Quantum Leap

University of South Carolina
Department of Physics and Astronomy

2018

2017 Nobel laureate Dr. Barry Barish describes the unique signatures of the general theory of relativity contained in the first gravitational waves that were detected by Advanced LIGO in 2015.

Distinguished Lecture Series in Physics and Astronomy Making an Impact

In 2016, the USC Department of Physics and Astronomy initiated a new public lecture series with support from the Office of the Provost and the Vice President for Research. Through the engagement of numerous faculty and staff and the continuing support of USC's SmartState Center for Experimental Nanoscale Physics, our department continues to offer a "Distinguished Lecture Series" in Physics and Astronomy. In just the last year, our department again hosted Nobel laureates and eminent scholars and leaders as part of this successful lecture series. Attendance at our public lectures regularly exceeds 200 people, and for several lectures, we have had standing room only in the 500-seat performance hall located in the Darla Moore School of Business. In addition to presenting a public lecture, every visiting speaker is scheduled for a range of informal meetings or lunches with students, faculty, and researchers.

Over the past year, we were treated to an especially distinguished slate of scholars. The president of the American Physical Society at the time, Dr. Laura Greene, explained the bizarre nature of high-temperature superconductivity. Dr. Greene is the Chief Scientist at the National High Magnetic Field Laboratory in Tallahassee, Florida and is also the Francis Eppes Professor of Physics at Florida State University. She illuminated the audience with a review of superconductivity and the behavior of this unconventional superconductivity. Next, the recipient of the 2014 Nobel Prize in chemistry, Dr. William E. Moerner, described the promise and challenges of super resolution microscopy. Dr. Moerner is the Harry S. Mosher Professor of Chemistry and a Professor of Applied Physics at Stanford University. He revealed how super resolution microscopy enabled single molecule imaging and what discoveries it may unveil in the future.

Only four months after being awarded the 2017 Nobel Prize in physics, Dr. Barry Barish presented evidence for the first detection of gravitational waves caused by merging black holes. Dr. Barish is the Linde Professor of Physics at the California Institute of Technology, the Director Emeritus of the LIGO Observatory, and a member of the National Academy of Sciences. Dr. Barish recounted the history of Einstein's prediction of gravitational waves and detailed the excruciating precision necessary for his team to observe a passing gravitational wave. Most recently, Dr. Arthur Hebard entertained us on "ah ha" moments in physics through his perspective as a condensed matter experimental physicist. Dr. Hebard is a Distinguished Professor of Physics at the University of Florida and also a member of the National Academy of Sciences. He illustrated a series of significant discoveries involving superconductivity that were based on memorable realizations and insights that exceeded expectations.

...continued on inside.

CONTENTS

UPDATES FROM THE CHAIR AND DIRECTORS

Message from the Chair....4
News from the Director of Graduate Studies....4
News from the Director of Undergraduate Studies — Trust In Science....5

RESEARCH GROUPS AND STUDENTS

Astronomy....7
Constraining Extinction Due to Dust in Distant Galaxies....7
News from the SmartState Center for Experimental Nanoscale Physics....8
News from Timir Datta's Group....10
News from Milind Kunchur's Group....11
A Change of Pace....11
Experimental Nuclear Physics Group....12
My Experience at Jefferson Lab....14
Undergraduate Experience with MUSE....15
High Energy Neutrino Physics Group....16
Particle Astrophysics Group....17
Theoretical Physics Group....19

SPECIAL ARTICLES

Midway Physics Day 2018 — Another Great Year in the Books....20
Society of Physics Students....21
Alumni News — From Ohm's Law to Tort Law....22
Alumni News — Mining for Dark Matter....22

...continued from cover page.

The impact of our lecture series is felt most directly by our students, but also benefits the entire university community. When well-known scholars make their visit to our campus, the experience is inspiring and eye-opening for our students. During gatherings with distinguished scientists, our students are able to join Nobel laureates for lunch or chat with a member of the National Academy of Sciences over tea. Many visitors will discuss their recent papers in a "journal club" setting, where students have a chance to learn how these scholars choose what to do and how to do it. Some of our lecturers also engage in free-ranging Q&A sessions with undergraduate and graduate students, where they share stories from their careers and discuss their vision for the future of the field. Students repeatedly express their excitement and appreciation for the opportunity to engage with some of the luminaries in their field.

This series also enhances the engagement of USC with the Columbia and Midlands community. For past public lecture events, we have successfully partnered with the South Carolina State Museum and groups like the Midlands Astronomy Club to help promote and advertise our events. We hope to form partnerships with other organizations in the community, such as libraries, civic organizations, parks, and local corporations. These exchanges help to reinforce the role of USC as a valuable partner in both Columbia and the Midlands. Beyond our neighboring communities, our public lecture events improve the broader public perception of the University and elevate its national status.

We are excited about our prospects for future public speakers as this series continues. In fact, we recently confirmed Dr. Megan Donahue as one of our future "Distinguished Lecture Series" speakers. An expert on galaxies and galaxy clusters, Dr. Donahue is a Professor of Physics and Astrophysics at Michigan State University as well as the president of the American Astronomical Society for the 2018-2020 term. Our public lecture series would not be possible without the generous support of our university and departmental sponsors. Our goal is to keep this program a regular hallmark of our Physics and Astronomy department while engaging with other departments and campus organizations to spread the program across a wide variety of disciplines. Through this program, we aim to enrich the educational experience of students at USC, encourage cross-disciplinary interaction, enhance the national and international reputation of USC, and strengthen USC connections to the Columbia community. To do so, we continue to seek the funding necessary to make this program sustainable and welcome additional financial support.

UPDATES FROM THE CHAIR AND DIRECTORS

Message from the Chair

By Ralf Gothe

It is with great pleasure that I welcome you all - alumni, friends, and current members of the Department of Physics and Astronomy - with this Quantum Leap edition back home to the Gamecock Family and the Carolinas. I hope we can all reinforce old and new bonds that let grow together what belongs together. While browsing through the 2018 newsletter, you may not only learn about recent developments, changes, and updates, but may also take your time to commemorate the great experiences seeded at USC that made our lives more balanced and better.

A lot of personnel changes have hit the department recently. After our Student Services Coordinator, Kelly Gibson, left last year, we also had to endure the loss of Business Manager Lisa Saxon since November 2017. Lisa shielded us so well against all financial faux pas, either initiated by anyone outside of her office or by ourselves, that some of us stopped realizing how exceptional she was. This changed quickly and became increasingly painful as soon as she was gone and became a Budget and Operations Accountant at the Darla Moore School of Business. Luckily, the college-wide attempt to centralize and restructure all business administration has started to bear fruit and work better month-by-month, but I still miss Lisa dearly. This "I" brings me back to the point why I have the privilege to write this message to you. Milind Purohit led our department for more than four years through some turbulent times. In January, he announced that he was leaving for greener pastures. As the new Dean of Faculty Affairs, Milind is now employing his talents and experience to drive the Okinawa Institute of Science and Technology Graduate University in Japan forward. From April, Rick Creswick was our Interim Chair before I was appointed as the new Chair of the Department of Physics and Astronomy, effective July 1, 2018, and I don't want to miss out on the opportunity to thank them both for their service to the department.

I am also happy to let you know that we have an ongoing new faculty search for a Tenure-Track Assistant Professor in Theoretical Physics, preferentially with expertise in particle physics, astrophysics, or cosmology. You can also cross your fingers for us as we are still awaiting the final word on our Excellence Initiative proposal on "Sustaining the SmartState Center for Experimental Nanoscale Physics and Enhancing Advanced Materials Research at USC", which would allow us to mitigate the loss of Richard Webb, who was the founding Chair of the SmartState Center for Experimental Nanoscale Physics. A second Excellence Initiative proposal on "Carolina STEM Distinguished Lectures" also made it into the final round. If successful, it would allow us to continue and expand an already very successful multi-disciplinary program of public lectures that brings distinguished scholars with broad appeal across the university and throughout the community to the USC campus.

Indeed, many things have changed since I came to the University of South Carolina and to the Department of Physics and Astronomy in 2002, but some things will never change such as my love for being here. I am proud to be part of a bigger family that strives to achieve the best and cares about everyone. There are still many alumni out there and nearby whom I have not met yet or heard of, but I really would like to meet in the future. Please contact me whenever you want or send me some of your Carolina stories. Until then, I wish that being at or connected to the University of South Carolina fills us with tolerance and happiness as we move forward together.

News from the Director of Graduate Studies

By Vladimir Gudkov

This year, we welcomed seven new students to our graduate program from four countries (three from the United States, one from China, two from Nepal, and one from South Korea). One of our new students, Jianghao Huyan, has been awarded a Graduate Stipend Enhancement Award from the College of Arts and Sciences.

Our students continue to excel. Francie Cashman was selected for the Graduate Research Award, Vincent Dowling for the Graduate Teaching Award, and Justin Roberts-Pierel for the Graduate Service Award. Francie Cashman is now in the third of a three-year NASA/South Carolina Space Grant Consortium Graduate Research Assistantship. Justin Roberts-Pierel also

Winners of our departmental Graduate Awards (April 2018). From left to right: Justin Roberts-Pierel (Service), Francie Cashman (Research), Dr. Rick Creswick, Vincent Dowling (Teaching).

received the same SCSGC assistantship and is currently in his first year of funding. Iuliia Skorodumina is in the second year of a JSA/Jefferson Lab Graduate Fellowship award.

The Department of Physics and Astronomy is continuously working to improve the quality of the program and better fulfill the needs of our students. We look forward to another productive and prosperous year ahead.

Congratulations to our recent graduates! **Doctoral:** Charles Dean, Jason Giamberardino, Alyssa Loos, Matt Seaton, Nahid Swails, and Clint Wiseman. **Master of Science:** Yu-Chun Yeh.

News from the Director of Undergraduate Studies — Trust In Science

By Jeff Wilson

Recently, I opened my news app and learned that we are now in a post-truth era. This seemed to mean that facts are fluid and everyone gets to choose which facts are true for them. This allows us to each make up our own version of reality. In some of these realities, science may have no special connection to truth, which certainly contradicts the way scientists view the world.

One explanation is that science is a belief system just like any other belief system. Even scientists will sometimes use the word "belief" in describing how they understand Newton's Laws, or Electromagnetism, or the Standard Model. I would suggest, instead, that science is actually a "trust" system.

Small groups of people have convinced themselves that the earth is flat by refusing to trust simple photographs from orbit, which clearly show the spherical earth. Other larger groups of people won't allow their children to be vaccinated because they don't trust scientific studies, which show that vaccinations are safe and effective. And lastly, even larger groups of people refuse to believe the conclusions of scientists who claim that the earth's climate is changing rapidly and that humans burning fossil fuels are driving the rapid change in large part. These are examples where the science is clear and convincing to most scientists, but lack of trust (in scientists?) causes many others to disregard the results.

Keep in mind that no scientist is capable of personally re-doing all of the original findings of scientists from centuries ago. Our undergraduates get a taste of how difficult it is to design and execute an experiment to test even simple aspects of fundamental physics principles. So we trust that the original creators of our laws of physics did their jobs.

