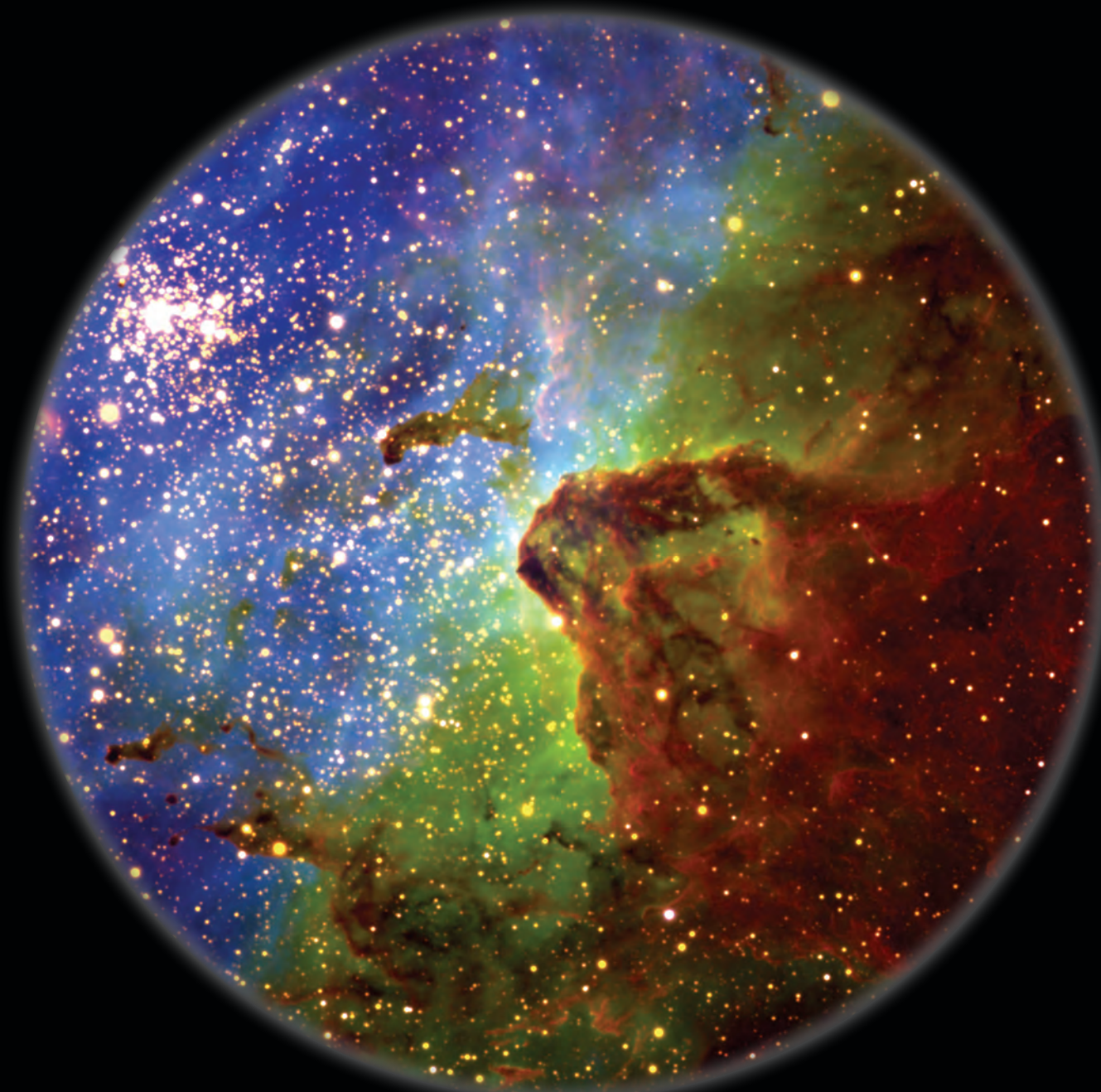


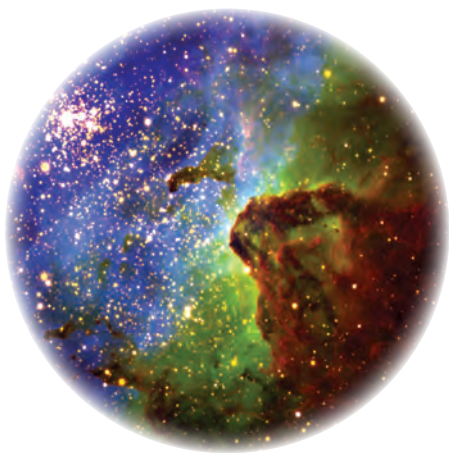
# STEWARDSHIP SCIENCE ACADEMIC ALLIANCES ANNUAL

Stewardship Science Academic Alliances

High Energy Density Laboratory Plasmas

National Laser Users' Facility





## On the cover

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A color composite (red=H2, green=HI, blue=OIII) of a small portion of Carina shows the spectacular structures that result when radiation from massive stars interacts with molecular globules that harbour newborn stars.

*Image Courtesy of Patrick Hartigan, Rice University, taken with the 4-m NOAO telescope at Cerro Tololo, Chile*

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2012

STEWARDSHIP SCIENCE  
ACADEMIC ALLIANCES ANNUAL

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Stewardship Science Academic Alliances

High Energy Density Laboratory Plasmas

National Laser Users' Facility



Mission First...  
Through Teamwork

*“I am so proud of our Stewardship Science Academic Alliances (SSAA) grant programs” is a common refrain of mine as I give briefings to Congressional members and their staff, and to senior leadership at the U.S. Departments of Defense and Energy as well as to the NNSA Administrator. Clearly, the value of our programs can be successfully measured by the extraordinary quality of students, the enthusiasm of the program participants, and by their numerous high impact papers and impressive research.*

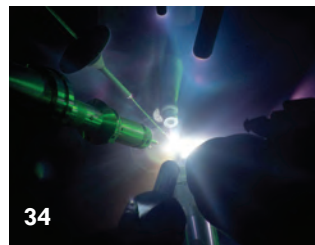
*Recently, while reading the February 2012 issue of “Scientific American,” I realized academic programs do much more. In the article entitled, “Graphic Science: How Science Degrees Stack Up,” data is presented on the change in degrees awarded over the last 20 years. There has been significant growth in non-STEM (science, technology, engineering and math) degrees versus only modest growth in STEM degrees. The article also mentions that in addition to the slow STEM growth rate, industry suffers a shortage of STEM graduates because “...people with STEM degrees often choose jobs in other fields....” Now in its 10th year, the NNSA SSAA Program, by the nature of the practicums, networking opportunities, and experiments at large NNSA facilities, helps to reverse the exodus of those trained in STEM to fields outside of these disciplines. The SSAA Program demonstrates that challenging and rewarding jobs that directly impact national security can be found in our unique national laboratories. This is a wonderful benefit for our laboratories and for our Nation.*

*I thank the NNSA program teams that make the SSAA a success and I look forward to seeing the Stockpile Stewardship Program of 2030 led by the alumni of SSAA, SSGF, NLUF and joint programs in HEDLP!*

*Dr. Christopher Deeney  
Assistant Deputy Administrator  
for Stockpile Stewardship*

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#### Publication Editors

Terri Batuyong, Millicent Mischo

#### Technical Editors

Mike Kreisler, Chris Werner, Alan Wootton

The *Stewardship Science Academic Alliances Annual* is a yearly publication of the DOE/NNSA Office of Stockpile Stewardship. It features select research conducted via the following NNSA-supported research programs: Stewardship Science Academic Alliances, High Energy Density Laboratory Plasmas, and National Laser Users' Facility. For more information, visit the NNSA website: <http://nnsa.energy.gov/about/ourprograms/defenseprograms/stockpilestewardship>.

Published February 2012

# SSAA

*Stewardship Science Academic Alliances*

The National Nuclear Security Administration's (NNSA's) Office of Stockpile Stewardship developed the Stewardship Science Academic Alliances (SSAA) Program to support research vital to the nation's Stockpile Stewardship Program. Since its inception in 2002, the SSAA Program has supported hundreds of students at universities across the United States, with approximately 100 students going on to pursue careers at NNSA's national laboratories, and produced more than 2,500 peer reviewed publications.

The SSAA Program supports U.S. scientific research at universities in the areas of fundamental science and technology of relevance to stockpile stewardship, with a focus on those areas not supported by other federal agencies, and for which there is a recruiting need within the NNSA laboratories. Through this program, we are able to offer the highest caliber of education and hands-on training to the next generation of scientists, physicists, and engineers.

This year's 2012 SSAA Annual provides an overview of the research areas supported under the SSAA Program. Within each research area, one Center of Excellence is featured along with highlights from the other Centers, as well as highlights from four grants. These highlights discuss some of the exciting experimental and theoretical results from the past 12 months. The grants programs are the SSAA Grants Program, High Energy Density Laboratory Plasmas Program, National Laser Users' Facility Grants Program, and the Stewardship Science Graduate Fellowship Program.

## ***Stewardship Science Graduate Fellowship Program***

The Stewardship Science Graduate Fellowship (SSGF) Program supports PhD students in science and engineering in areas of interest to stockpile stewardship. The program provides a yearly stipend, tuition and fees, a yearly academic allowance, and the opportunity to complete a 12-week practicum at a NNSA laboratory. This program is administered by the Krell Institute. Visit [www.krellinst.org/ssgf](http://www.krellinst.org/ssgf) for more information.



2011 SSGF Class: (L-R) Christopher Young (Stanford University), Walter Pettus (University of Wisconsin-Madison), Jennifer Shusterman (University of California, Berkeley), Adam Cahill (Cornell University), Geoffrey Main (Stanford University), and John Gibbs (Northwestern University).

## ***SSAA Grants Program***

The SSAA Grants Program was created to support fundamental science at U.S. universities in the areas of properties of materials under extreme conditions and hydrodynamics, low energy nuclear science, and high energy density physics. In 2012, radiochemistry was added with an emphasis on studies of the heavier elements including actinides. Along with grants, this program supports NNSA's Centers of Excellence. Each Center of Excellence consists of a multi-investigator team that addresses an overarching theme or themes of interest to the SSAA Program.

## **2011 SSAA Symposium**



NNSA Administrator Tom D'Agostino (left) and Devesh Ranjan, Texas A&M University.



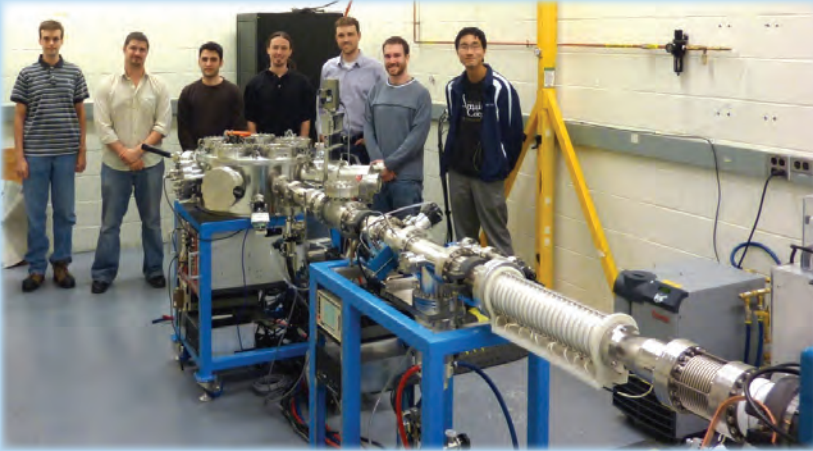
Rick Kraus of Harvard University (left) and Chris Deeney, Assistant Deputy Administrator for Stockpile Stewardship, NNSA.



