joshua Socolar earned his B.A. degree at Haverford College in 1980 and his Ph.D. at the University of Pennsylvania in 1987 for work with Paul Steinhardt and Tom Lubensky on tiling theory and physical properties of quasicrystals. After five years at Harvard and IBM Watson Research Center, he came to Duke, where his research has focused primarily on nonlinear dynamics in systems involving time-delay feedback, stress distribution in granular materials, and dynamics of complex regulatory networks, with an occasional foray into tiling theory. He likes teaching at all levels and hopes all his former students are doing well. He also enjoys playing jazz piano, singing, biking, and living in Chapel Hill, especially when both kids are home.***

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*Photo by Jimmy Dorff*