There is no way of proving that every single scientist is trustworthy, but that is the beauty of science as a whole - it doesn't revolve around the skill (or integrity) of individuals. Every important conclusion is checked over and over. The same human feature that drives us to be the first person to discover something new and wonderful also drives us to want to be the person that successfully pokes holes in that new wonderful theory and also drives some of us to continue to test old, established theories. A positive feature of science is the public availability of detailed descriptions of experimental tests including, in many cases, tabulation of the data generated and analyzed. This helps aid

Recent graduates Annastasia Haynie (left) received the Nina and Frank Avignone Fellowship Award and Eric McLean (right) received the Lovelace Family Endowed Scholarship Award. Dr. Jeff Wilson (Director of Undergraduate Studies) presented these awards to Annastasia and Eric on the USC Horseshoe at Awards Day (April 2018).

in the inspection process by parties uninvolved in the original research. The Internet has made it even easier for anyone to peer over the shoulders of current researchers and listen to detailed explanations from experts in many research areas.

My request is that you continue to use the skills you developed as an undergraduate or graduate student. Be a citizen scientist. A scientist understands the reasons why we consider some things truth, or fact, but a scientist also understands why it is always necessary to carry around a healthy skepticism at all times.

RESEARCH GROUPS AND STUDENTS

Astronomy

By Varsha Kulkarni

USC astronomers, students, and collaborators continued to explore the wonders of the cosmos using both space-based and ground-based telescopes. Prof. Kulkarni and her team worked on various aspects of the evolution of galaxies and the material around them. Graduate student Suraj Poudel, Prof. Kulkarni, and their collaborators discovered several high-redshift galaxies with unusual chemical composition and internal chemical variations. These galaxies are so far away that the light we receive from them now left those galaxies about 12.5 billion years ago (i.e. more than 90% back in the history of the Universe). The analysis of the chemical composition of these galaxies may suggest leftover signatures from element production in early generations of massive stars. Suraj Poudel led a paper about the early results from this survey and is now close to completing a second paper about more such high-redshift galaxies. Graduate student Francie Cashman, Prof. Kulkarni, and collaborators continued to work on analyses of multiple images of gravitationally lensed quasars to measure the small-scale spatial variations within the foreground galaxies, using optical and UV spectra obtained with the Magellan II telescope (located near La Serena, Chile) and the Hubble Space Telescope. A paper about this work was recently submitted while another one is in preparation. A proposal led by Cashman was awarded observing time on the Gemini-North telescope in Hawaii for high-resolution spectroscopy of a gravitationally lensed quasar. Collaborator Celine Péroux, Prof. Kulkarni, and others have mapped out the internal variation of metallicity and star formation rates in some distant galaxies using the Very Large Telescope (also in Chile), and were recently awarded more observing time on the VLT. Kulkarni, former post-doctoral researcher Monique Aller (now an assistant professor at Georgia Southern University), and collaborators studied the chemistry of interstellar dust grains in gas-rich galaxies using optical and infrared observations. Aller and Kulkarni were awarded observing time on the Hubble Space Telescope to determine the dust grain composition in a distant galaxy.

Graduate student Kyle Lackey continued the analysis of infrared images of polar ring galaxies - peculiar galaxies with rings of star formation perpendicular to the galaxy major axis, possibly resulting from earlier collisions with other galaxies. Graduate student Harry Oslislo has been assisting with computational aspects of quasar data analysis and has recently started working on spectral properties of some nearby galaxies. New graduate student Arjun Karki has started working on the analysis of spectral features for dusty galaxies. Another new graduate student, Jianghao Huyan, has also joined our team recently. Undergraduate student Alex Kirby has been working on characterizing the dust extinction curves for distant galaxies using ultraviolet, optical, and infrared data for active galactic nuclei. Undergraduate students Zachary Kraje, Joshua Rapoport, and Matthew Hawkins have also been participating in various astronomical research projects with our team. Last year, Matthew worked with us on a summer research project as a high school student, and it is a pleasure to have him back in our team, now as a USC student!

In other news, former graduate student Debopam Som (who worked at the Laboratoire d'Astrophysique de Marseille in France after completing his Ph.D. from USC) just started a research associate position at the Ohio State University. He continues to collaborate with us on projects related to the circumgalactic medium of galaxies. Sienna Brent, a rising high-school senior from the South Carolina Governor's School for Science and Mathematics, worked with our team on a summer project involving gravitationally lensed quasars. Sienna enjoyed the research experience and was a pleasure to work with!

Our group has experienced many opportunities to give a number of presentations over the past year. Prof. Kulkarni gave invited talks at several international conferences on the intergalactic/circumgalactic medium and the chemical evolution of the Universe, as well as several invited seminars/colloquia. Graduate student Cashman gave a talk at a NASA Laboratory Astrophysics workshop. Both Cashman and Poudel gave talks at the American Astronomical Society's January meeting in Washington, D.C. Several more presentations were made at the Meeting of Astronomers in South Carolina in Florence, SC.

Constraining Extinction Due to Dust in Distant Galaxies

By Alex Kirby

I have loved astronomy ever since I was a small child. I fondly remember the days when I would excitedly come home from school and play with the planetarium software that was installed on our computer instead of video games. I have been immensely fortunate to be able to combine this childhood love with my newfound love of physics and math through research projects over the past few years. The amount that I have learned over these past few years has been incredibly worthwhile. In March 2018, I was fortunate enough to be able to share some of that knowledge with experts at a talk that I gave at the Annual Meeting of Astronomers in South Carolina (MASC) and a poster presentation at the Southeastern Section of the American Physics Society (SESAPS) meeting. I was also able to share my research with the public through both an oral presentation at the South Carolina State Museum's "Astronomy Day" as well as through another poster presentation at the annual "Discover USC" session, which brought together student researchers from all areas of campus. One could understandably be nervous about any of

Undergraduate Alex Kirby presents his research at the South Carolina State Museum's "Astronomy Day" in April 2018.

those and I definitely was. Through success in my public speaking courses and the support of my research advisor through trial runs of my presentations, I was able to be moderately successful at all of these. Despite my nervousness, however, I learned a large amount through these experiences and I look forward to being able to continue to spread my research.

That research is based on the dust in other galaxies and how it affects what we see in the night sky. When we think of space, we usually think of something that is entirely empty aside from large clumps of matter, such as the sun and planets. However, that is not the case. A large amount of the visible matter in a given galaxy is in the form of interstellar dust. This is not quite what we would think of as dust, but is instead typically very small grains of some element or compound, usually less than a micron in diameter. There are different ways to model what this dust does to light (depending on the size), but they all share two very important characteristics in that they dim and redden the light that interacts with them. This effect may seem trivial at first glance, but it can have major consequences to very important findings in astrophysics. When American astronomer Edwin Hubble first determined the expansion of the universe, he found an age of the universe, which was smaller by billions of years than the known age of the Earth. This is because extinction was not a known effect at the time. After more accurate data was taken, an age of the universe that is more consistent with the current age was found.

Very good models for the dust in our galaxy and the galaxies immediately surrounding us have been created using observations of objects in those galaxies. However, this is much more difficult to do for a more distant galaxy in which individual objects like stars cannot be resolved. My project has been to use background quasars, which are extremely massive black holes that have a very bright disk of stellar matter. These quasars are drawing towards themselves to determine just how much reddening has occurred due to the dust in different galaxies in an attempt to see just what the dust there is like. This is possible because we have a good understanding of what a quasar should look like and can compare that with data that we see when we look at the quasar through the galaxy in question. This is a nearly completed project, but the final comparisons have not yet been made at every wavelength available to us.

News from the SmartState Center for Experimental Nanoscale Physics

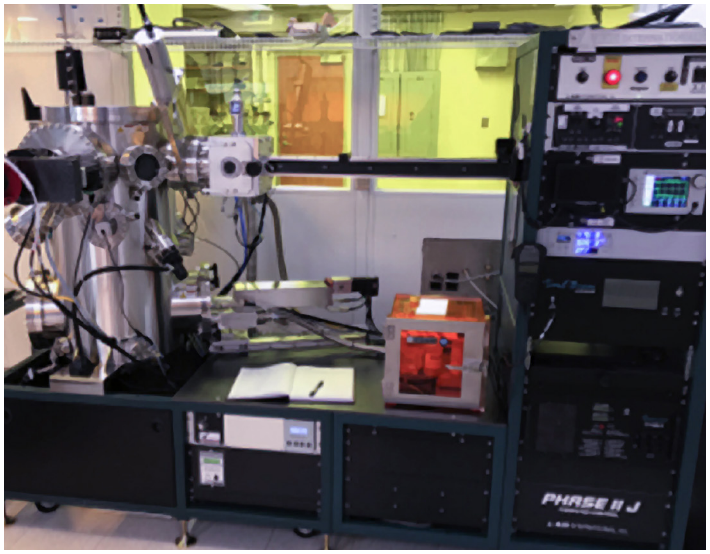
By Thomas Crawford

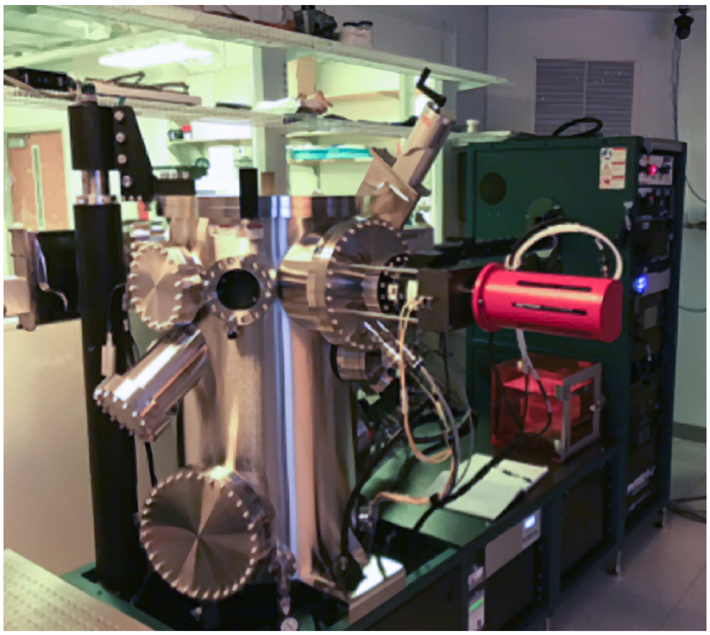
This past year, the Department of Physics and Astronomy and the SmartState Center for Experimental Nanoscale Physics took a key step toward recruiting a new colleague to hold the open SmartState Chair by submitting a proposal to the Office of the Provost's "Excellence Initiative" program to fund the start-up for a new Chair. However, even without a Chair, the work of the Center continues.

SmartState®
SC Centers of Economic Excellence

The Center hosted two world-renowned visitors serving as the kick-off of the Richard A. Webb Condensed Matter Symposium Series. APS president and Chief Scientist of the National High Magnetic Field Laboratory, Florida State University Professor Laura Greene visited in the fall of 2017, met with Center faculty, and gave an outstanding public lecture on the future of superconducting materials. In the spring of 2018, physicist and Stanford professor W. E. Moerner, who won the 2014 Nobel Prize in Chemistry for his pioneering work on single molecule imaging, visited our department and gave another excellent public lecture.