Brian Maple of the University of California, San Diego (left) and Keith LeChien, SSAA Program Manager, NNSA.

## High Energy Density Laboratory Plasmas Program

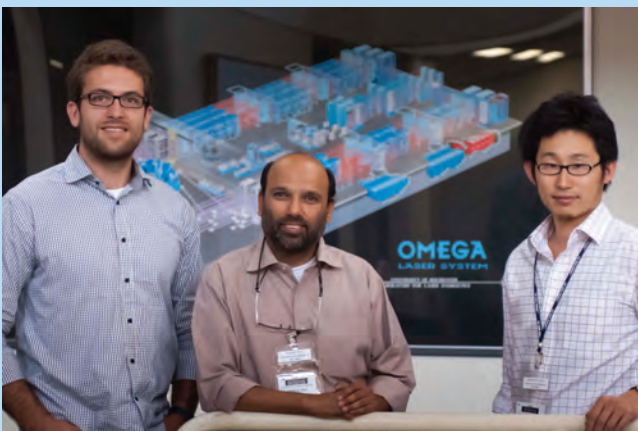
The High Energy Density Laboratory Plasmas (HEDLP) Program, established in 2008, is a joint program with NNSA's Office of Inertial Confinement Fusion and DOE's Office of Science. HEDLP science is the study of ionized matter in laboratory experiments where the stored energy reaches approximately 100 billion Joules per cubic meter, or equivalently the pressure is approximately 1 million atmospheres. Currently, the areas emphasized are high energy density (HED) hydrodynamics, radiation-dominated dynamics and material properties, magnetized HED plasma physics, nonlinear optics of plasmas and laser-plasma interactions, relativistic HED plasmas and intense beam physics, and warm dense matter.



Massachusetts Institute of Technology (MIT) PhD students posing with the MIT Linear Electrostatic Ion Accelerator. (L-R) Alex Zylstra, Mario Manuel, Nareg Sinenian, Daniel Casey, Caleb Waugh, Mike Rosenberg, and Hong Sio.

## National Laser Users' Facility Grants Program

The National Laser Users' Facility (NLUF) Grants Program's primary purpose is to provide facility time for university- and business-led high energy density experiments on the University of Rochester/Laboratory for Laser Energetics's Omega Laser Facility. Through the NLUF Grants Program, one of NNSA's major high energy density facilities, the Omega Laser Facility, is accessible to a broad community of academic and industrial research interests, for use as a tool for conducting basic research experiments in both low and high energy density physics and laser-matter interactions; and in providing research experience necessary to maintain a cadre of trained scientists to meet the nation's future needs in these areas of science and technology.



Professor Farhat Beg (center) of the University of California, San Diego, and his team, postdoctoral fellow Hiroshi Sawada (right) and graduate student Charlie Jarrott (left), work on the integrated fast ignition experiment on OMEGA/OMEGA EP at the Laboratory for Laser Energetics.

## SELECT AWARDS

### 2012 Tom W. Bonner Prize in Nuclear Physics

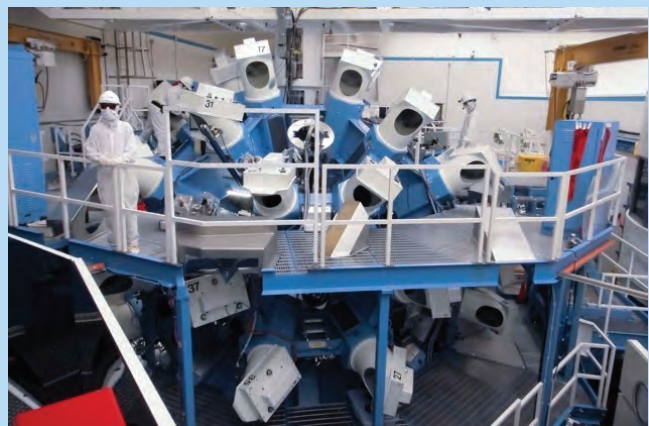
Witold Nazarewicz of the University of Tennessee received the esteemed award "for his foundational work in developing and applying nuclear Density Functional Theory, motivating experiments and interpreting their results, and implementing a comprehensive theoretical framework for the physics of exotic nuclei." For more information, visit <http://www.aps.org/units/dnp/awards/bonner.cfm>.

### Massachusetts Institute of Technology, Richard D. Petrasso

Three National Ignition Facility and Photon Science Awards were received by MIT staff and students for "outstanding contributions in designing and implementing diagnostics that have been essential to the progress of the National Ignition Campaign." The awards were for advanced neutron spectrometer (Dr. Johan Frenje), particle time-of-flight detector (student Hans Rinderknecht), and proton spectrometer (student Alex Zylstra).

### University of Colorado at Boulder, Henry Kapteyn and Margaret Murnane

The 2012 Willis E. Lamb Award for Laser Science was awarded to Henry Kapteyn and Margaret Murnane of the University of Colorado at Boulder. The Willis E. Lamb Award for Laser Science and Quantum Optics is presented annually for outstanding contributions to the field.



Graduate Student Christine Krauland, University of Michigan, in the Laser Bay at the Omega Laser Facility.

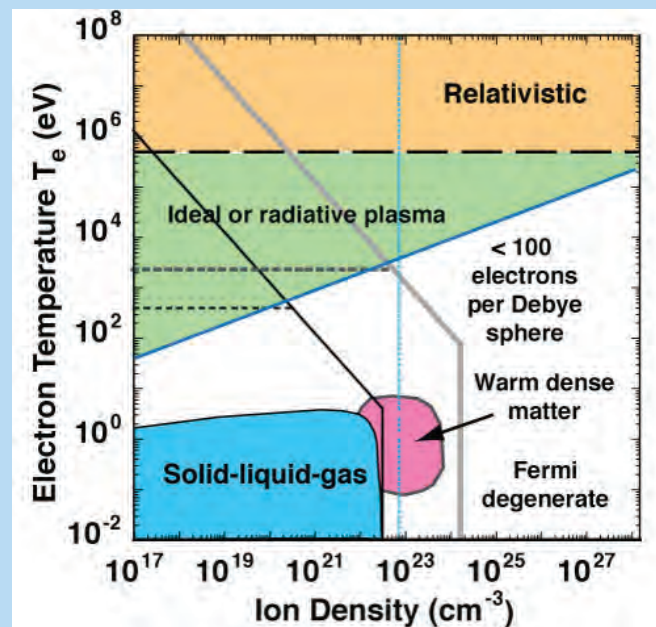
# HEDP

High Energy Density Physics

High energy density physics (HEDP) is an emerging interdisciplinary field that draws on many subdisciplines of physics such as plasma physics, laser and particle-beam physics, nuclear physics, astrophysics, atomic and molecular physics, materials science and condensed matter physics, intense radiation-matter interaction physics, fluid dynamics, magnetohydrodynamics (MHD), radiation hydrodynamics and, at very high temperatures, high energy physics. A National Research Council study of HEDP<sup>1</sup> proposed a definition of the HED regime as energy densities exceeding  $10^{11}$  Joules per cubic meter ( $J/m^3$ ). This is equivalent to pressures greater than 1 megabar (Mbar), electromagnetic wave intensities exceeding  $3 \times 10^{15}$  watts per square centimeter ( $W/cm^2$ ), or static magnetic fields exceeding 500 Tesla (T). Some of the boundaries of this parameter space<sup>2</sup> are shown in Figure 1, which provides a map of density-temperature space with the HED region to the right and above the solid black line (pressure = 1 Mbar). Above the knee in this curve, we find pressure proportional to the product of density and temperature. Below the knee is the Fermi-degenerate regime, and pressure is density-independent. The regime where radiation pressure is greater than 1 Mbar is above the broken horizontal black line. Between the broken and solid black lines, a mixture of radiation and matter that is optically thick has pressures near 1 Mbar. The grey lines describe similar boundaries as do the black lines, but for pressures near 1 gigabar (Gbar). The seminal textbook by Zeldovich and Raizer<sup>3</sup> presents much of the science that underpins modern HED physics.

This physical parameter regime for this field has conditions found in only three places in the space and time of our universe: the Big Bang; the interiors of stars and planets; and thermonuclear weapons.<sup>4</sup> Nothing within orders of magnitude of these extraordinary conditions has been available for laboratory experiments until now. Very high energy lasers and pulsed power machines have enabled laboratory experiments to access much of the HED regime enabling new regimes for study,<sup>5</sup> many of which are of importance to national security. These regimes include radiation sources and radiative properties, hydrodynamics, nuclear astrophysics,

Figure 1. The region in density-temperature space referred to as the High Energy Density regime is above and to the right of the solid black line. Other regions are described in the text. Credit: R. Paul Drake, adapted from Phys. Plasmas 16, 055501 2009.



nonlinear optical physics and other areas of science.<sup>4</sup> Elucidating the physics of high energy density plasmas through experiment, theory, and numerical simulation is of considerable scientific importance in order to understand physical phenomena in laboratory-generated high energy density plasmas and astrophysical systems. Because the field is developing rapidly, a study of compelling research opportunities and synergies among related subfields is particularly pertinent. HEDP is essential in the quest for controlled thermonuclear fusion energy which has spawned two different approaches: magnetic confinement and inertial confinement. Magnetic confinement fusion requires higher temperature but somewhat lower density conditions<sup>6</sup> whereas inertial confinement fusion requires very high material densities and temperatures.

Some of the focus areas of recent HED investigation include<sup>4</sup>:

- Scaled astrophysical investigations, including the study of the evolution and chemistry of condensed matter during planet formation, the study of destruction of clumps of denser matter by radiative shocks, and the study of magnetic field generation in novel regimes.
- The study of the fundamental building blocks of matter and how they interact and combine to form the nucleons, elements, and exotic nuclear states that constitute the observed universe from the Big Bang through its expansion.

- Materials properties under extreme conditions of temperature and pressure such as those found in the interiors of planets, brown dwarfs, and stars.
- Investigation of fluid instability in extreme radiation-hydrodynamic conditions.
- Investigation of nearly collisionless (very large electron kinetic energy) and collisional plasmas.

A particularly interesting example of recent HED research is illustrated in Figure 2. Quasi-isentropic compression of diamond to tens of megabars pressure has opened up new regimes in materials science. An extensive study of the research potential at the National Ignition Facility (NIF) was recently completed which represents a good summary of the exciting frontiers of laboratory HED science.<sup>3</sup>

There is exciting research in HEDP supported by SSAA. Featured in this Annual are articles from the University of Texas-Austin (Principal Investigator [PI]: Todd Ditmire), University of Michigan (PI: Paul Drake), Cornell University (PI: Bruce Kusse), Massachusetts Institute of Technology (PI: Richard Petrasso), University of Nevada, Reno (PI: Aaron Covington), University of Wisconsin-Madison (PI: Riccardo Bonazza), Ohio State University (PI: Anil Pradhan), Harvard University (PI: Stein Jacobsen), and the University of Colorado and JILA (PIs: Henry Kapteyn and Margaret Murnane).