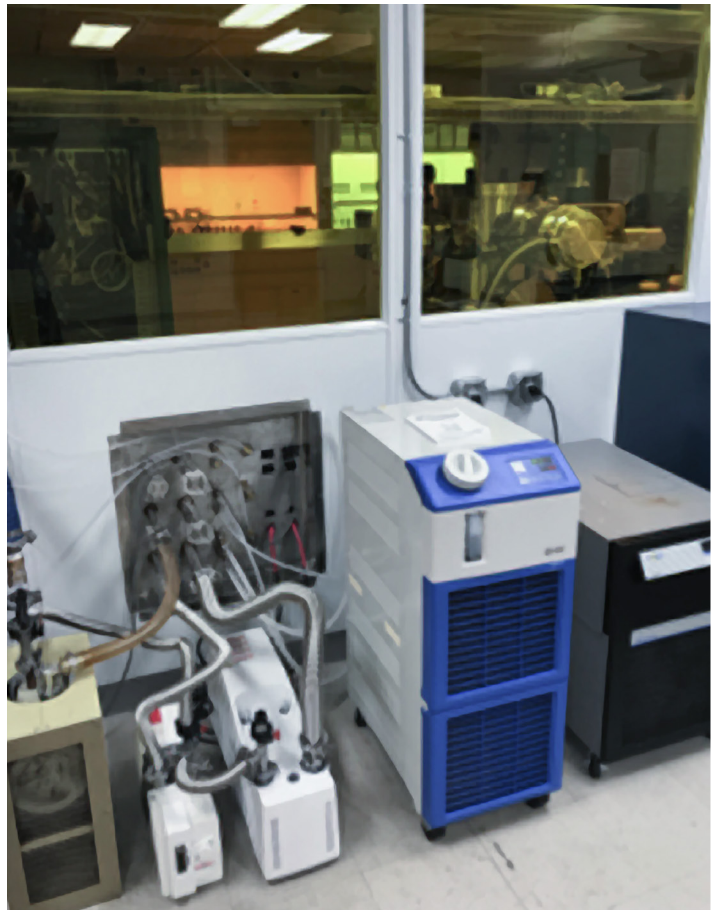
During summer 2018, the Center took delivery of a new ultra-high vacuum electron beam evaporator that has been installed in the SmartState Center cleanroom on the first floor of Sumwalt (the photos show the evaporator from inside and outside the cleanroom). This instrument replaces the Center's original Torr system that was purchased by Prof. Webb and installed in 2005. At 13 years old, the electron-beam system failed regularly and the system took several hours to achieve a vacuum in the low 10^{-6} Torr range. The new system is load-





locked, allowing for rapid transfer in and out of a main chamber that will easily achieve low 10^{-8} Torr vacuum. This system is significantly cleaner than the previous system and will allow much greater throughput because of the load-lock. Combined with its ability to both rotate and tilt the substrate, the Center anticipates many researchers at USC, within physics and in other departments, will make excellent use of this significant upgrade in the Center's fabrication capabilities.

The new evaporator, together with upgrades to the Center's overall physical footprint, including CarolinaCard locks on the hallway doors, a reorganization of the support facilities, and the introduction of a full gowning protocol for the cleanroom set the stage for the Center's experimental research going forward. Coordinating these modifications along with the evaporator acceptance and installation processes were handled by our Center Technical Associate (and 2015 USC Physics alumnus), Heath Smith. We expect these significant improvements and upgrades will help us attract a world-renowned Chair to lead the Center while improving ongoing research activities within the Center as well as external collaborations.



Center start-up MagAssemble, LLC participated in two start-up competitions during the 2017-2018 annual year. Since early 2018, MagAssemble has been collaborating with another South Carolina photonics startup, CIRTEMO, LLC, which tendered an offer to purchase MagAssemble in April 2018. This merger will offer a chance for MagAssemble to better pursue customer development and commercialization activities for its Pattern Transfer Nanomanufacturing Technology in the area of diffractive micro-optics as well as for Life Science applications.

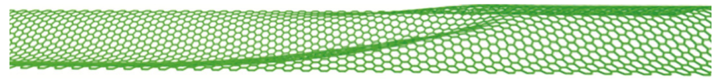
Our center faculty members have also been busy with research over the last year. Associate Professor Crittenden, collaborating with Profs. Altschul and Crawford, published an article in Physical Review B describing Dr. Fiona Oxsher's Ph.D. research on novel chemically-induced surface magnetism. Graduate student Kenneth Stephenson published his first two research papers. Some of his results are reported in the Journal of Applied Physics. This article originated from the experimental studies of epitaxial graphene. While Ken is an experimentalist, the work is theoretical and puts to a test some customary methods of electron mobility analysis, widely used in labs worldwide. Prof. Bazaliy assisted Ken with this study. The second paper was the result of a collaboration with USC's Department of Chemistry and Biochemistry, which reports on properties of conductive polymers synthesized in the research group of Prof. Natalia Shustova. Working with another graduate student, Ekaterina Dolgopolova (Chemistry), Ken measured the resistance of the novel material. This paper is published in a prominent chemistry journal, Angewandte Chemie. Finding one's own

MagAssemble™

path in the world of science is crucial for young researchers and it is particularly pleasing when they succeed in their first steps.

This past spring, the Condensed Matter group hosted a research visitor, Prof. Oleksiy Kolezhuk, who spent a month with the department. He delivered a series of open lectures on quantum magnetism, which is the field of his specialization. The lectures proved to be quite popular and provided a chance for a number of faculty members to take a step back from their daily research. Together with local faculty members, our visitor worked on quantum properties of pure spin currents. This was an effort to provide theory support for the experimental measurements conducted by another departmental graduate student, Ning Lu. Ning is currently in the final stages of his Ph.D. preparation and analyzing the data collected during his time at Carolina. Prof. Kolezhuk was supported by a grant from the Office of the Provost, received by Prof. Bazaliy.

Assoc. Profs. Bazaliy and Pershin continued their international collaborations with Toulouse, France and Novosibirsk, Russia respectively. Together with his Ph.D. student, Ruslan Yamaletdinov, based at the Nikolaev Institute of Inorganic Chemistry (NIIC) SB RAS, Novosibirsk, Prof. Pershin co-authored two papers on properties of buckled graphene. In the first paper published in Physical Review B, they introduced graphene kinks and antikinks, which are topological excitations of buckled graphene membranes with unusual properties. Their second paper, published in Scientific Reports, is related to the application of graphene membranes in information processing and storage technologies. In collaboration with Valery Slipko from Poland, Prof. Pershin found an analytical solution for a switching synchronization problem in 1D memristive networks and reported this result in Physical Review B. His ongoing study of ionic transport through porous membrane (in collaboration with Toyota Central R&D Labs and University of California San Diego) resulted in an article on nanotechnology. Prof. Pershin's research at Novosibirsk was supported by a grant from the Russian Science Foundation. During the past year, Dr. Pershin received an ASPIRE award in the area of emerging computing technologies as well as an equipment grant from the NVIDIA corporation.



An example of a graphene kink introduced by Prof. Yuriy Pershin and Ruslan Yamaletdinov.

Asst. Prof. Wu graduated her first Ph.D. student, Dr. Matthew Seaton, publishing an article on optical gating of semiconductor quantum dots interacting with plasmonic silver nanostructures. Prof. and Center Deputy Director Crawford received a new collaborative award from the NSF- DMR - Experimental Condensed Matter Physics Program, to study the physics of magnetic nanoparticle self-assembly in extreme field gradients. This award also funds one of Crawford's collaborators, Prof. Karen Livesey, at the University of Colorado (Colorado Springs). Dr. Livesey is a theorist who studies magnetism in nanoparticles.

News from Timir Datta's Group

By Timir Datta

This was an exciting and busy year. First, graduate student Lei Wang's doctoral graduation and move to Yale University was followed by a flurry of visits by a number of renowned scientists, including two Nobel laureates. These guests also encouraged several of our former associates to pass through their old labs, triggering a couple of mini-reunion celebrations.

The first to visit was the President of the American Physical Society (APS), Professor Laura Greene. Recently, she moved from the University of Illinois Urbana Champaign to join Florida State University and the leadership of the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. Her visit was timely because Lei Wang had just completed his high-field in low temperature (large B/T) Ph.D. work at the NHMFL. In a public lecture, she reviewed worldwide research about the nature of the quantum phase in high Tc superconductivity, which is a question that has remained unresolved for nearly four decades. Supported by the SmartState Center for Experimental Nanoscale Physics, Dr. Greene also met with USC's Condensed Matter Physics group and several university officials.

In early February, Yeuncheol Jeong flew in from Seoul, South Korea. Taking advantage of his winter break at Sejong University, Yeuncheol coordinated his stay with the visit by the 2017 Physics Nobel Prize co-winner, Professor Barry Barish from Caltech in Pasadena, CA. A Director Emeritus of the Laser Interferometer Gravitational-Wave Observatory (LIGO), Dr. Barish led the upgrading of the observatory up to the status of "Advanced LIGO"; This increased operational sensitivity of the interferometer to a level of $\sim 10^{-21}$, and is a spatial resolution of about a thousandth of a single proton.

The February 2018 trip was Prof. Barish's second visit to USC. He gave a "Q&A" session to the department as well as participated in numerous meetings with our faculty and students. Dr. Barish presented a lecture on the long-sought and Nobel winning discovery of gravitational waves. News of this public lecture was covered on both local television and various media outlets through USC Student Media.

In his presentation, Dr. Barish explained that gravitational waves, or the radiation of energy carrying geometric ripples in space-time, were anticipated in Albert Einstein's general theory of relativity a century ago. But, they are qualitatively different from most other collective oscillations in a medium, including the familiar water waves, sound waves, or radio waves in vacuum. Furthermore, the amplitude of space-time distortions of the waves produced even by massive objects several times bigger than our sun is so minute that Albert Einstein considered the effect to be immeasurably small or negligible. Coincidentally, Joseph Weber, one of the inventors of the concept of maser-laser, initiated the first experimental search for gravity waves. In the 1960s and 1970s, he developed a type of levitated resonant superconducting detectors known as "Weber bars," but his effort was not successful.

The search for gravitational waves eventually achieved success in 2015. In September 2015, the extremely sensitive instruments of Advanced LIGO picked up the first signals of gravitational waves ever recorded. The data was analyzed to be the gravitational radiation from the inward spiraling, the merger and the ring down of two (~60 solar mass) black holes. The waves have been radiated away from a cataclysmic astrophysical event that took place more than a billion light years from our solar system. Dr. Barish showed that data from other events detected at LIGO, answered another crucial question - gravitational waves travel at the speed of light!

We were also fortunate to have another Nobel laureate, Prof. William E. Moerner from Stanford University, visit. In the 1980s, when Dr. Moerner was at IBM in San Jose, CA, he and Dr. Datta were interested in the physics of unconventional (non-central limit) stochastic phenomena. Dr. Moerner hosted Prof. Datta's visit and talk at the Almaden Laboratory, IBM's Silicon Valley facility in San Jose. Since that time, W.E. Moerner's work on spectral hole burning led to the discovery of optical 'blinking' and experimental techniques that broke the infamous 'Abbe-limit' of diffraction. This limit, discovered in 1873 by the German physicist Ernst Abbe, had restricted the amount of details that can be resolved in images produced by waves using conventional processes. With this technique, Prof. Moerner would be the first to optically image single molecules and invent a new type of super-resolution optical microscope. In 2014, Prof. Moerner's invention was acclaimed by his co-winning of the Nobel Prize for Chemistry. On the last day of his visit, Dr. Moerner presented a public lecture explaining the principles of super-resolution and how his team is applying molecular imaging optical microscopy to solve current biophysical problems.

Among other news, Ph.D. graduate Lei Wang moved to New Haven, CT and joined Yale University as a Research Support Specialist at their new lithography and cleanroom facility. Lei has a number of refereed publications already in print and we continue to compose papers from his dissertation. Also, the productive collaboration with Prof. Ming Yin's Department of Energy program at Benedict College in Columbia is ongoing. This past March, we chaired sessions and presented a number of papers at the American Physical Society's annual meeting in Los Angeles, CA. At the meeting, we also met up with former members, including Prof. Carmen Almasan (Kent State University; Kent, OH) and others.

News from Milind Kunchur's Group

By Milind Kunchur

Professor Milind Kunchur's group research group works in two areas: (1) superconductivity, thin-films, and nanofabrication; and (2) psychoacoustics, auditory-neurophysiology, and high-end audio. Two students from his group completed their doctoral theses in the summer of 2018-Charles Dean and Nahid Swails. They have begun faculty positions at Allen University and the University of South Carolina Lancaster respectively. Two undergraduate students-Christine Reid and Leslie Thelan-worked in Dr. Kunchur's group during 2018.

A Change of Pace

By Charles Dean

I am a recent Ph.D. graduate from USC as of this past summer. While working in Dr. Milind Kunchur's Condensed Matter group over the past few years, I published many papers, as both a lead and supporting author. I decided to take my analytical experience and dive into some big data science. This is a field that has always been very interesting to me, but as I lacked specific training in the area, I was not having any luck finding a job. I took a step back and started working under Dr. Joe Johnson (USC) on some of his clustering analyses. I figured it would be great to gain some experience and maybe even a reference. This project has been going quite well and will hopefully be a full-blown research group in the next few months.

Carey Abraham Gibbs Hall on the campus of Allen University (Columbia, SC) houses mathematics and science courses, laboratories, and faculty offices.

Sadly, science alone does not pay the bills and I also needed to find a part-time job. Between a wife, house, and three-year-old, I could not afford to completely take a year off. At the same time, Allen University, a historically black college right down the road in Columbia, was looking for an adjunct physics instructor. They were seeking a part-time teacher for one or two semesters. The fit was all too perfect. I applied and soon after interviewed with the department head. Not long after, I was talking with the head of the science department and the Vice President of Academic Affairs. In August, I accepted a full-time faculty position here at Allen. Needless to say, things were looking up. One minor catch…classes started in a few days.

The students at Allen have been quite gracious about the entire situation. The atmosphere at Allen is quite different from USC. Being such a small school (less than a thousand students) means you get to know just about everyone very quickly. My first day on the job, I was approached by almost a dozen different students. They introduced themselves to me and wanted to get to know more about me. These were not students in my classes or even my department. They just saw a new face and decided to turn a stranger into a friend. It was in that moment that I realized I was in for a very interesting time.

I dove right in to the role. It has been quite the experience, creating a curriculum for classes, while teaching them all at the same time! We are currently working on multiple grants, HBCU targeted infusion projects, a joint collaboration between Allen and USC, and a collaboration with another local school. While it is daunting, the task of being the only physics teacher on staff (and having to build everything from the ground up), I am very excited about the challenges ahead. I look forward to growing both personally and academically.

I did not see myself becoming a teacher, at least not so early in my career. I have been a member of the American Association of Physics Teachers for six years now. While I've always enjoyed their work, seeing things from this side has truly given me a new outlook on life. The point is this: do not count yourself out of anything too early. You won't always know what you will end up doing or where you'll end up going. Just keep pushing and move on to the opportunities that present themselves. I am looking forward to the future partnership between USC and the growing department here at Allen University. Go Yellow Jackets and go Gamecocks!

Experimental Nuclear Physics Group

By Ralf Gothe, Yordanka Ilieva, and Steffen Strauch

The study of the atomic nucleus and its constituents at the quark level is at the core of our research. We are leading experiments at one of the flagship facilities for nuclear physics research in the U.S., the Thomas Jefferson National Accelerator Facility (JLab) that recently has been upgraded to higher energies and at the Paul Scherrer Institut (PSI) in Switzerland. We have also been responsible for the construction of critical equipment for major nuclear physics experiments at JLab and PSI. Our studies on Quantum ChromoDynamics (QCD) and nuclei are recognized as U.S. nuclear science frontiers, and our research helps to address basic questions such as: what is the origin of confinement and most of the visible mass in the universe, what is the nature of neutron stars, and what are the properties of dense nuclear matter? Answering these and related questions is a complex task requiring dedicated experimental observations and careful testing of theoretical predictions against measured observations.

Currently, our group is comprised of faculty members Ralf Gothe, Yordanka Ilieva, and Steffen Strauch, postgraduates Arjun Trivedi and Hao Jiang, graduate students Gary Hollis, Lin Li, Chris McLauchlin, Krishna Neupane, Nicolas Recalde, Iuliia Skorodumina, and Nick Tyler, and is joined by many undergraduate students working with us on various research projects.

The most exciting news from the past year is that we were successful to secure funding from the National Science Foundation for our research during the next three years. The funding allows us to maintain the impact our group has in the field by carrying out our ongoing research, continuing to support our students, and fulfilling our commitments to the

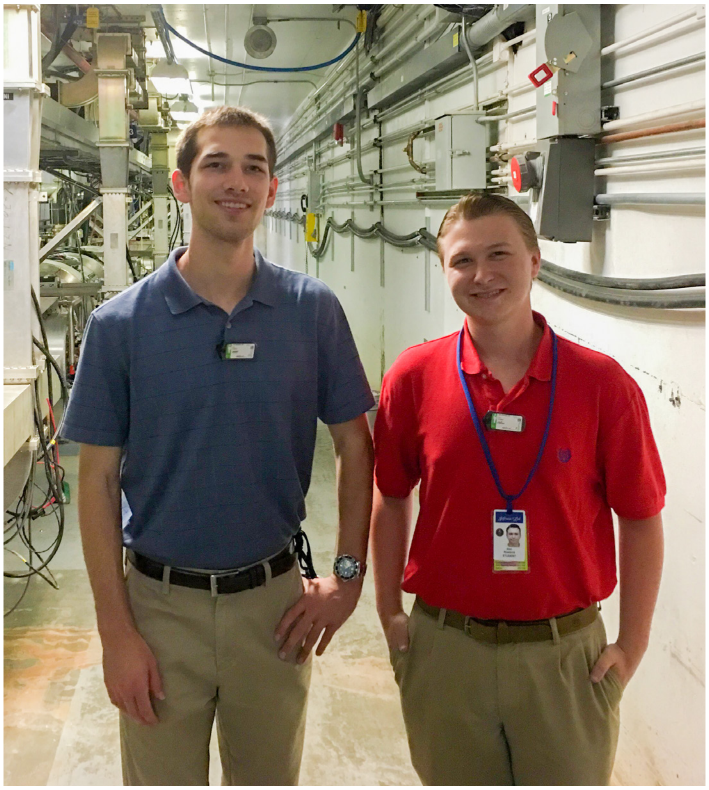


Figure 1: USC undergraduates Andrew Dunton (left) and Alan Rowland (right) captured while on tour of the JLab accelerator in Summer 2018. Both Alan and Andrew were accepted to present their research at the Fall Meeting of the Division of Nuclear Physics in Hawaii in October 2018.

scientific programs at JLab and PSI. This is especially critical as the first sets of our new JLab experiments have started to collect data in Fall 2017 and our PSI experiment is nearing production data taking.

Another highlight is the recent approval of beam time for a novel project we are leading at JLab aimed to provide a first glimpse at the role that gluons play in nuclei. We will smash very high-energy electrons on deuteron nuclei and measure the chance that particles consisting only of charm quarks (called J/ψ) are produced in the collisions. Since deuterons do not contain charm quarks, the key players in the production process are the gluons in the deuteron. This experiment will begin to take measurements in 2019 and USC approved a sabbatical leave for Y. Ilieva to spend three months at JLab in Spring 2019 to carry out the study. Learning details about nuclear gluons is a key scientific objective of a future Electron Ion Collider (EIC) in the U.S., but until EIC begins to operate, our J/ψ study will be an important resource to learn about this interesting physics.

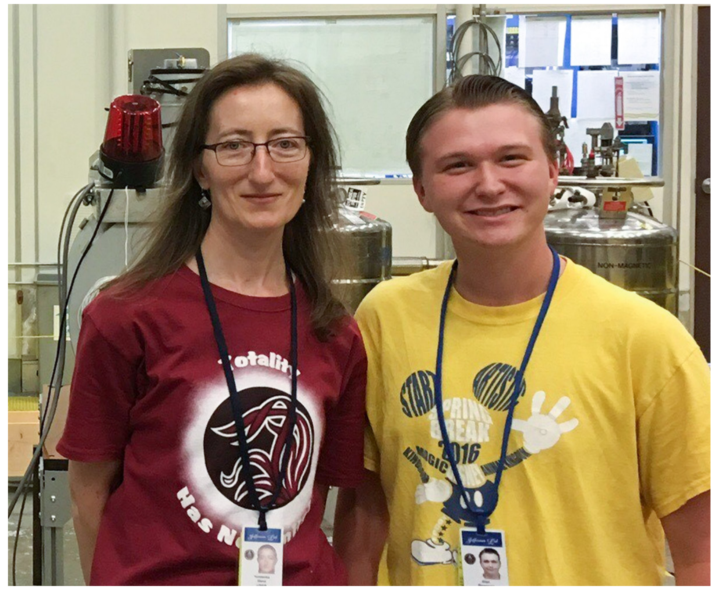
After years of hard work, countless hours of analysis, checks, and re-checks, we have now begun to reap the fruits of our effort on past JLab experiments. Some notable publications in the last year include two reports (Phys. Rev. C 96, 035204 and Phys. Rev. C 96, 065201) of measurements of strange (particles containing strange quarks) and non-strange particles produced when photons (highly-energetic electromagnetic waves) collide with neutrons. These elaborate measurements were taken in such a way that we can study the excited states of the neutron. Of particular interest was the possibility to search for new excited states that were previously predicted but not observed. Although, our results alone do not provide evidence for such new states, they help to improve the knowledge of poorly known states by placing unique constraints on theoretical models. We expect to publish more results in the upcoming year that will shed further light on this topic. Undergraduate student Andrew Dunton, under the mentorship of Y. Ilieva, researched an aspect of this program in Summer 2018 at JLab (see Fig. 1).