At the NNSA laboratories, there are three primary HED facilities—the NIF laser at



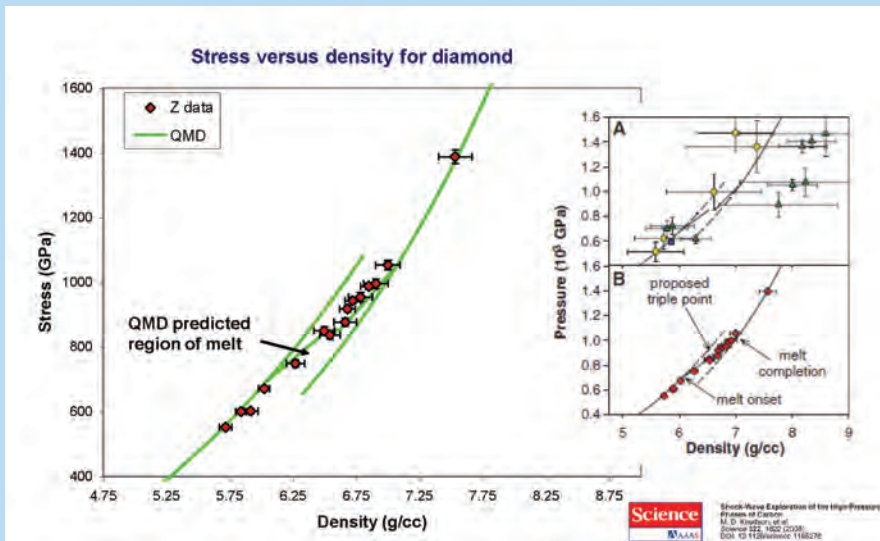


Figure 2. In a thermonuclear weapon, three of four key stages involve the HED regime.

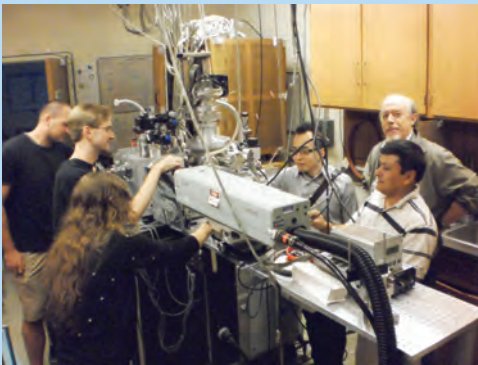


Figure 3. Dr. Victor Kantsyrev's research group at the Plasma Physics and Diagnostics Laboratory at the Physics Department of the University of Nevada, Reno (UNR). L-R: Steve Keim, Glenn Osborne, Veronica Shlyaptseva, Mineyuki Nishio, Ishor Shrestha, and Victor Kantsyrev.



Figure 4. UNR students aligning the laser-based plasma diagnostics system. L-R: Showera Haque, Matt Tooth, and Frank Greenhall.



Figure 5. Gabriel Cossio, a University of Texas at Austin undergraduate student, is shown setting up a pulse autocorrelation measurement on the Texas Petawatt Laser.

Lawrence Livermore National Laboratory, the Z pulsed power machine at Sandia National Laboratories, and the OMEGA Laser Facility at the Laboratory for Laser Energetics, University of Rochester—that are world leading HED research venues. These facilities are actively engaged in the research areas of laboratory astrophysics, nuclear physics, materials at extremes and planetary physics, as well as beam and plasma physics. Both Z and Omega have developed user programs that are expected to grow over the coming decade. Similarly, a user program at the NIF will be strengthened over the coming years.

There are many opportunities in HEDP to learn, participate and contribute to this important new field. The High Energy Density Science Association (HEDSA, visit the webpage at <http://www.hedsa.org/>) is an organization for academic and small business involvement in the field. Workshops and summer schools are now annual events, and an international journal specific to the area, *High Energy Density Science*, is published. Funding opportunities are provided through calls for proposals from NNSA and also, for example, from the Office of Fusion Energy Science and the National Science Foundation.

Many of our academic partners are contributing to the field of HEDP through their exciting research. Figures 3 and 4 showcase our partnership with the University of Nevada at Reno and Figure 5 showcases our partnership with the University of Texas at Austin.

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- <sup>1</sup>National Research Council, *High-Energy-Density Physics: The X-Games of Contemporary Science*, National Academies, Washington, D.C., 2003.
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- <sup>3</sup>Y. Zeldovich, Y. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, Academic Press, 1966.
- <sup>4</sup>*Basic Research Directions for User Science at the National Ignition Facility*, John Sarrao, et al., U.S. Department of Energy / NNSA publication.
- <sup>5</sup>R.P. Drake, *High-Energy-Density Physics*, Springer-Verlag, 2006.
- <sup>6</sup>C. Braams and P. Stott, *Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research*, Institute of Physics, 2002, and Dale Meade, *Nuclear Fusion* 50, 014004, 2010.

## The Texas Center for High Intensity Laser Science

University of Texas at Austin

PI: Todd Ditmire (tditmire@physics.utexas.edu)

The Texas Center for High Intensity Laser Science (TCHILS), a SSAA Center of Excellence at the University of Texas at Austin (UT), is devoted to research in high energy density (HED) physics. TCHILS has during the past year been incorporated into a larger entity within the University of Texas, the Center for High Energy Density Science (CHEDS). CHEDS presently involves five UT faculty members and over 40 staff scientists, support staff, postdoctorates, graduate and undergraduate students. During the past year we have produced a number of exciting scientific results within CHEDS, most notably with the Texas Petawatt Laser, which is presently the highest power laser in the world.

CHEDS focuses on research in high energy density plasmas produced and probed by high intensity, ultrafast lasers. For example, we study the properties of plasmas at solid density and temperatures of over 1 million °C. These exotic plasmas approach the conditions found in the center of astrophysical objects such as brown dwarf stars, and have rather extreme properties, e.g. pressures in excess of a gigabar (1 billion atmospheres). Ultrafast lasers are a unique tool for creating such high temperature, high density plasma states because the laser pulse is so short that it can heat the material on a time scale much faster than it can expand. The same laser pulse, if split and delayed, can then be used as a probe which can provide a stroboscopic snapshot of the plasma before and while it expands, thus yielding information on physical properties like the pressure, ionization state and conductivity of that plasma.

We also study the acceleration of particles to high energies. For example, we are examining the energy spectra and divergence characteristics of protons produced by irradiating a thin foil at high intensity. The multi-mega-electron-volt protons produced have a number of potential applications, including heating and probing HED matter. CHEDS faculty is also working on producing waves in plasmas from the passage of an intense laser pulse through that plasma. Such a plasma wakefield can be used to accelerate electrons to high energies. Just as a surfer gains energy from the ocean by surfing a wave, so electrons can gain energy from the plasma by surfing a plasma wave. We use a femtosecond (fs) pulse to create

the plasma wakefield, and predict to accelerate electrons to many gigaelectron volts (GeV). These electron energies, if achieved, would be within 10% of the energy of electrons accelerated by the 3 km long accelerator at the Stanford Linear Accelerator Laboratory (SLAC). While such plasma wakefield accelerators require many improvements before they could ever replace well established technology like that employed at SLAC, it is nonetheless tantalizing if laser-driven plasma wakefields could be demonstrated at the many GeV level.

Another major thrust of CHEDS research involves generating fusion neutrons from the intense laser irradiation of gases of atomic clusters. In these experiments, we focus a femtosecond (fs) laser pulse into a pulsed jet of deuterium gas, which has frozen out into tiny ice droplets which are usually called clusters. When the laser strikes these clusters, they explode

violently, and ions from neighboring clusters can collide and fuse. The result is a bright, very short burst of neutrons from the nuclear fusion reactions between deuterium ions. Our goal is to produce sufficient numbers of neutrons to allow probing the dynamics of how such an intense burst of neutrons damage materials.

We have made significant progress in all of these research areas during the past year. The centerpiece research facility for CHEDS experiments is the Texas Petawatt Laser. Figure 1 shows the Texas Petawatt operating; it delivers laser pulses with energy up to 180 J and duration around 140 fs. Figure 2 illustrates the inside of the pulse compressor tank, where the high energy pulses are temporally recompressed down to fs durations. Since our first demonstration of a petawatt of power in 2008, we have worked to make this laser a robust target shooter and a

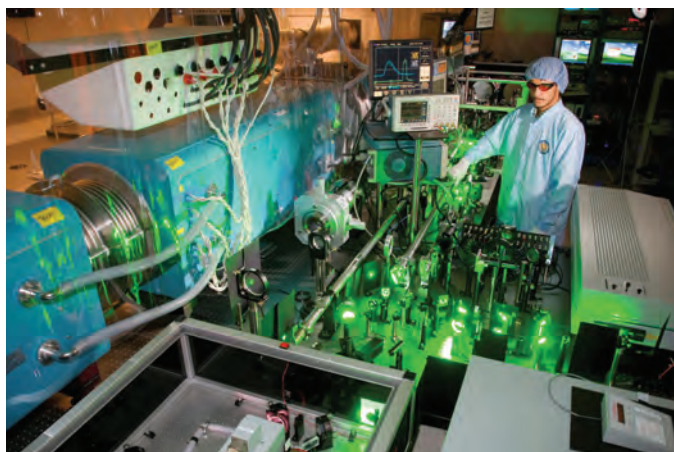


Figure 1. The Texas Petawatt laser bay.

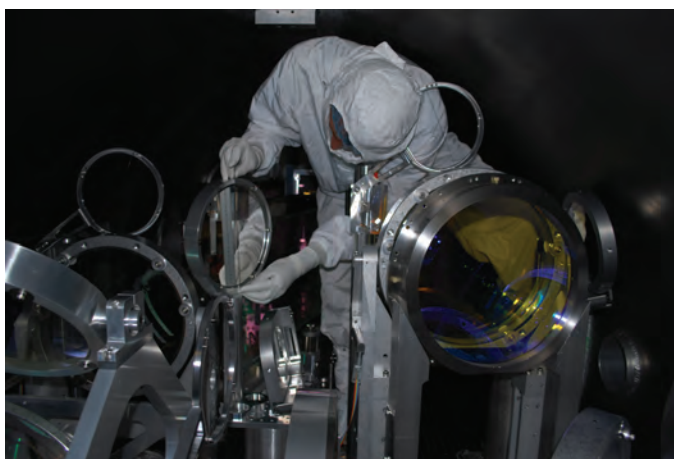


Figure 2. Texas Petawatt Laser staff aligning optics inside the pulse compressor tank.

reliable tool for graduate students and visiting scientists. This year, Dr. Mike Donovan, a former detailee from the Army to NNSA, joined CHEDS as the Facility Director of the Texas Petawatt. He has formed a peer reviewed user-collaborator program on the Texas Petawatt laser. Under this program, the Texas Petawatt has been used by three faculty research groups from within the University of Texas, as well as by visiting researchers from the group of Professor R. Freeman at the Ohio State University, the Cyclotron Institute at Texas A&M University, and the group of Professor Edison Liang at Rice University. Upcoming experiments involve additional collaborations not only with these visiting scientists, but also with scientists from Los Alamos National Laboratory and Lawrence Livermore National Laboratory.

One of the greatest achievements of the Texas Petawatt is the involvement of a very large number of students in the research program. Figure 3 shows students working in the target chamber bay on the cluster fusion experiment, one of the scientific successes of the Texas Petawatt research program in the past year. In this experiment a CHEDS led team (which also involved a number of students and scientists from Texas A&M) demonstrated fusion neutron yields of up to  $2 \times 10^7$  neutrons per shot. This collaboration also succeeded in measuring the ion temperature of the cluster plasma formed by the Petawatt pulse by measuring the ratio of fusion yield between deuterium-deuterium fusion and the deuterium-helium ( $\text{He}^3$ ) fusion reaction. This measurement confirms predictions about the energies of ions ejected from these exploding clusters. Figure 4 shows a photo of the gas jet nozzle used to create the cluster fusion plasma.

There have been other promising results on the Texas Petawatt. Professor Mike Downer of UT succeeded in producing plasma wakefields and observing self-injection of electrons into those wakefields, an unexpected result at the plasma and laser parameters used in the experiment. A collaboration with Rice University examined the hot electron production from irradiation of solid targets at intensities in excess of  $10^{20}$  W/cm<sup>2</sup>; rather high electron energies and potential signatures for positron production have been observed.