We have also been successful to publish first results on nucleon resonance electro- and photo-excitations (Phys. Rev. C 96, 025209 and Phys. Lett. B, D-18-00893R1) that will be essential to further pin down the theoretical understanding of how mass and confinement are generated by strong QCD. To refine the experimental results further, Arjun Trivedi extracted new polarization-dependent observables in double pion electroproduction for the very first time. The analysis has already been approved by the collaboration and the publication is pending. Congratulations also to Iuliia Skorodumina, whose JSA Graduate Fellowship was renewed in recognition of her outstanding research work and service contributions to the JLab community. Nick Tyler and Chris McLauchlin presented their research work at the latest Gordon Research Conference "From Quarks to Nuclei in Photonuclear Reactions" in Holderness, NH. And last, but not least, Ralf Gothe who is leading these efforts and continues to coordinate all approved experiments on the electro-excitation of nucleons in Hall B at JLab during the current first-data-taking campaign with CLAS12, has also become our new Department Chair here at USC.

Our NSF funded detector construction project for our Muon Scattering Experiment (MUSE) at the PSI is nearing completion. MUSE is a scattering experiment of muons and electrons off a proton target that aims to compare the extracted proton charge radii for these two leptonic probes to study the Proton Radius Puzzle. Over the past three years, a team of USC undergraduate students (including A. Flannery, H. Howell, J. Kappel, T. Lannen, E. McLean, T. Rogers, K. Rolon, and C. Yoke) spent combined almost 1,000 hours in the group's lab to construct over 100 high-resolution scintillation detectors. All detectors have been shipped to and commissioned at PSI. We have achieved time resolutions of, on average, 55 ps for the largest bars down to better than 40 ps for the shortest. All detectors met or exceeded the experiment's requirements. This past spring, USC undergraduate students Eric McLean and Krystal Rolon helped to mount the detector bars in their support frames at PSI; see Fig. 2. The group will continue to play a leading role in MUSE with our development of the detector simulation (Lin Li, Ph.D. project) and in the management of the experiment. Lin presented results of her work on MUSE at the 2018 Gordon Research Conference in Holderness. We expect to start data taking in 2019. This project is led by Steffen Strauch.

Figure 2: USC undergraduate student Krystal Rolon, with Dr. Alexander Golossanov from the George Washington University, next to the newly completed detector frame at the Paul Scherrer Institute in May 2018.

In a much anticipated study report, the National Academy of Sciences (NAS) endorsed the construction of a U.S. based EIC by finding that *the science questions* (i.e. How do the mass and the spin of the nucleon arise? and What are the emergent properties of dense systems of gluons?) *that an EIC would answer are central to completing our understanding of atomic nuclei as well as being integral to the agenda of nuclear physics today*. Another findings were that *An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics* and *The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development*. The positive NAS review was an important milestone in the long process of realizing the collider and is a significant achievement for all of us who have been working to make the EIC happen. More specifically, as part of the JLab R&D efforts related to building an EIC in the U.S., our group is responsible for the maintenance and operation of a dedicated test facility at Jefferson Lab, where the performance of small size photon sensors in high magnetic fields can be evaluated. After setting up the facility in 2014, we carried out a series of tests of micro-channel-plate photomultipliers (MCP-PMT) in magnetic fields of up to 5 Tesla. We have secured funding to continue this activity in 2018-2019 through a collaborative EIC PID Consortium proposal and plan more measurements in summer 2019. Undergraduate student Alan Rowland (see figure at top-right) contributed to this project led by Yordanka Ilieva.



Dr. Ilieva (left) and Alan (right) after finishing up the last day of taking data for the summer at Jefferson National Accelerator Facility (Newport News, VA).

My Experience at Jefferson Lab

By Alan Rowland

When I started my first semester at USC last Fall, I thought to myself, "I will worry about research later on, probably my junior or senior year." I came from a small town in the upstate and I had no practical knowledge of what physics was past a free-body diagram. As the semester went on, though, I heard about freshmen and sophomores beginning research and working on projects I couldn't imagine doing. Because of this, I decided to attempt to join a research team as well! I had no idea who to ask, so I thought to ask my physics lab professor, Dr. Ilieva. When I looked up her research topic on the departmental website, I could only understand the phrase "nuclear physics", so I thought I would just ask her after class about it. When I finally spoke with her outside of class, she blew my mind with a half-hour lecture about quarks, gluons, and the interactions between them. While I couldn't understand all of it, that conversation only made me more curious to study it! I asked if I could join the nuclear physics group with Dr. Strauch, which sadly had no room. It was after being told that, though, that Dr. Ilieva invited me to go to Jefferson Lab with her!

As an inexperienced freshman interested in research, I immediately agreed to go, but I had no idea what I was going to be doing. I tried to prepare for the Lab, reading papers and attempting basic coding, but nothing could prepare for what I was getting into, for it was one of the best learning experiences I've ever had.

When I arrived at Jefferson Lab in Newport News, Virginia, living out-of-state for the first time in my life, I immediately jumped into the work. Dr. Ilieva taught me the basics of coding (which I am so thankful for now) and gave me a few tasks with understanding data from last year. She also introduced me to an electrical engineer, Jack McKisson, who became a second mentor to me. At the beginning of all this, I was terrified. Jack left me in a room with a voltage supply, a charge injector, and an oscilloscope on the first day, and told me to "figure it out." It was through this way of learning that Jack helped me strengthen my understanding of physics and thrive at Jefferson Lab.

Our main task at Jefferson Lab this past summer was to study the gain and analyze the response of microchannel plate photomultipliers (MCP PMTs), small devices that convert light into an electric signal, under strong magnetic fields. In the current designs of the central detector of a future Electron Ion Collider being built at Jefferson Lab, MCP PMTs will be used to readout Cherenkov detectors in a magnetic field. We were studying different types of MCP PMTs because we needed an MCP PMT that could maintain a high gain response inside the magnetic field of the detector, which can go up to 3 Tesla. My tasks dealt with confirming the amplification value for the MCP PMT pre-amplifier card we were planning to use later in the summer, analyzing the data taken from another MCP PMT taken the previous year, and assisting with data taking during the experiments for the MCP PMT. The tasks always appeared like a mountain of work, but I loved to work on these projects and to tackle them was uplifting.

By my last two weeks at Jefferson Lab, it felt like my second home. I was done with the projects I had at the beginning of the summer and was now taking shifts for data taking on the main experiment. Although I was just the undergraduate intern, I didn't feel like it, with beginning runs and once ramping up the superconductor magnet. I now understood the physics jargon and could offer knowledgeable opinions about what we were doing! Although these may seem like normal things, for me, it was life changing. I learned more physics this summer than I had ever known. When I look back at this experience, it was easily one of the coolest things I have ever done in my life, and I have Dr. Ilieva to thank for that. She gave me, the freshman that just wanted to know what the phrase "Quantum Chromodynamics" meant, a life-changing opportunity that I will always treasure.

Undergraduate Experience with MUSE

By Krystal Rolon

On September 10, 2016, I received a message from a fellow physics undergraduate about a research opportunity. It later blossomed into a committed project of nearly three hundred hours and I was able to witness the completion of USC's latest contribution to the MUon proton Scattering Experiment (MUSE). MUSE attempts to tackle what is known as the proton radius puzzle. Essentially, the measurement of the radius of the proton appears roughly 5% smaller when muons (rather than electrons) are scattered off a proton. More than a seven sigma difference exists between the electronic and muonic methods which suggest something is missing. Is there possibly a problem with the extractions themselves such as underestimated uncertainties or an issue with fits? Perhaps there is new physics. Whether the answer relates to experimental methods, incomplete theory, or something beyond the Standard Model of physics, the need for more data is apparent. MUSE aims to examine that discrepancy by running both electron-proton and muon-proton scattering experiments for a direct comparison.

Undergraduate Krystal Rolon received hands-on experience assembling and repairing scintillator bars for the MUSE experiment at Paul Scherrer Institut in Villigen, Switzerland (Summer 2018).

Our contribution here at USC involved assembling nearly a hundred scintillator detectors for the project. Within the week of being contacted about the opportunity, I met with Dr. Steffen Strauch. Joining his team, I worked on testing photomultiplier tubes (PMTs), preparing the scintillator bars, and even assisting with the installation of the finished products in Switzerland. Going to Paul Scherrer Institut in Switzerland alone was just amazing. It was my first time leaving the country and the only time anyone in my family had left the United States in nearly a century. I gained a tremendous amount of knowledge by interacting with scientists outside of a lecture hall and how they tackled problems in real time. Seeing the whole operation in person meant a lot to me because I finally witnessed what all those hours of meticulous work were for and how it connected. I took great pride in my work over the course of the two years working on this project. It was my first experience with research and gave me the confidence to tackle later commitments. In the future, I hope USC undergraduates continue to have research opportunities as fulfilling as MUSE was for me.

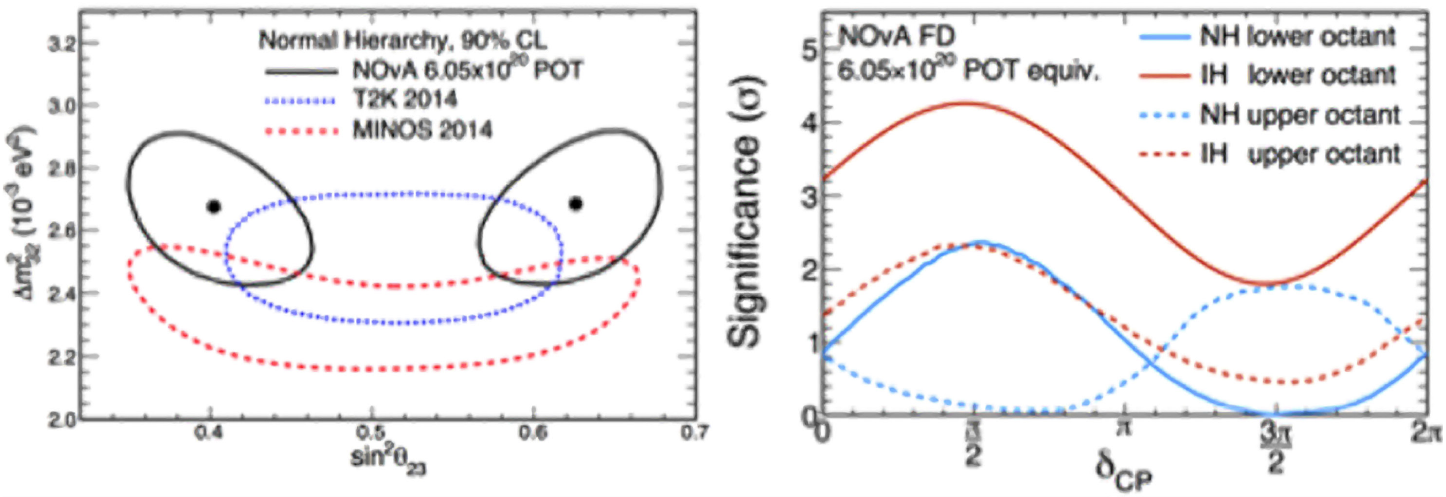


Figure 1. Results from the NOvA experiment at Fermilab published in 2017. Left panel: allowed regions at 90% CL for the oscillation parameters consistent with the new NOvA measurement of muon-neutrino disappearance (solid line) compared with previous measurements from other experiments (dashed lines). Right panel: significance at which each value of the CP-violating phase δ_{CP} is disfavored by the combination of the NOvA ν_e appearance and NOvA's latest ν_μ disappearance measurements.

High Energy Neutrino Physics Group

By Sanjib Mishra and Roberto Petti

The focus of the Carolina Neutrino Group is the NOvA and DUNE experiments. The group currently comprises two faculties, Prof. Sanjib. R. Mishra and Assoc. Prof. Roberto Petti; one post-doctoral fellow, Dr. Hongyue Duyang; and two graduate students, Bing Guo and Chatura Kuruppu.

NOvA Experiment

The NOvA experiment is designed to measure the oscillation of muon- to electron-neutrinos by comparing the electron neutrino event rate measured by a Near Detector (ND) located on the Fermilab site with that measured by a Far Detector (FD) located 810 kilometers from Fermilab. The FD will see the appearance of electrons in the muon neutrino beam produced at Fermilab, and the concurrent disappearance of muon neutrinos. The data analysis consists of comparing the measured event rates of different neutrino flavors in the 222 metric-ton ND and in the 15 metric-kiloton FD. An accurate measurement of the oscillation parameters in NOvA could shed light on the ordering of the neutrino mass states and on the mechanisms responsible for the matter/anti-matter asymmetry in our universe.

Carolina has been a founding member of NOvA. After a decade's worth of work, NOvA has been collecting data since 2014, and, in 2017, published updated measurements of neutrino oscillations using both the electron appearance and the muon disappearance channels (Fig. 1). Future data-taking in antineutrino mode will help resolve the remaining degeneracies in the mixing parameters, as well as search for possible hints of CP violations. In addition, the NOvA experiment also measured some of the fundamental properties of neutrino interactions and cross-sections. The Carolina group's responsibilities on NOvA include Monte Carlo simulation, beam studies, data-acquisition system, and data analysis. Mishra, Petti, Duyang, Guo, and Kuruppu work on NOvA.

The Carolina group has a duplicate of the NOvA control room fully operational in our Physics Department at USC. The Carolina control room, which was approved by the NOvA collaboration, is connected remotely to Fermilab and is used to monitor in real time the actual data taking of the experiment. The NOvA remote control room offers an invaluable learning experience for both undergraduate and graduate students since it places them in direct contact with the core activity of frontier research in High Energy Physics. They can interact with scientists, personnel, and students at Fermilab and follow in real time how neutrino interactions are selected, recorded, and reconstructed in the NOvA detectors.

DUNE Experiment

The Deep Underground Neutrino Experiment (DUNE) is a next generation oscillation experiment with greatly increased physics sensitivity with respect to NOvA. The unique capabilities and accelerator infrastructure at Fermilab joined with a far detector of 40 metric-kilotons located 1,300 km away at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, present an extraordinary opportunity to develop a world-leading program of long-baseline neutrino science. This baseline distance, between near and far neutrino measurements, is optimal for oscillation studies and not currently available at any existing facility. The DUNE experiment plans to take physics data starting in 2023 - initially with a 1.2-MW beam, but later with a 2.3-MW upgraded beam. Since 2015, the DUNE evolved into a leading-edge international collaboration, including 890 scientists from 160 institutions and 29 countries. The Carolina group's commitment to the DUNE program has been deep and critical to its progress and success in achieving

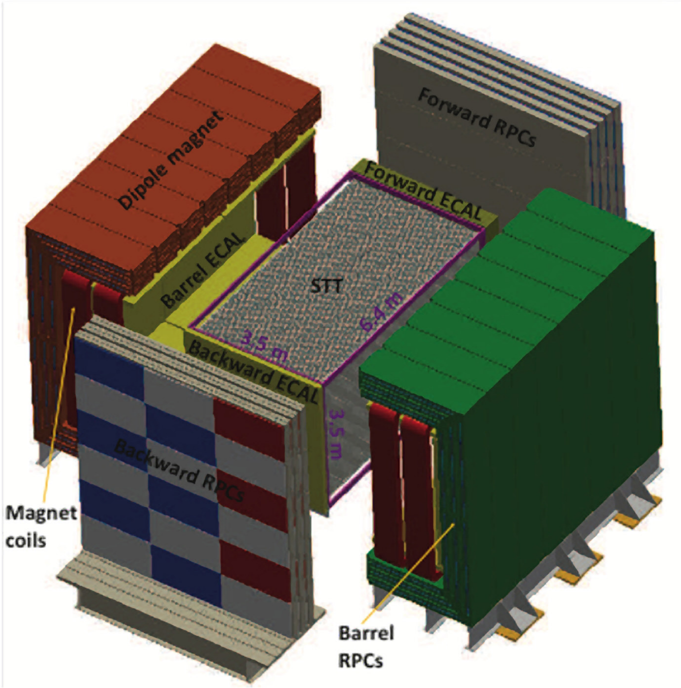


Figure 2. Schematic of the reference Near Detector of the DUNE experiment. The central Straw Tube Tracker (STT) is surrounded by a 4π electromagnetic calorimeter (ECAL) placed inside a large aperture dipole magnet. Muon identification is provided by RPC located inside the iron yoke of the magnet and in the forward and backward regions.

the various milestones during the preparation of the Conceptual Design Report (CDR) and the following external reviews.

Mishra and Petti proposed a high resolution near detector, the Fine Grained Tracker (FGT), as a generational advance in the investigation of systematic errors affecting the neutrino oscillation and mass measurements in the precision neutrino-interactions made possible by the unprecedented neutrino fluxes foreseen in DUNE. The DUNE collaboration has chosen FGT as the reference ND design and passed the Department of Energy CD1 approval stage in July 2015. The FGT detector (Fig. 2) comprises a 7 metric-tons high-resolution, low-density (0.1 gm/cm^3) straw-tube tracker (STT), surrounded by a fine-grained electromagnetic-calorimeter (ECAL) and embedded within a 0.4 T dipole magnetic field. Muon-detectors instrument the magnet and two stations downstream of the STT. The Carolina group along with Fermilab has been working with a consortium of Indian institutions, which proposed to the Indian funding agencies to design, R&D, and fabricate the FGT detector in India, which would then be shipped to Fermilab and installed in the DUNE near-detector hall. The FGT detector would combine for the first time an accurate reconstruction of the momentum and energy of the particles produced in neutrino interactions, together with an increase in statistics by two orders of magnitude over past experiments. This detector would perform over 100 new measurements and searches, each surpassing the best previous result, and, in the course of a ten year operation, would result in over 300 publications and many potential physics discoveries. In 2017, the DUNE collaboration decided to augment the ND capabilities by adding a 30 ton modular liquid argon detector in front of the FGT. The Carolina group is expected to play a leading role in the R&D phase in preparation for the CD2 approval in 2019.

Mishra and Petti are leading the ND detector and physics groups in the DUNE collaboration. Duyang, Guo, and Kuruppu are participating in the DUNE-related research.

Particle Astrophysics Group

Faculty: Frank Avignone, Richard Creswick, Vincente Guiseppe, Carl Rosenfeld, David Tedeschi and Jeffrey Wilson; Graduate Students: Douglas Adams, Christopher Alduino, David Edwins, and Kevin Wilson. Recent Ph.D. graduates are Dawei Li (2016), Nicholas Chott (2017), and Clint Wiseman (2018).

Particle Astrophysics focuses on the study of phenomena in astrophysics and cosmology associated with the properties of elementary particles including neutrinos, axions and candidates for Cold Dark Matter (CDM). In 1933, Fritz Zwicky discovered that far more mass is needed to explain the dynamics of the Coma Cluster of galaxies than can be accounted for by stars, gas, and dust alone. The gravitational influence of CDM on the velocity distribution of stars in spiral galaxies has been well established by Galactic Rotation Curves. The USC group was a pioneer when, in 1985, it led the first terrestrial search for CDM in the Homestake goldmine in Lead, South Dakota. This experiment used a unique low-background detector developed in collaboration with the Pacific Northwest National Laboratory (PNNL). The results eliminated heavy Dirac neutrinos as the major component of CDM over a very large range of neutrino masses. As a result of that collaboration, three Ph.D. graduates from our group have joined the PNNL staff. Two are now PNNL Laboratory Fellows.

The USC Group also led the first search for axions emitted by the sun. Axions are elementary particles predicted by the theory of Roberto Peccei and Helen Quinn that explains why the strong interaction, described by quantum chromodynamics (QCD), does not violate charge-parity (CP) symmetry. Without the Peccei-Quinn solution, or some alternative one, the CP-violation predicted by QCD would result in an electric dipole moment of the neutron about ten orders of magnitude larger than the experimental upper bound. One USC-led axion search was based on an analysis developed at USC by Rick Creswick. It uses the coherent Bragg conversion of axions to photons in single crystals to predict a characteristic time-dependent event rate. This technique was used by other groups worldwide for solar axion searches. Rick continues to provide critically important theoretical guidance to all of our efforts. His student, Dawei Li, recently made a further improvement in the technique and applied it to the data from the Cryogenic Underground Observatory for Rare Events (CUORE) now operating in the Gran Sasso Laboratory in Assergi, Italy. Clint

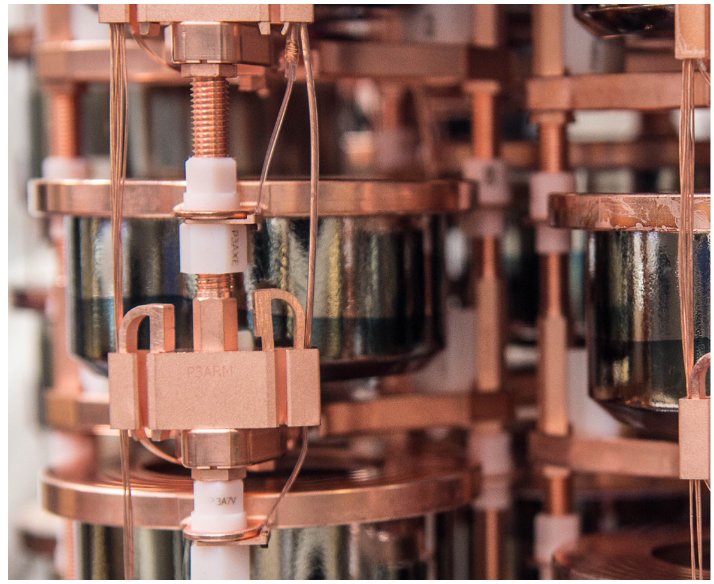
Wiseman, who received his Ph.D. in 2018 under the direction of Vincente Guiseppe, conducted a search for axions produced by atomic transitions in the core of the Sun.