Finally, CHEDS is working in collaboration with Sandia National Laboratories (SNL) to expand the involvement of academic groups nationwide in HED

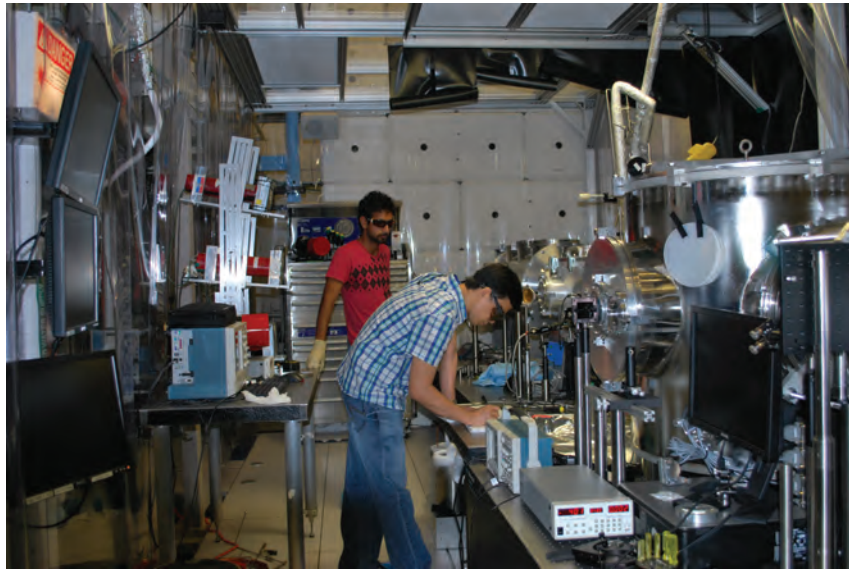


Figure 3. Students preparing for a shot on the cluster fusion experiment in the Target Chamber 2 area of the Texas Petawatt.

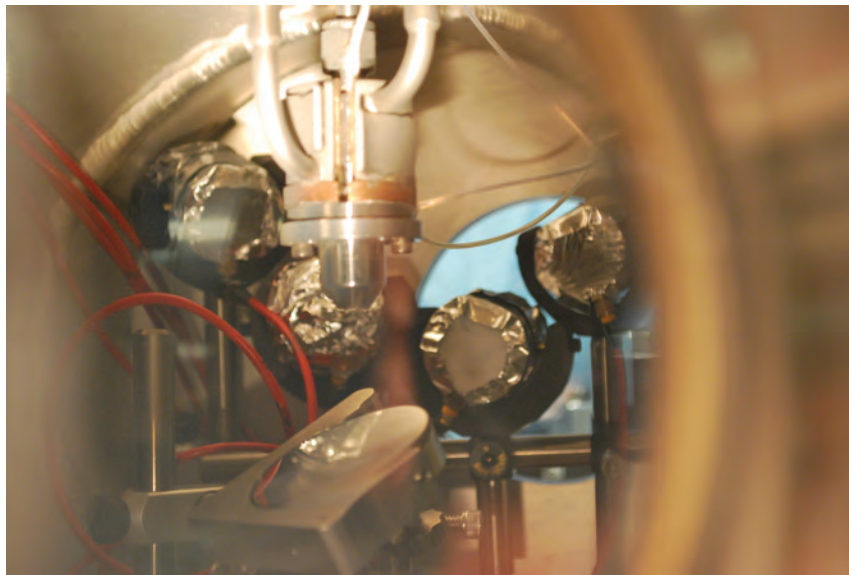


Figure 4. Inside of Target Chamber 2 on the Texas Petawatt showing the nozzle of the cryogenically cooled gas jet that produces deuterium clusters for the cluster fusion experiments.

research, both on the Texas Petawatt and on the Z accelerator at SNL. To this end, a component of CHEDS, the Institute for High Energy Density Science (IHEDS), directed by Dr. Alan Wootton, has been formed as a joint institute with SNL. A series of national workshops has resulted in new experimental work in astrophysics and planetary science, involving new-to-HED scientists and students.

Further information on the Center can be found at <http://www.ph.utexas.edu/~utlasers>. The Texas Petawatt is actively seeking collaborative users for science experiments. CHEDS has instituted a periodic peer review of

proposals for time on the Texas Petawatt. Details can be found on the Texas Petawatt website at <http://texaspetawatt.ph.utexas.edu/>. Information about IHEDS can be accessed at <http://www.ph.utexas.edu/~iheds/>.

**Contact Information**

General questions about CHEDS: Todd Ditmire ([tditmire@physics.utexas.edu](mailto:tditmire@physics.utexas.edu))

Questions about proposing an experiment on the Texas Petawatt Laser: Mike Donovan ([mcdonovan@physics.utexas.edu](mailto:mcdonovan@physics.utexas.edu))

Questions about IHEDS: Alan Wootton ([wootton1@comcast.net](mailto:wootton1@comcast.net))

## Center for Laser Experimental Astrophysics Research (CLEAR)

University of Michigan

PI: R. Paul Drake (rpdrake@umich.edu)

Experiments performed under high energy density (HED) conditions, where pressures exceed 1 million atmospheres, can be relevant to astrophysical phenomenon. HED facilities, such as the Omega Laser Facility, make it possible to create such conditions. The specific experiment described here explores the contribution of radiative shock waves to the evolving dynamics of binary star-accretion disk systems in which they reside. Radiative shock waves produce shocked matter so hot that it radiates away most of its thermal energy. This radiation causes variable structure to develop depending on the optical properties of the material on either side of the shock. In order to control these properties and understand the shock front emission, we devised an experiment that accelerates a plasma flow into vacuum and then develops a radiative shock when the flow is impeded. We aim to image the system and observe its radiative flux with diagnostics available at the Omega Laser Facility.

This work is motivated by the dynamics of a cataclysmic binary system. In some binary star systems, a reverse shock develops when the supersonic plasma falling from the companion star impacts a denser, flowing, accretion disk around a white dwarf.<sup>1</sup> The morphology surrounding this collision and the time-dependent emission from it are difficult to calculate. This is particularly true when the optical depth of the shocked material can be characterized as intermediate between optically thick and optically thin. While known binary systems span this regime,<sup>2</sup> very few attempts to treat it, in theory or in simulations, have been published.<sup>2,3</sup> Our goal is to take the first steps in experimentally producing the colliding supersonic flow into a denser stream and creating the reverse shock in a laboratory experiment.

These experiments employ a laser configuration of 10 laser beams with a wavelength of 351 nm. Each beam has an energy of 450 J for a total laser energy of 4.5 kJ delivered in a 1 ns square pulse. The laser beams are smoothed by the technique Smoothing by Spectral Dispersion and distributed phase plates so that speckles remain on the 5  $\mu\text{m}$  scale. The beams deposit a total energy of  $\sim 4.5$  kJ, giving an average irradiance of  $\sim 1.2 \times 10^{15}$  W/

$\text{cm}^2$ . This generates a laser ablation pressure of  $\sim 75$  Mbars, which is deposited in the initial layers of the target.

The experiment target consists of a 10  $\mu\text{m}$  plastic ablator that is irradiated with the laser. Behind that layer is 5  $\mu\text{m}$  of tin (Sn), which is mounted on one side of an evacuated acrylic tube. The large pressure created by the laser pulse drives a shock into the plastic and Sn layers. After this ablative shock breaks out of the Sn into vacuum, the Sn plasma will expand, cool, and accelerate down the target cylinder at an average velocity of the order of 150 km/s. About 4 mm from the laser drive surface, the Sn ejecta impacts a 100  $\mu\text{m}$  thick, cold Al foil. In response, a reverse shock will develop in the flow and a forward shock will be driven into the Al end wall. The traditional 'upstream' velocity in the shocked system is defined by the Sn flow, which is fast enough that the reverse shock will have radiative effects play a significant role in its dynamics. The dynamics of the system are shown in Figure 1.

An additional 5 laser beams irradiate a zinc foil on an additional target for 1 ns, creating the x-rays used to image the reverse shock onto x-ray film and image plates. To investigate the effects of different flow velocities and oblique collisions, we also shot targets that had varied plastic-Sn thicknesses and tilted the Al foils, respectively. Figure 2 shows an image from a single target, taken  $\sim 29$  ns after the drive laser pulse was turned off and a few nanoseconds after the collision. In this particular target, the aluminum wall is  $\sim 13$  degrees from the normal to

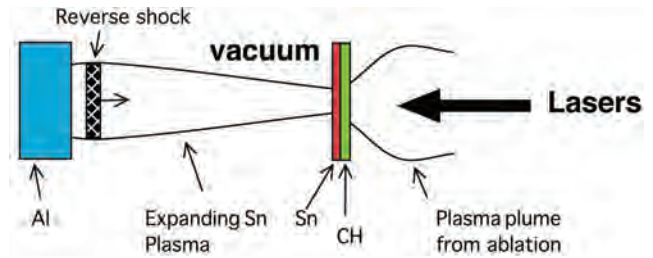


Figure 1. A schematic of the laser experiment. The laser irradiates a thin plastic layer, launching a shock in the plastic and subsequently the tin layer. The plasma flow accelerates until it reaches the cold aluminum wall. The interaction between the plasma flow and the wall create a radiative reverse shock.

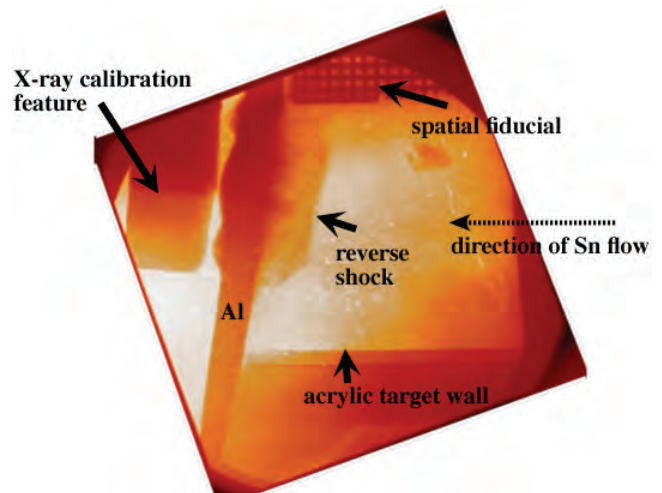


Figure 2. X-ray radiograph of a radiative reverse shock in Sn plasma. One can see the radiating shock, an acrylic tube wall, the spatial fiducial, and the x-ray calibration feature used in the experiment. The reverse shock, which forms in the incoming Sn flow, is to the right of the Al wall where the laser drive is 4 mm away. As the unshocked Sn moves from right to left, it is not dense enough to resolve while the reverse shock absorbs the diagnostic x-rays, revealing its structure.

the tube axis. This work was performed by graduate student Christine Krauland under the guidance of Drs. R. Paul Drake and Carolyn Kuranz.

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- <sup>2</sup>P. J. Armitage and M. Livio, *Hydrodynamics of the Stream-disk Impact in Interacting Binaries*, *Astrophysical Journal* 493, 898 1998.
- <sup>3</sup>M. Rozyczka and A. Schwarzenberg-Czerny, *2-D Hydrodynamical Models of the Stream/Disk Interaction in Cataclysmic Binaries*, *Acta Astronomica* 37, 141, 1987.

## Exploring Matter Under Extreme Conditions Using Pulsed Power Machines

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Cornell's Center for the Study of Pulsed Power Driven High Energy Density (HED) Plasmas studies HED plasmas produced by 0.5-1.5 MA pulsed power generators. During 2011, we focused on investigating the fundamental properties and applications of HED plasmas with densities up to  $10^{22}/\text{cm}^3$  and temperatures up to 2,000,000 K produced from exploding thin metal foils and from fine metal wires. We are modifying the 1 MA COBRA pulsed power generator so it will also accommodate a tri-axial gas puff valve. Computer simulations, detailed atomic physics calculations, and development of new diagnostics all contribute to our investigations of HED plasmas.

### Highlights

In radial foil experiments, a 1 mega amp (MA) current flows radially inward through a thin aluminum (Al) foil from a 2-3 cm radius circular anode to a 1 mm (typical) radius metal pin cathode at the center that carries the current back to the generator. Magnetic bubbles and HED pinched plasmas and plasma jets are formed as the foil explodes and is accelerated by the magnetic forces. These experiments have been carried out both with and without externally applied magnetic fields, (B-fields). The laser interferometer image shown to the right (Figure 1), from an experiment carried out without an applied B-field but with two central pins, shows a well-resolved plasma sheet between two adjacent plasma bubbles. With an applied B-field, preliminary results suggest that a transverse field produces a spreading or deflection of the jet in the plane perpendicular to the applied field, whereas an axial field produced by a Helmholtz pair appears to induce a radial divergence of the jet near the point where the applied B-field lines begin to diverge.

Radial foil experiments have also demonstrated some of the limitations of standard magnetohydrodynamics (MHD) computer codes, as some of the observed phenomena require extended MHD to obtain agreement. PERSEUS, a code developed at Cornell, includes the *Hall term* and electron inertia in the Generalized Ohm's Law. Its results agree with radial foil observations that cause problems for standard MHD.

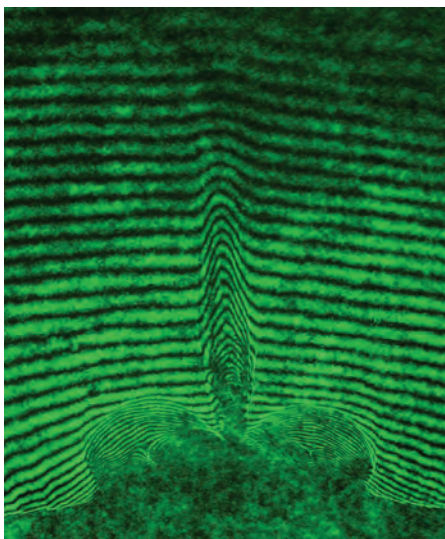


Figure 1. Laser interfergram at  $t=120$  ns showing the interaction between two magnetic bubbles forming above the planer Al foil on both sides of a central plasma sheet.

In other thin foil experiments, very thin (1-20  $\mu\text{m}$ ) copper (Cu) foil cylinders 4 mm in diameter provided by General Atomics Technologies have been imploded by 1 MA current. X-pinch x-ray backlighting along the axis, shows a relatively uniform plasma ion density of about  $10^{18}/\text{cm}^3$  within the cylinder and on axis long before the foil begins to move. By contrast, in a similar mass per unit length 16 Cu wire array, the density builds up to about  $2 \times 10^{19}/\text{cm}^3$  in the precursor plasma on axis at a comparable time. Visible light emission from foils having different thicknesses shows that the foils initiate uniformly if the current density rise-time in the foil exceeds 2 million amps per

$\text{cm}^2$  per ns. Transverse laser backlighting appears to show the development of an instability on the outer surface of the foil that is due to plasma flow along the surface. This instability is reproduced in PERSEUS computer simulations but not in simulations using standard MHD.

Continuing wire-array z-pinch research at Center partner Imperial College included Thomson Scattering applied to the ablated plasma streams with both Al and W wires. Results show that the stream from each wire undergoes additional acceleration inside the array, reaching peak velocities of 120 km per second for Al and 100 km per second for W. On-axis precursor plasma ion temperatures peak near 10 keV for W and 1.5 keV for Al, consistent with thermalization of incoming ion kinetic energy, but these temperatures rapidly decay to less than 100 eV due to radiative cooling. This work was selected for an invited paper at the November 2011 APS/DPP Meeting.

A new spectroscopic approach to measure the B-field in diagnostically difficult density regimes in HED plasmas developed by Center partner Weizmann Institute of Science is being applied in exploding wire experiments at Cornell. A line shape analysis of the Al III 4s – 4p doublet (5696 and 5722  $\text{\AA}$ ) enables the simultaneous determination of the B-field and the electron density up to a density of  $\sim 10^{18}/\text{cm}^3$ . Spatially resolved spectra have provided compelling evidence for  $\sim 3.5\text{T}$  B-fields about 0.5 mm from the center of the exploding wire in some experiments. Uncertainties are being reduced to provide more quantitative values for the B-field.

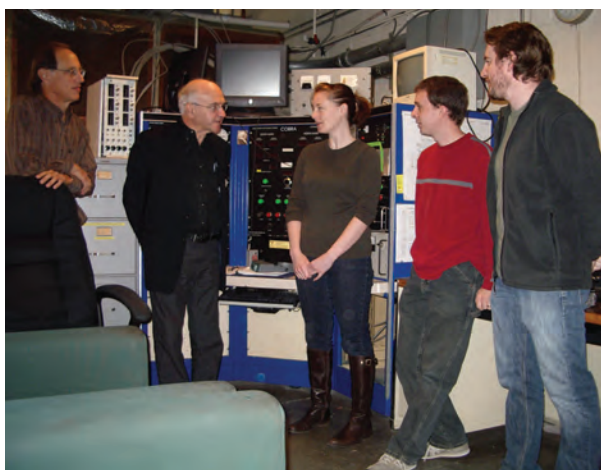


Figure 2. Graduate students (right to left) Cad Hoyt, Adam Cahill and Kate Blesener, and Senior Research Associate Dr. John Greenly (far left) chat with Dr. Victor Reis, Senior Advisor in the Office of the Undersecretary of Energy for Science and founder of the Stockpile Stewardship Program, who visited the COBRA facility on October 6, 2011.

**HEDP Research at Omega and the National Ignition Facility**

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The Massachusetts Institute of Technology (MIT) work in FY 2011 included a wide range of experiments at the Omega Laser Facility and at the National Ignition Facility (NIF), providing unique research opportunities for 8 MIT graduate students and several undergraduates. Along with many other topics, the work included application of proton radiography to the study of high energy density physics (HEDP) and inertial confinement fusion (ICF), plus a completely new class of experiment for study of basic nuclear physics at an ICF facility. That work is ushering in a new and exciting field of research, Plasma Nuclear Science, blending the separate disciplines of plasma and nuclear physics, as discussed in press releases<sup>1</sup> from MIT, the Lawrence Livermore National Laboratory, and the Laboratory for Laser Energetics. In addition, three National Ignition Facility and Photon Science Awards were received by MIT staff and students for “outstanding contributions in designing and implementing diagnostics that have been essential to the progress of the National Ignition Campaign.” The awards were for advanced neutron spectrometer (Dr. Johan Frenje), particle time-of-flight detector (student Hans Rinderknecht), and proton spectrometer (student Alex Zylstra).

We have used MIT-developed methods of monoenergetic, charged-particle radiography in new types of studies of plasmas and fields in HEDP and in ICF. These projects, undertaken at the Omega and Omega EP laser facilities, were performed because of their importance to the future of ICF, HEDP, and the physics of fields generated by laser-plasma interactions. Topics studied include electric and magnetic fields in laser-generated plasmas; reconnection of MG magnetic fields in high- $\beta$  plasmas; self-generated electromagnetic fields in ICF implosions; the dynamics of ICF capsule implosions; electromagnetic fields in laser-driven hohlraums; and the development of a proton backlighter utilizing short-pulse beams from Omega EP. The work has already resulted in nine publications in *Science* and *Physical Review Letters*, plus other papers, including three submitted this year.<sup>2</sup> The work has successfully addressed basic physics issues and issues



Figure 1. The CPS-2 charged-particle spectrometer during installation on the Omega target chamber. The cone-shaped end contains the entry aperture, while the cylindrical section contains a 7.6 kG magnet and CR-39 nuclear track detectors. In the experiment described here, CPS-2 was used to simultaneously measure energy spectra of deuterons and tritons elastically scattered by 14.1-MeV neutrons, and protons from DD reactions in a deuterium-tritium-gas-filled thin-glass capsule implosion.

directly relevant to the future success of ignition experiments at the NIF.

As described in one of the Physical Review Letters<sup>2</sup>, and illustrated in Figures 1 and 2, we performed the first basic nuclear physics experiment in the context of an ICF facility, measuring the differential cross section for 14.1 MeV elastic neutron-triton ( $n\text{-}^3\text{H}$ ) and neutron-deuteron ( $n\text{-}^2\text{H}$ ) scattering at Omega utilizing an MIT-developed, magnet-based charged-particle spectrometer. By simultaneously measuring elastically scattered  $^3\text{H}$  and  $^2\text{H}$  ions from a deuterium-tritium gas-filled inertial confinement fusion capsule implosion, the differential cross section for the elastic  $n\text{-}^3\text{H}$  scattering was obtained with significantly higher accuracy than achieved in previous accelerator experiments. The results compare well with calculations that combine the resonating group method with an ab initio no-core shell model, which demonstrate that recent advances in ab initio theory can provide an accurate description of light-ion reactions.

**References**

<sup>1</sup>MIT, LLNL and Univ. of Rochester joint press releases can be found, respectively, at

<http://web.mit.edu/press/>

<https://www.llnl.gov/news/newsreleases/2011/Sep/NR-11-09-08.html>

<http://www.rochester.edu/news/show.php?id=3934> (*New Era of Plasma Nuclear Science Opens on the Omega Laser Facility*)

<sup>2</sup>J.A. Frenje, C.K. Li, F.H. Seguin et al., Phys. Rev. Lett. 107, 122502 (2011).

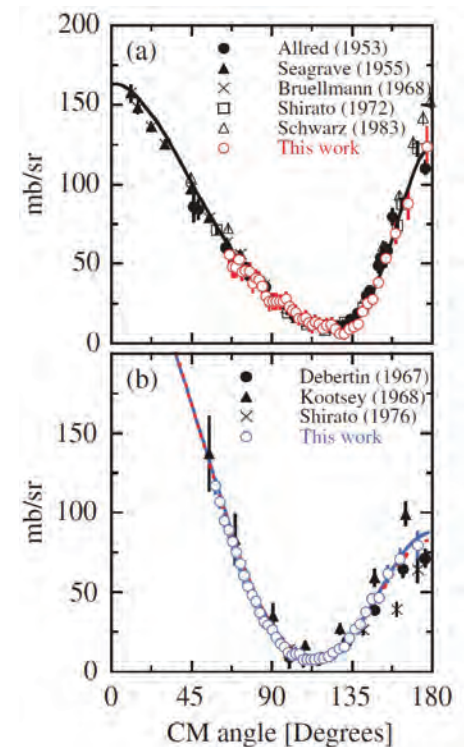


Figure 2. (From Ref. 2) (a) Measured differential cross section for the elastic  $n\text{-}^2\text{H}$  scattering, normalized to a Faddeev calculation. (b) Measured and calculated differential cross section for elastic  $n\text{-}^2\text{H}$  scattering. The experimental data have been normalized with the deuterium-tritium fuel-ratio modified normalization factor derived in (a). The blue solid curve represents an ab initio NCSM/RGM calculation, and the red dashed curve represents an R-matrix calculated  $n\text{-}^3\text{H}$  cross section.

## Investigations of High Energy Density Plasmas at the Nevada Terawatt Facility

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Researchers at the Nevada Terawatt Facility (NTF) are continuing to investigate fundamental and applied high energy density plasma physics. The main NTF experimental platforms include a 1 MA, 2 TW z-pinch and a 50 TW, 350 fs one micron glass laser. Each of these platforms can be used for experiments in a standalone configuration. Alternatively, they can be used in a coupled z-pinch plus laser mode providing a unique set of experimental tools.