The main effort of our group currently concentrates on two searches for the exotic zero-neutrino nuclear double-beta decay, which is only possible if neutrinos have mass and are their own antiparticles (Majorana particles). This decay mode would also violate the law of lepton-number conservation. Neutrino oscillation experiments clearly demonstrate that neutrinos have mass, but they can only measure mass differences of the mass eigenstates. The measurement of the rate of decay would determine the absolute masses of all three neutrino-mass eigenstates.

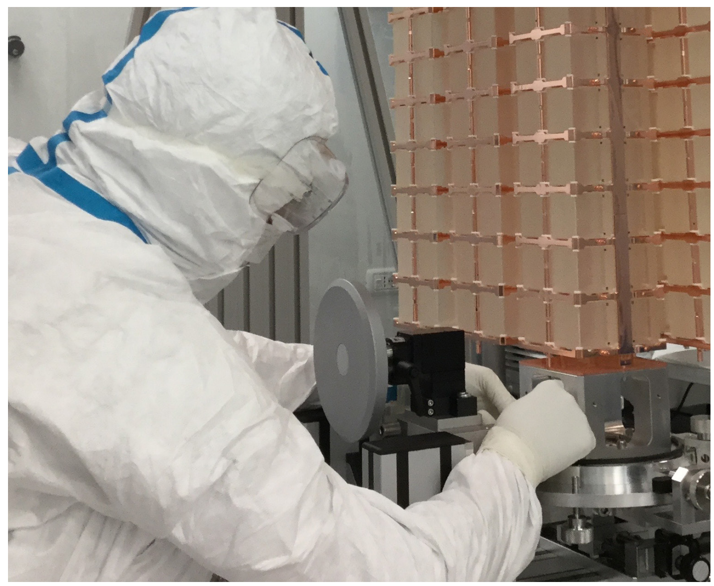
The USC group was deeply involved in the construction of the CUORE double-beta decay experiment in the Gran Sasso Laboratory from the very beginning. CUORE is an array of ~750 kg of TeO_2 cryogenic detectors operating at ~0.008-K. It began operation recently and is performing well and taking physics data. The USC group's main construction responsibility was the fabrication of the front-end electronic system led by Carl Rosenfeld. The USC group has been maintaining a presence of students and staff at the Gran Sasso Laboratory year-round since 2001.

When Jeff Wilson joined the USC Particle Astrophysics Group, he brought computational expertise in Monte Carlo simulations using GEANT and the most up-to-date data analysis techniques. He previously worked on data analysis for the BaBar experiment at the Stanford Linear Accelerator Collider (SLAC) facility. Jeff has guided several graduate students in their orientation to the CUORE computational tools. Our group is applying a new concept of using the CUORE array to study the decay of ^{130}Te to the first excited 0^+ state in ^{130}Xe followed by a gamma-ray cascade to the ground state. By tracking these gamma rays, it is possible to essentially eliminate the background. Our group introduced this technique to the Collaboration by applying it to data from the first prototype experiment, CUORICINO. Jeff Wilson is guiding Christopher Alduino in carrying out the complex simulations needed to compute the efficiencies of the many possible gamma-ray interaction scenarios and the design of the associated data analysis codes. Kevin Wilson previously worked with Rosenfeld and Avignone playing a major role in the fabrication of the CUORE electronics. He is now a graduate student in the group.

Our group also played a leading role in development of the MAJORANA DEMONSTRATOR, led by Vincente Guiseppe. The DEMONSTRATOR research and development project was designed to establish the feasibility of building and operating a ton-scale ^{76}Ge double-beta decay experiment. The principal technology being used in MAJORANA is a vastly improved version of the IGEX experiment, which was led by the USC group in the 1990s. Currently, the collaboration is operating two detector modules containing 45 kg of Ge, including 30 kg enriched to 86% in ^{76}Ge, within a low background shield. Clint Wiseman spent significant time on-site preparing the detectors for their final deployment in the shield, loading and installing of the strings of Ge detectors that form the detector array inside the vacuum cryostat module, and fine-tuning the detector electronics to optimize their performance. Prof. David Tedeschi leads the experiment's data production and chairs the data quality committee to ensure analysis-ready data is collected in a timely manner. Graduate student David Edwins leads the run selection task with responsibility over maintaining a good run list and calculating the experiment's live time and exposure. Prof. Vincente Guiseppe is a Co-Spokesperson of the MAJORANA Collaboration and continues to manage the operation of the experiment's mechanical systems and contributes to data analysis topics. MAJORANA collaborator's



The MAJORANA DEMONSTRATOR array of enriched Ge detectors held in place by low-background holders made from underground electroformed Cu. Photo Credit: Sanford Underground Research Facility



A CUORE researcher constructing the towers of bolometers at LNGS.

analysis effort resulted in two recent publications on its sensitive search for neutrinoless double-beta decay of ^{76}Ge. Clint Wiseman studied the low-energy response of the detectors to understand the sensitivity to new physics, such as interactions with dark matter or solar axions. Clint is now a postdoctoral research associate at the University of Washington.

Recently, members of the Majorana and GERDA collaboration, another experiment looking for decay in ^{76}Ge, formed the next-generation LEGEND collaboration. LEGEND will combine detectors and the best technologies from both MAJORANA and GERDA in the existing GERDA cryostat at LNGS in Assergi, Italy. These existing detectors will be supplemented by new detectors for a total of 200 kg of enriched Ge. This is anticipated to be the first step in the construction and operation of a ton-scale, ^{76}Ge double-beta decay experiment. The group looks forward to an exciting future working on the cutting edge of particle astrophysics.

Theoretical Physics Group

Members: Brett Altschul, Alessandro Baroni, Vladimir Gudkov, Pawel Mazur, Matthias Schindler

It is our great pleasure to congratulate postdoctoral researcher Alessandro Baroni on being the recipient of the 2018 Jefferson Science Associates Thesis Prize for the best Jefferson Laboratories-related thesis completed in 2017. Dr. Baroni was awarded the prize for his thesis on "Nuclear chiral axial currents and applications to few-nucleon systems," completed at Old Dominion University under the supervision of Professor R. Schiavilla. Dr. Baroni traveled to Jefferson Lab in June 2018 to receive his award and to present his work at the annual JLab Users Group meeting.

The search for violations of fundamental symmetries, such as parity and time-reversal invariance, continue to be a central research focus of the group. Both Drs. Gudkov and Schindler are involved in a variety of projects to study symmetry violations in nuclear systems and their theoretical work supports several experimental programs in the US and abroad. Drs. Gudkov and Schindler presented their research at an array of workshops and conferences, including at the National Institute of Nuclear Theory in Seattle, WA, and the Kavli Institute for Theoretical Physics in Santa Barbara, CA, as well as in France, Germany, and Japan.

In the spring of 2018, Richard DeCosta, a graduate student working with Dr. Brett Altschul, published a paper in Physical Review D as the first author. The paper, "Mode analysis for energetics of a moving charge in Lorentz- and CPT-violating electrodynamics," provides a detailed solution of a recent puzzle that Dr. Altschul had uncovered in his research. In the extremely exotic theories of CPT-violating beyond the standard model physics that Altschul studies, it may be possible to have Cerenkov radiation (emission of the single photon by charge moving with a constant velocity) in vacuum, because the speed of light is not necessarily the same in all directions. Charges moving faster than the speed of light in the direction of motion can produce a "sonic boom" of light. This is a well known phenomenon in solid matter, where photons are slowed down by interactions with the medium, but it takes a violation of the boost invariance of special relativity for it to be possible in vacuum.

However, Prof. Altschul uncovered a situation in which the energy radiated by a moving charge appeared to always be zero, even when vacuum Cerenkov emission was possible. DeCosta's paper demonstrated that the reason for this is that some of the emitted electromagnetic waves do carry energy, but the longest-wavelength waves actually carry negative energies (something that cannot happen in conventional electrodynamics). The zero net energy loss was thereby shown to be a result of a cancelation between the energies carried by the positive- and negative-energy modes.

In the summer of 2018, Dr. Altschul served on the faculty of a summer school for graduate students and post-doctoral researchers at the Indiana University Center for Spacetime Symmetries. He prepared two high-level lectures of aspects of the CPT violating physics related to his (and Dr. Schindler's) research and was asked to fill in with a third lecture when one of the other summer school faculty members was unable to attend.

Dr. Camilo Posada-Aguirre, a former graduate student in our group, is now a post-doctoral fellow working with the relativistic astrophysics group (RAG) of Professor Z. Stuchlik at the Opava University in the Czech Republic.

Professor Pawel O. Mazur's work on the macroscopic quantum nature of supercompact objects known as (astro-)physical black holes, or gravastars, is well known. It has been cited 663 times as of October 15, 2018 (Google Scholar Citations). Rotating gravastars are physical black holes with a regular interior, and they are the final state of gravitational collapse of matter. In the interior of a gravastar, a new state of matter forms in the final phase of gravitational collapse of matter: the Bose-Einstein condensate. Thus, one may think of the spinning gravastar, whose exterior gravitational field is described by the celebrated Kerr metric, as a spinning droplet of a superfluid. The black hole uniqueness theorem does apply to the exterior gravitational field. The problem of finding the source of the Kerr black hole has now been solved for the rapidly rotating case. This required the proper handling of the highly nonlinear equations describing the superfluid interior of a spinning gravastar.

SPECIAL ARTICLES

Undergraduate Ben Ranson demonstrates torque and angular momentum with a student holding a spinning tire while atop a rotating platform.

Graduate student Doug Adams demonstrates electromagnetic induction by launching an aluminum ring into the air using a coil of wire with an iron core.

Midway Physics Day 2018 — Another Great Year in the Books

By Sam Beals

The annual South Carolina State Fair has come and gone once again and we enjoyed an excellent Midway Physics Day with over 2,500 students and 60 schools represented from around South Carolina. From senior-level IB Physics to ninth-grade Physical Science courses, many high schoolers initially attend Midway Physics Day understanding some of the technical aspects of physics, but, afterwards, the practical component often comes alive like never before.

For the fourth year in a row, our event was preceded by hurricanes (Florence and Michael), which sadly caused catastrophic damage across the Carolinas, resulted in numerous school closures, and prevented a number of our regular attendees from joining us for our department's largest outreach event. However, we were fortunate to still host a very large group of science teachers and their classes as they came out for a fun afternoon of "real physics" demonstrations led by over 20 departmental faculty, staff, and student volunteers. A very special thanks goes out to faculty coordinators Jeff Wilson and Dave Tedeschi for their leadership and relentless enthusiasm to make Midway Physics Day a great experience for everyone involved each year.

Longtime participant Dani Stroud from Gilbert High School introduced attendees to a unique and innovative resource known as Google Science Journal. This exciting phone app allowed participants at Midway Physics Day to transform their devices into powerful measuring tools as they recorded various data and observations on popular fair rides such as the ferris wheel, roller coaster, rotating swings, and many more. Google Science Journal was unleashed to a number of attendees at our teacher training session prior to the fair, which turned out to be a big hit. Our follow-up evaluations revealed that Google Science Journal brought an entirely new dimension to fair physics for both the teachers and students. We hope to implement similar technology at future events.