During the past year, several exciting new plasma diagnostic techniques have been implemented that are giving new insights into plasma phenomena. For example, recent coupled experimental campaigns carried out by NTF students working under the guidance of Vladimir Ivanov were able to measure small-scale (~10-30 micron) instabilities in dense stagnated z-pinch. <sup>1</sup> These experiments used high-resolution UV laser diagnostics and are revealing instabilities and micro-pinch at unprecedented levels of detail (see Figure 1). These experimental campaigns were supported using 3D resistive magnetohydrodynamics (MHD) Gorgon and radiation transport simulations provided by Drs. Jerry Chittenden and Roberto Mancini, respectively.

In another set of coupled experiments, NTF researchers used x-ray absorption spectroscopy to measure the ionization states and electron temperatures during the z-pinch plasma ablation stage. <sup>2</sup> In these experiments, a laser-produced Sm plasma backlighter was monitored using two identical spectrometers. One spectrometer collected the Sm spectrum attenuated by an ablating Al wire array, while the other recorded the unabsorbed Sm x-ray spectrum. The difference between these spectra allowed the absorption spectrum to be determined (Figure 2), but the interpretation of these data required sophisticated MHD and radiation transport modeling to determine plasma parameters.

A survey of other recent NTF highlights include both experimental and theoretical work in a variety of High Energy Density Physics (HEDP) related areas, including:

- Modified HED targets: Investigations of the influence of wire coatings on the ablation and energy deposition in current-carrying metallic wires

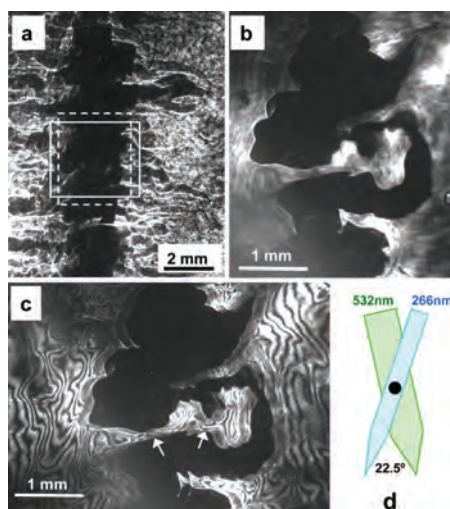


Figure 1. Shadowgrams (a), (b) taken 0.6 ns after the maximum of the x-ray pulse and an interferogram (c) of the central part of the pinch at the wavelength of 532 (a) and 266 nm (b), (c). The z-pinch is produced by the implosion of a cylindrical 16-wire array 8 mm in diameter. Directions of probing lasers are presented in (d).

and the development of metallic coated or deuterium loaded wires and targets for multi-component plasma studies.

- Mitigation and control of plasma instability formation: Shear flow stabilization of conical wire arrays, <sup>3</sup> nested wire arrays and magnetically activated Kelvin-Helmholtz instability formation in plasmas.
- Fundamental interactions between plasmas and magnetic fields: Penetration of laser-produced plasmas across z-pinch produced magnetic fields.
- Particle plasma probes: Efforts are ongoing to use laser-produced proton radiography to probe the structure of dense z-pinch plasmas.
- Scaled laboratory astrophysics experiments: Investigations of the properties of solar and stellar environments; Investigations of supernova remnant dynamics. <sup>4</sup>
- Neutron and gamma ray sources and detection: Development of novel laser and z-pinch targets for neutron production, novel techniques for increasing neutron yields such as staged z-pinch.
- Fundamental atomic physics in high-field environments.

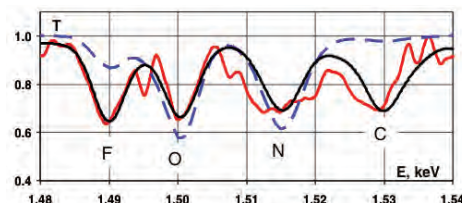


Figure 2. Experimental transmission spectrum of ablating plasma (red) with one-temperature modeling of plasma absorption (blue dashed line)  $T_e = 20$  eV, and two-temperature (black solid line)  $T_e = 14$  and 30 eV.

- Plasma modeling: PIC simulations of laser-target interactions.
- Radiation transport and atomic processes in plasmas: Radiative properties of different target materials and target geometries for the production of x-rays.
- Design and testing of novel plasma diagnostics: Optical diagnostic development including laser-based probes and new optical, VUV and x-ray spectrometers.
- Research opportunities abound for students: The NTF has continued to foster undergraduate and graduate student leadership in a number of experiments. A majority of our experimental campaigns are now student-led, and students at all academic levels are now graduating with HED research skills. In the past year, UNR has granted eight PhD degrees in Physics to students working on HEDP topics, and three of these have gone on to post doctoral positions in the NNSA laboratories.

The NTF has also recently completed upgrades to our laser system enabling researchers to operate the Leopard laser at energies exceeding 80 J in long pulse (~1 ns) operation. This should increase the signal-to-background ratio in absorption spectroscopy measurements and will also expand the reach of our experimental capability.

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## Experimental Study of the Richtmyer-Meshkov Instability

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The propagation of a shock wave through an interface between fluids of different density and/or chemical composition causes any perturbation on the interface to grow and results in turbulent mixing between the two fluids. This phenomenon is termed the Richtmyer-Meshkov instability (RMI).<sup>1</sup> The RMI plays an important role in the experiments for the achievement of inertial confinement fusion (ICF) where a laser-driven shock wave traverses the shell containing the deuterium-tritium fuel: the turbulent mixing of the shell material with the fuel, caused by the RMI, reduces the reaction's energy yield. The RMI also occurs at astrophysical scales, in the overturn of supernova cores. The turbulent mixing data generated at the University of Wisconsin-Madison may aid in the development of compressible-turbulence fluid models for very large-scale numerical simulations conducted at the national laboratories for ICF capsule design and performance.

The RMI is studied experimentally at the Wisconsin Shock Tube Laboratory<sup>2</sup> whose main facility is a vertical shock tube of large, square internal cross section ( $25 \times 25 \text{ cm}^2$ ) with structural capability to withstand a Mach 5 shock wave in air at room conditions. In all experiments, a planar shock wave propagates downwards and it interacts with a gas interface 1m above the bottom of the shock tube. In the current grant period, a new type of interface has been developed in our laboratory, consisting of a horizontal shear layer separating helium from argon. The objective is to achieve an initial condition containing a broad spectrum of length scales. To establish it (see Figure 1) He and Ar are flowed vertically into the tube to form a flat stagnation surface. Ar and He are also injected horizontally above and below this surface, respectively, giving rise to a shear layer with concentration and velocity fields characterized by Fourier spectra covering 1.5 decades in wavenumber space. Once the shear layer has become statistically steady, a downward-traveling shock wave accelerates it causing the onset of the RMI. The interface is imaged before and after shock arrival using planar laser induced fluorescence: the helium injected in the shock tube is seeded with acetone vapor at 5.3% volume concentration (the acetone is fully mixed with the helium and

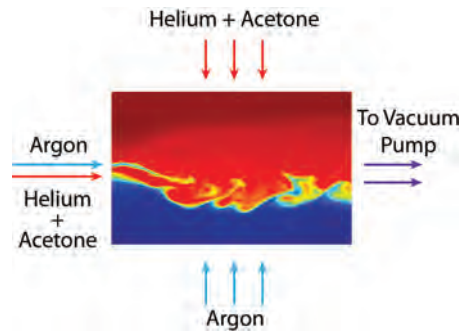


Figure 1. Initial condition setup and the resulting 2-D He mole fraction field.

accurately traces its motion and its mixing with the argon); 308 nm light sheets from two excimer lasers (470 mJ/pulse) are shone upwards into the tube through its end wall; and the fluorescence propagating in a direction perpendicular to the laser sheet is collected using two UV-sensitive CCD cameras. The digital images are processed to correct for non-uniformities in the laser beams, and the attenuation of the laser sheet along its propagation direction. The intensity of the corrected images corresponds to the relative acetone concentration or light-gas mole fraction,  $X$ . Several important turbulence parameters are extracted from the images, including: large-scale characteristic lengths; mixing fraction; dissipation rate; gradient angle (between the concentration gradient and the horizontal); power spectra; and others. Examples of mole fraction and dissipation rate fields are shown in Figure 2. The dissipation rate, highlighting the location and magnitude of gradients, shows that the mixing becomes more intense, at smaller scales, and broadly distributed throughout the layer at later times.

The probability density function of the gradient angle,  $\theta$ , is shown in Figure 3. The concentration gradient angle is expected to be initially close to  $90^\circ$  because at early times the structures are mainly horizontal, signaling a gradient in the vertical direction. The gradient angle exhibits a peak in the  $90^\circ$  direction (streamwise). This peak increases after the shock interaction, when the shock wave compresses the interface in the streamwise direction, magnifying the gradients in that direction. In the realizations at later times, this peak has reduced significantly. By the final image time, the gradient angle has only a slight preference for  $90^\circ$ , signifying

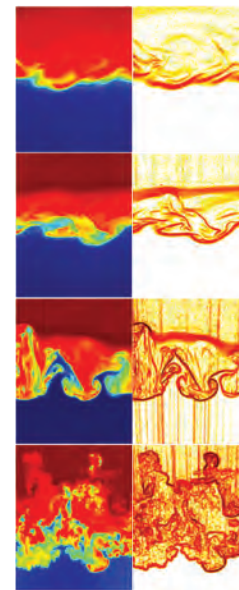


Figure 2. Time sequence for  $M=1.56$  shock. Left column: He mole fraction. Right column: dissipation rate. From top to bottom, times are: 0.0 ms, 0.137 ms, 0.881 ms, 2.104 ms.

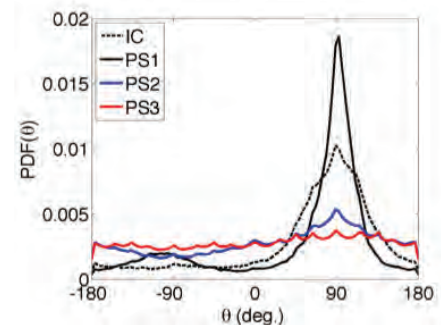


Figure 3. Concentration gradient angle for the four times of Figure 2.

that the mixing region has become nearly isotropic by this time.

The experimental data can now be compared against analytical models and numerical calculations for validation and calibration purposes.

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## Laboratory Tests of Stellar Interior Opacities

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Opacity is a fundamental quantity in astrophysics and plasma physics. It governs the flow of radiation in stars as well as laboratory sources such as fusion devices. Accurate calculations and measurements are essential to ascertain opacities over a wide range of temperatures, densities and chemical composition. Several outstanding astrophysical problems depend on the precise values used in models. One of the most important is the large discrepancy in the abundances of volatile elements in the Sun obtained, on the one hand, from most recent spectroscopic measurements and 3-dimensional non-local thermodynamic equilibrium models and, on the other hand, those favored by stellar models and helioseismology (see Figure 1). Because the Sun is the standard for absolute abundances of all elements in the Universe, it is important to solve this problem.

Within the past few years helioseismology has evolved into astroseismology. Hundreds of Sun-like stars are now being studied to detect extra-solar planets by space missions KEPLER and CoRoT. However, it is important to ascertain precisely the effect of internal stellar oscillations on their light curves as the exoplanets transit across and dim the starlight ever so slightly. Accurate opacities again play the key role.

In recent years, it has become possible to measure stellar interior opacities in the laboratory. Experiments are now being carried out at the refurbished Z at SNL. First results indicate serious disagreement with existing theoretical opacities.

We are methodically examining the source of the discrepancy between the experimental and available theoretical opacities (see Figure 2). At the same time, our main theoretical effort is to recompute atomic data for radiative processes with much higher accuracy for a subset of iron (Fe) ions prevalent at the base of the convection zone (BCZ) and those corresponding to the Z-pinch plasma. The new calculations are carried out using the Breit-Pauli R-Matrix (BPRM) method, including relativistic fine structure in an ab-initio manner. The largest contributor among the Fe ions under BCZ conditions is Neon (Ne)-like Fe XVII. First results for the monochromatic opacity of Fe XVII are presented in Figure 3. Owing to the

presence of autoionizing resonances, the BPRM results show considerably more structure than earlier Opacity Project (OP) results. While calculations are still under way, preliminary indications are that

the Rosseland mean opacities could be higher, helping solve the aforementioned solar abundances problem.



Figure 1. Left - Thermouclear energy from the core diffuses through the radiative zone and drives convective motions at the BCZ (see arrow). Right - The OSU group with students and co-PIs Sultana Nahar and Anil Pradhan. Other co-PIs are Jim Bailey who leads the experimental program at Sandia, and OSU astrophysicist Marc Pinsonneault.

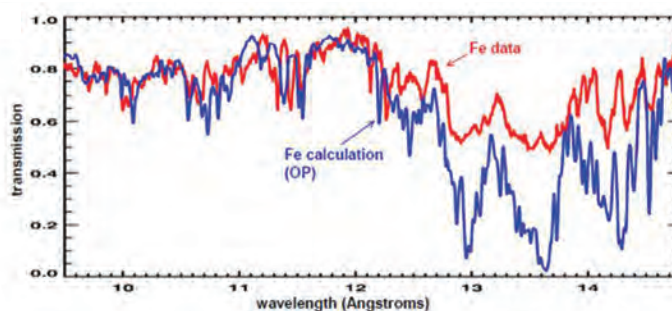


Figure 2. Preliminary results from opacities measurements (red) and theoretical opacities from the OP (blue). These results refer to plasma conditions at the BCZ. Customized OP opacities are available on-line from the Ohio Supercomputer Center at <http://opacities.osc.edu>.

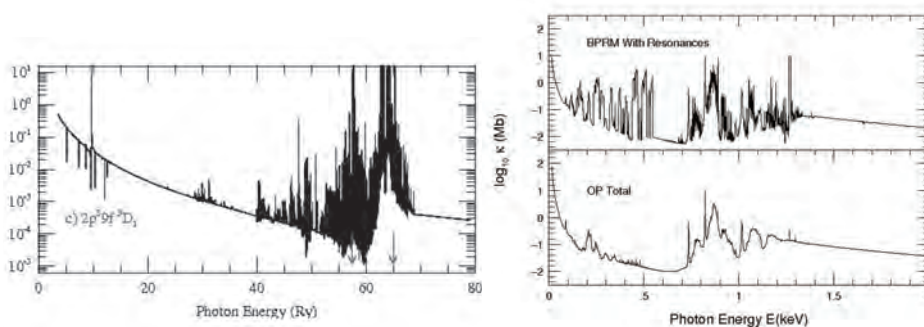


Figure 3. Left - Large photo-excitation-of-core (PEC) resonances in bound-free photoionization cross sections (Megabarns) for a bound state of Fe XVII (the arrows mark the peak energies). PEC resonances have intrinsically asymmetric profiles, in contrast to symmetric line profiles generally employed in opacities calculations, and attenuate the bound-free absorption by orders of magnitude above the background. Right - The cumulative monochromatic opacity of Fe XVII incorporating myriad PEC and other resonances computed using BPRM codes are shown in the top panel, compared to the Opacity Project (Nahar et al., Phys. Rev. A, 83, 053417, 2011). The BPRM opacity of Fe XVII shows considerably more structure owing to resonances than the earlier works.

## Planetary Science and Astrophysical Applications of Experimental Studies with the SNL Z Facilities

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The recent discoveries of numerous extra-solar system planets (exoplanets) with very high masses and extended atmospheres in close proximity to their *suns* have fundamentally challenged our theoretical understanding of planetary structures. Planetary formation models predict the existence of not only giant gaseous planets, but also massive rocky (Earth-like) ones which could potentially be habitable. Such planets, called Super-Earths, range in mass from 1 to about 10 Earth masses and constitute a new type of planet unknown in our Solar System.

In the last few years, the NASA Kepler mission has succeeded in discovering numerous extrasolar planets around a number of stars. With the current technology limitations, only mass and radius of an exoplanet can be observed, so classification of these planets into gas giants and Super-Earths has to be made by comparison of these parameters with results of theoretical modeling of planetary internal structures.

In anticipation of new results from the NASA Kepler mission, graduate student Li Zeng has explored a range of plausible planetary compositions to derive mass-radius relationships that were used to identify a few Super-Earths among the exoplanets found by Kepler (Figure 1). By their high-mass nature, Super-Earths are expected to contain silicates and silicate-metal mixtures under very high pressures and temperatures significantly exceeding those in the Solar System terrestrial planets. The lack of experimental data on equations of state (EOS) for the appropriate materials at such extreme conditions is the major limitation of the current models of Super-Earths that rely upon extrapolations of the available low-pressure data. The acquisition of such data is the primary research objective of the Harvard-Sandia research team.

The team employs a modern approach to determination of material properties at ultrahigh pressures and temperatures that involves compressing targets at the Sandia National Laboratories (SNL) Z accelerator, capable of accelerating flyer plates up to 40 km/s, and ab initio molecular dynamics simulations of material properties. This approach has proven to yield precise EOS up to ~1.5 TPa. So far, the EOS of  $\text{SiO}_2$  has been established, and the measurements of Fe

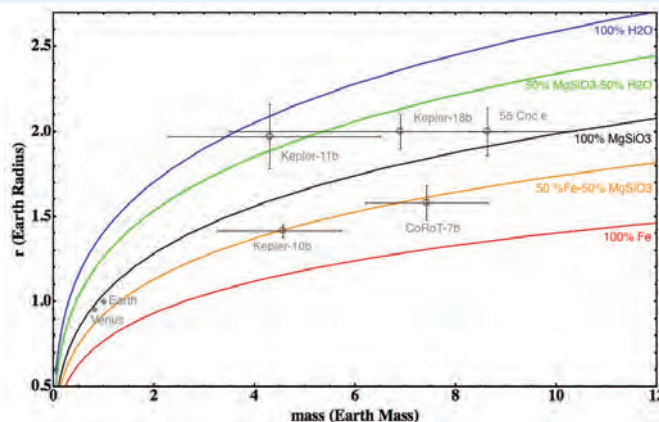


Figure 1. Currently known transiting exoplanets are shown with their measured mass and radius. Earth and Venus are shown for comparison. The calculated curves are for planets made of pure Fe, 50% Fe and 50%  $\text{MgSiO}_3$ , pure  $\text{MgSiO}_3$ , 50%  $\text{H}_2\text{O}$  and 50%  $\text{MgSiO}_3$  and pure  $\text{H}_2\text{O}$ .

metal and Mg silicates and oxides are the logical next steps.

The radius of a planet of given composition is critically dependent upon the distribution of its mass between core and mantle. The cores of the terrestrial planets were likely formed by physical separation of Fe metal and other siderophile elements from silicates during the process of accretion. Metal segregation to form Earth's core is widely believed to have happened in an early terrestrial magma ocean, with the final metal-silicate equilibration taking place at very high pressure and temperature. The evolution of the Earth's core thus relates directly to the processes of planetary accretion and differentiation.

For modeling the chemical evolution and structure of Earth-like planets (cores and mantles), it is important to have a proper quantitative model for chemical partitioning between metal and silicate during core formation. Graduate student Gang Yu has developed such a model and tested it by modeling the formation history of the Earth-Moon system (Yu and Jacobsen, 2011). Currently, the

model relies upon extrapolation of the experimental metal-silicate partitioning data obtained at temperatures and pressures of up to about 2000 K and 40 GPa, respectively. The extrapolated data were verified by our dynamic metal-silicate partitioning experiments at temperatures and pressures of up to 20,000 K and 280 GPa, respectively, attained during laser-driven shock compression of metal-silicate targets at the SNL ZBL facility. The metal-silicate partitioning of Fe, Ni and Si in our experiments (Figure 2), broadly consistent with extrapolations of the available lower-P and T data, indicates that, surprisingly, at least some melts trapped by the metal-silicate targets appear to retain equilibrium partitioning from the peak pressures and temperatures experienced by the target material. We are conducting similar experiments under more controlled conditions to better understand our previous results.

## Reference

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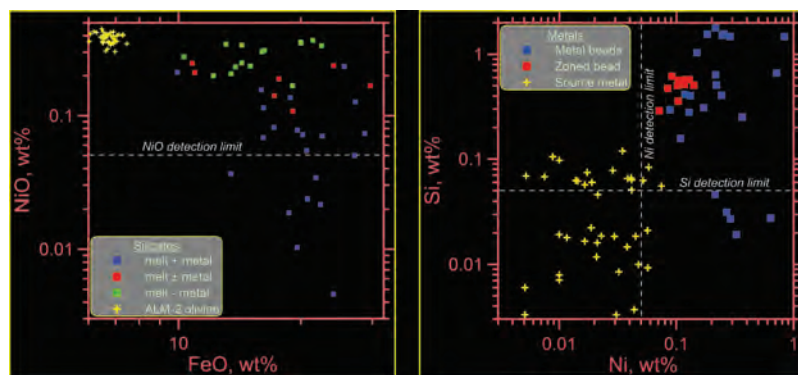


Figure 2. Chemistry of the melt phases - Fe-Ni-Si. Compared to the source  $\text{Mg}_2\text{SiO}_4$  (olivine), the silicate melt is enriched in FeO and depleted in  $\text{SiO}_2$  and MgO. When present, metal beads effectively extract Ni from the silicate melt.

**Ultrafast X-ray Probes of Matter Under Extreme Conditions**

University of Colorado and JILA

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Ultrafast x-rays are powerful and unique probes of matter on the smallest spatial scales, the fastest timescales, and under extreme conditions. Unlike visible light, x-rays can penetrate dense plasmas or solids. X-rays can also deposit energy at high densities, which is why hohlraums are used to convert laser energy into x-rays to drive fusion implosions on the National Ignition Facility at Livermore. Very recently, students and scientists at JILA, a joint University/NIST institute at the University of Colorado, made major breakthroughs in generating bright laser-like x-ray beams from femtosecond lasers, and in using them to demonstrate the highest-spatial resolution tabletop x-ray microscope to date.<sup>1,2</sup> This will make it possible to capture and understand how laser-heated solids evolve into a dense plasma state, called warm dense matter (WDM) that is not well understood.

To create warm dense matter in a university-scale lab, the first challenge is to generate bright ultrafast x-ray beams on a tabletop, and then focus them to a very small spot. To generate laser-like bursts of x-rays, Kapteyn, Murnane, and their students used a process called high harmonic generation, essentially a coherent version of the Rontgen x-ray tube in the soft x-ray region. A laser pulse first plucks an electron from an atom, then accelerates it to high velocity, before finally slamming it back into the ion, where it can release its kinetic energy of motion as an x-ray photon. The JILA team developed a simple and universal scaling rule<sup>1</sup> that combines the quantum nature of the electron, the plasma physics of the gas used to generate the x-rays, and the nonlinear optics of how to combine together x-ray emission from many atoms in a medium. By using short driving laser wavelengths at  $0.4\ \mu\text{m}$ , the conversion of laser light into harmonics is most efficient, making it possible to create WDM within a few femtoseconds – before the solid has time to explode. The team has already created WDM plasmas in the laboratory, proving that a tabletop setup can generate high focused x-ray intensities to create extreme matter (see Figure 1).

The second challenge is that the total plasma volume is  $<1\ \mu\text{m}^3$ , so even observing this requires very short-wavelength light, since the resolution of any imaging system is limited by the wavelength of the light. The

Figure 1. Right - The high energy coherent x-ray beam-line on a tabletop, with students Dimitar Popmintchev, Ming-Chang Chen, Susannah Brown, Chris Mancuso, and postdoctorate Tenio Popmintchev. Also shown is materials damage following plasma creation by focused 20 nm harmonic light.