The State Fair will celebrate its 150th anniversary in 2019 and we are already looking forward to being part of the fun once again! We always appreciate the continuous support of the Fair's general manager, Nancy Smith, and her wonderful team as they help provide a creative outlet for science students from across our state to better understand and appreciate the subject of physics year after year.

Society of Physics Students

By Yanwen Wu and Eric Rohm

This year, the USC campus saw the liveliest, most engaged, and active SPS group yet! Physics is an extremely tough field and it can be overwhelming to freshmen students just entering and facing college life for the first time. For some, it can be too much, leading them to choose a different major. The retention rate of physics majors at our university has historically been on the low side, an issue that was at the forefront of our efforts this year. Our goal was to speak to freshmen very early on in the semester to inform them about the supportive network of colleagues and opportunities within our chapter of SPS. Club officers went to first-year physics classes to speak to students and distributed informational flyers around the department. To keep newcomers and returning members engaged, we stay very active throughout the academic year.

SPS members judge projects at a local science fair. From left to right: Camille Yoke, Shamar James, Dr. Yanwen Wu, Alan Rowland, and Eric Rohm.

This year, SPS has met on a weekly basis to discuss news, upcoming events, and the overall well-being of our members. In the first meeting, a general interest gathering open to all students, we discussed the mission of the organization and the ways in which members could benefit. Our meetings have become heavily interactive with the USC community. We have had several expert guest speakers visit and talk with our group about various pertinent physics topics. During one meeting, Dr. Matthias Schindler, an Associate Professor of Physics at our university, came to answer our questions about the department and ask us some questions about the department's means of advertising the Physics and Astronomy program. On another occasion, Dr. Rick Creswick, another Professor of Physics here, gave a thorough presentation about graduate school in physics and the complete process of applying and choosing a concentration. Over a series of weeks, our faculty advisor, Dr. Yanwen Wu, went through a "career toolkit" and gave a broad overview of the many places you can go with a degree in physics. The speakers aren't all professors, however. Two recent USC graduates, Annastasia Haynie and Zachary Davis, came to present their experiences in preparing for, taking, and surviving the GRE Physics Subject Test, along with their processes of applying to Ph.D. programs in physics across the nation. On another occasion, Bryan DeMarcy, a former SPS member and physics graduate, came to present about the outreach opportunities provided by his new position as the Observatory Outreach Manager at the South Carolina State Museum here in Columbia. Meetings are a great time for professional growth as well. Andrew Dunton and Annastasia Haynie both gave mock presentations of posters that they created for research they pursued in recent months. Professors and students alike were able to attend and give constructive feedback as well.

Meetings were not always just business! Periodically, we held social nights for playing board games, getting ice cream, and eating pizza. We let a fun night make us some money once with our annual "Group Raise" meal at a local campus restaurant, Uncle Maddio's Pizza, in order to raise proceeds for our future activities. We were delighted to see many professors, staff members, students, and friends come to support us that night. Some professors also made direct donations to our organization through the organization's fundraising efforts. There has been no shortage of campus activities for our group this year!

Alumni News — From Ohm's Law to Tort Law

By Kyle Hair

Studying the laws of thermodynamics one year and studying the laws of contracts the next may sound like a strange change of pace. The truth is, going to law school after receiving a B.S. in Physics is a smoother transition than one might think. My undergraduate experience in the University of South Carolina's Physics and Astronomy department gave me a unique and helpful foundation for pursuing a J.D. from the South Carolina School of Law.

Late into my junior year of college, I still did not have a plan for what kind of career I wanted. I had an engineering internship and was still considering a graduate degree in physics, but I really was not sure what I wanted to do long-term. My dad suggested that I take the LSAT. He's a lawyer, so I grew up with the idea of perhaps going to law school. But when I decided to study physics, I mostly put that idea out of my mind. After all, I considered physics and law completely unrelated.

I wanted to at least humor my old man, so I met with a couple of attorneys who litigate patents. Both had engineering degrees and told me that their practice was an intersection of science and law. They both seemed to genuinely enjoy it and I left thinking that I might finally have an idea of what I wanted to do.

Eventually, I decided to take the LSAT and pursue law school at the South Carolina School of Law. I could not be happier with my decision. The work and material is very different, but I was more prepared for the task than I thought I would be. I think that was due, in large part, to the great professors and courses in the Physics and Astronomy department. Specifically, doing research and crafting a thesis paper under Dr. Guiseppe really helped me grow as a student into someone who was up for the challenge of law school. It was also a relief to find out that no single major can really prepare anyone for law school. Law school is a unique experience and everyone starts from scratch, equally terrified. I went to school confident that I wanted to be a patent lawyer, but after one year of classes, I enjoy numerous aspects of law school. I still have a heavy interest in patent law and intellectual property, but my experience so far has opened my mind to a lot of different opportunities and career paths.

I am now in my second year of law school. I have associate positions at two law firms for next summer. One is at Duane Morris' office in Atlanta, GA that focuses on patent litigation, so I have the chance to learn about the practice area that brought me to law school in the first place. The other is at Haynsworth Sinkler Boyd in Charleston, SC, where I will get to work in a variety of practice areas. Wherever I end up, I plan to take the valuable experience I gained in South Carolina's Physics and Astronomy department to the practice of law. I would encourage others who are undecided on a career path, with that ominous graduation date looming, to consider law school. While it is not the most traditional route for a physics student, it was the right route for me.

Alumni News — Mining for Dark Matter

By Nicholas Chott

For those of you who don't know me, I graduated from USC in December 2016 under the advisement of Dr. Frank T. Avignone III. Over the course of my graduate career, I spent a significant amount of time at the Laboratori Nazionali del Gran Sasso (LNGS) in the Abruzzo region of Italy during the construction, commissioning, and detector optimization phases of both CUORE and the smaller scale CUORE-0 experiment. This opportunity allowed me to gain invaluable experience, related to both hardware and data analysis, that is applicable to other neutrino and dark matter experiments.

Upon entering graduate school, I wasn't exactly sure what I wanted to do research-wise. I was mainly interested in particle physics and cosmology and knew that I preferred the more hands-on approach that experimental physics had to offer. Almost immediately, I began doing research with Dr. Avignone

Dr. Nicholas Chott participates in a recent spelunking trip to Grotta a Male in Assergi, Italy.

on CUORE as a member of the USC Particle Astrophysics group. Prior to passing the Admission to Candidacy exam, most of my time was spent on campus where I focused on classwork and TA obligations. During the summers, however, Dr. Avignone would send me to LNGS for one or two months mainly to participate in shifts, help out where manpower was needed (i.e. "grunt work"), and familiarize myself with the experiment. After passing the A to C exam, I re-located to Italy for the better part of two years to help with the construction of CUORE as well as the building and operation of CUORE-0.

As an experimental physicist, my research experience is related to both hardware/R&D and data analysis. One of my primary hardware related activities involved the construction and commissioning of the CUORE cryostat, sometimes referred to as the "coldest cubic meter in the known universe." During this time, I learned a great deal about vacuum systems, thermometry, as well as operating and maintaining cryogenic systems. I also gained invaluable experience assembling, installing, operating, and analyzing data of low-temperature detectors. As for physics analysis, my research has focused on experimental searches for neutrinoless double beta ($0\nu\beta\beta$) decay and solar axions with TeO_2 bolometric detectors. In particular, I performed analysis on available TeO_2 low-energy data to search for solar axion signals produced via two different mechanisms. The method of detection for both searches relied on the axioelectric effect in TeO_2 bolometers. The first analysis searched for a solar axion signal from the characteristic $K_{\alpha1}/K_{\alpha2}$ X-rays of Fe; the first experimental search for axions generated from atomic transitions in the solar core. The second analysis searched for an axion signal generated from the M1 ground state transition of ^{57}Fe in the sun.

In June 2018, I began my current position as a post-doctoral researcher within the Experimental Dark Matter group at the South Dakota School of Mines and Technology (SDSM&T), working on two next-generation dark matter experiments: the LUX-ZEPLIN (LZ) experiment and the Super Cryogenic Dark Matter Search (SuperCDMS). The SDSM&T Dark Matter group is one of 37 institutions working on LZ and one of 26 institutions on SuperCDMS. The LZ experiment is located in the Davis cavern at the Sanford Underground Research Facility (SURF) in Lead, South Dakota (formerly the Homestake gold mine) where Ray Davis performed his Nobel Prize winning neutrino experiment. SuperCDMS is being constructed in Canada at the Sudbury Neutrino Observatory Laboratory (SNOLAB) in Sudbury, Ontario. Both experiments are currently under construction at their respective underground facilities and will begin operations in the early 2020s, searching for Weakly Interacting Massive Particles (WIMPs).

The group at SDSM&T is tasked with building, commissioning, and installing radon reduction systems (RRS) for each experiment, used to provide low radon air to clean spaces during construction. Radon and its daughters are one of the main sources of background in sensitive dark matter and neutrino experiments, specifically ^{222}Rn. Due to its gaseous nature, radon can travel long distances and diffuse into gaps before decaying and leaving long-lived daughters behind on sensitive detector components. In addition to operating these sensitive detectors deep underground to reduce the background from cosmic rays, they also need to limit the radon in the air that could contaminate and throw off the experiment. These radon reduction systems will take regular air from the facility (already safe for humans) and will reduce the levels by 1,000 times or more to ensure the cleanest possible environment for the best overall results.

As for the future, I'm not really certain what is in store for me. While in graduate school, I always intended to stay in academia as a post-doctoral researcher with the hope it would lead to a permanent position. However, as I've never had a desire to be a professor, I plan to try to go the research scientist route. Although, at times, the idea of transitioning to industry can be quite alluring, where the hours and pay are better, I often wonder if that would just be a "grass is always greener" kind of feeling. Ideally, I would like to pursue further research in the scope of neutrino and dark matter physics.

Pursuing a Ph.D. in Physics at the University of South Carolina has been one of the most challenging (and stressful) experiences of my life, but also one of the most rewarding. It has led to opportunities and experiences that I would have never thought possible during my high school years and undergraduate physics career. I consider myself lucky to have been a part of it and am proud to call myself a Gamecock.

Quantum Leap

Department of Physics and Astronomy
University of South Carolina
712 Main Street, PSC #404
Columbia, SC 29208

Telephone: 803-777-8105
Fax: 803-777-3065
Email: beals@mailbox.sc.edu
www.physics.sc.edu

Non-Profit
Organization
U.S. Postage
PAID
Permit #766
Columbia, SC

Chair:
Ralf Gothe

Director of Graduate Studies:
Vladimir Gudkov

Director of Undergraduate Studies:
Jeffrey Wilson

Editors:
Sam Beals
Vincente Guiseppe

Layout & Design:
David Bishop

Space Elements imaged by Alex Mowery from the Melton Observatory

UNIVERSITY OF
SOUTH CAROLINA