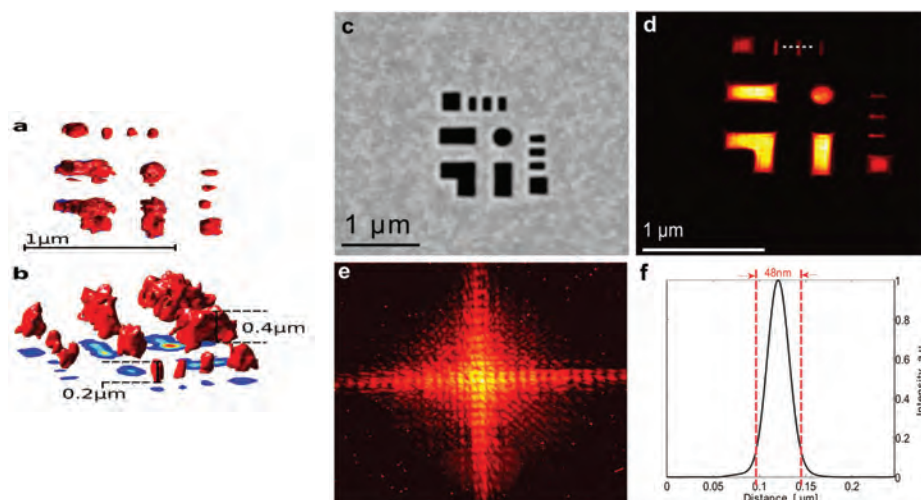
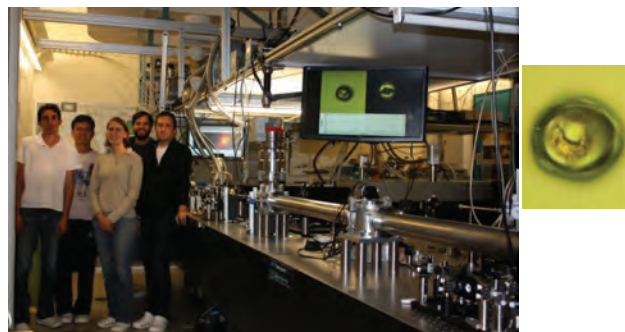


Figure 2. Coherent Diffractive Imaging. a, b 3D imaging of sample shown in c. c Scanning electron microscope image of sample. d Retrieved 2D image. e Scatter pattern in 2D. f Lineout with spatial resolution of  $\approx 22\text{nm}$ , a record for a tabletop x-ray microscope.

solution is to harness the short wavelength of x-rays to probe nanoscale features, by also using x-rays to image the plasmas. Standard x-ray microscope geometries do not work, because they require very exotic and expensive x-ray lenses that need to be too close to the plasma to survive undamaged. Instead, the JILA team used Coherent Diffractive Imaging (CDI) that simplifies the microscope to the bare essentials, while maintaining the ability to image at the spatial resolution limited only by the wavelength of the x-rays. In CDI, an object is illuminated with a coherent beam, and the light scattered from the object is directly captured with a digital imager. A normal imaging system would use a lens to create an image on a detector; instead, in CDI, a computer algorithm reconstructs missing data, extracting the shape of the object. The team demonstrated that using  $13\text{nm}$  wavelength harmonics, they could generate images with a resolution nearly at the wavelength limit— $22\text{nm}$ , with 3D information.<sup>2</sup> This work represents the highest resolution full-field imaging

microscope ever implemented on a tabletop (see Figure 2). In addition to its relevance to NNSA, this research will also make it possible to understand charge and energy transport in energy-harvesting, catalytic, electronic, data storage and nano systems.

Students working on this project have been very successful to date. A recent PhD student, Dr. Richard Sandberg, is now Los Alamos National Laboratory staff working on related imaging projects. Graduate students Matt Seaberg, Susannah Brown and Paul Arpin were awarded NSF IGERT Fellowships in the area of computer-aided imaging, while Principal Investigators Kapteyn and Murnane will share the 2012 Willis Lamb Award for Laser Science.

**References**

- <sup>1</sup>T. Popmintchev et al., *The Attosecond Nonlinear Optics of Bright Coherent X-ray Generation*, Nat Photon 4, 822 (2010).
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# LENS

Low Energy Nuclear Science

Low energy nuclear science (LENS) studies the atomic nucleus, responsible for most of the mass of an atom, yet a tiny fraction of the atomic volume. The atomic nucleus is composed of nucleons—protons (which carry charge) and neutrons (with no charge)—held together by the strong force. The masses of the nucleons as energy equivalents are about 1,000 million electron Volts (MeV) compared to the mass of the electron which is only about 0.5 MeV. Figure 1 illustrates the nuclear landscape. While 288 nuclei are stable (black squares), about 3,000 nuclei (the pink region) have been synthesized in the laboratory. Most unstable nuclei transform into more stable nuclei by beta decay, where an electron or positron is emitted along with an anti-neutrino or neutrino, often followed by gamma radiation. Some heavy nuclei decay by alpha emission. The heaviest nuclei, when modestly excited, fission into two (or sometimes more) unstable nuclei, releasing tremendous energy as well as neutrons.

Open questions in low energy nuclear science include what arrangements of neutrons and protons can be brought together to form nuclei that are stable to spontaneous proton or neutron emission or spontaneous fission into smaller nuclei. Another question is how elements are formed in stars and explosions in the cosmos, since only the lightest elements, hydrogen, helium, and lithium, were formed in the Big Bang. The fission process itself is not fully understood, although it is the basis for explosions of nuclear weapons and energy generation in nuclear reactors.

Low energy nuclear scientists use accelerators to investigate the properties of atomic nuclei, to produce the heaviest ones (even if they live for small fractions of a second), to mimic the reactions that take place in stars, and to produce nuclei near the limits of nuclear existence and study their decay. The accelerators need to provide sufficient energy to overcome the Coulomb repulsion between the positively charged ion beams of nuclei and the positively charged nuclei of the targets. To probe the limits of nuclear existence or to reproduce reactions that take place in stellar explosions, the frontier efforts exploit accelerated beams of radioactive

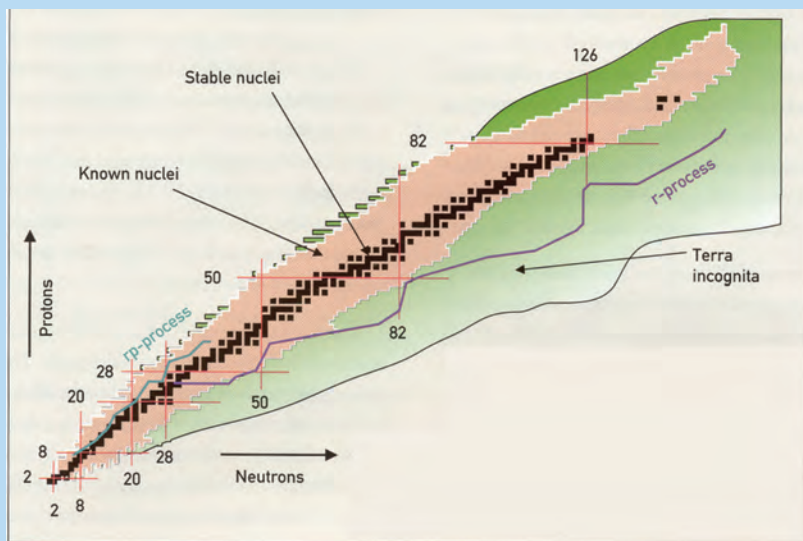


Figure 1. The landscape (number of protons and number of neutrons) of atomic nuclei extends from the lightest elements to the yet-to-be-discovered superheavy elements. Two hundred eighty-eight nuclei (black squares) are stable, while about 3,000 nuclei (pink region) have been synthesized in the laboratory, a small fraction of the nuclei predicted to exist (green regions), terra incognita. The nuclei most likely to be produced in the r-process lie far from stability, extending into unknown regions of the chart of nuclei. (Adopted from *Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade*, April 2002, DOE/NSF Nuclear Science Advisory Committee.)

nuclei, which may only live for seconds or fractions of a second. Because the intensities of radioactive ion beams are low (sometimes as low as a few particles per day), nuclear scientists are developing highly segmented, large solid angle, high efficiency arrays of detectors of gamma rays, charged particles, and neutrons. The technologies for these new arrays also find applications in homeland security, for example, as portal detectors at seaports or border crossings.

How the elements heavier than iron were formed is one of the unanswered questions in astrophysics. About half of the heavy elements are believed to be formed in the rapid neutron capture (the r-process) of nucleosynthesis, which may occur in explosions of supernovae or collisions of neutron stars. Most of the other heavy elements are formed in older stars, via slow capture of neutrons (the s process). One approach to understanding the synthesis of heavy elements by capture of neutrons is by direct studies of neutron capture on long-lived heavy nuclei of heavy elements. Such measurements are performed with the highly-segmented Detector for Advanced Neutron Capture Experiments (DANCE), an array of high-efficiency  $\text{BaF}_2$  gamma-ray detectors based at the Lujan Center at LANSCE at Los Alamos National Laboratory (LANL) shown in Figure 2. Nuclear scientists,

graduate students and postdoctorates, from universities and other national laboratories across the United States, participate in the measurements. However, only longer lived (with half lives  $> 100$  days) nuclei are amenable to making the targets for direct studies of neutron capture.

Understanding neutron capture on unstable nuclei, especially the very short-lived species that are most likely to be produced in the r-process, requires indirect methods. Two approaches are needed. When the nuclei are relatively weakly bound, the neutron is captured directly into particular states in the final nucleus, a process known as direct capture. The probability of direct neutron capture is proportional to the single-particle wave function of the final state, a property that can be measured with neutron transfer onto a beam of a short-lived radioactive nucleus. Studies at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory have made important contributions to such studies near  $^{78}\text{Ni}$  and  $^{132}\text{Sn}$ , two nuclei with extra stability because of closed shells of both neutrons and protons. Critical tools for these measurements include the Oak Ridge Rutgers University Barrel Array (ORRUBA) shown in Figure 3, consisting of two rings of position-sensitive silicon strip detectors, developed under support from the SSAA Program.

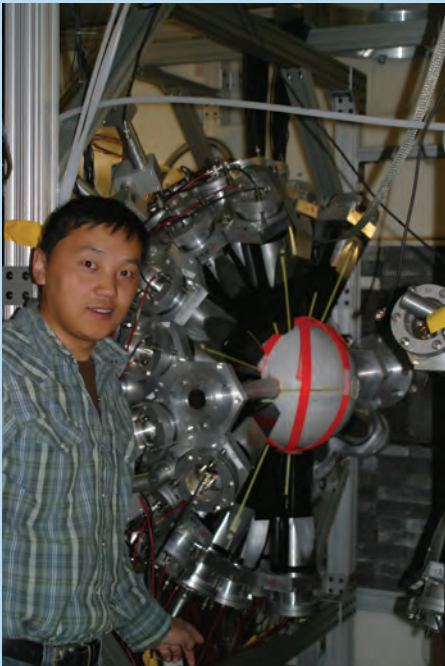


Figure 2. Reactions in which a nucleus captures a neutron are important for the synthesis of heavy elements in stars, energy generation in reactors, and the power of nuclear explosions. The DANCE array of high-efficiency  $\text{BaF}_2$  gamma-ray detectors, was developed at the LANL Lujan Center at LANSCE to measure the probabilities of neutron capture reactions that emit gamma rays, especially for rare isotopes such as actinides. Bayarbadrakh Baramsai from North Carolina State University worked with LANL scientists as part of an SSAA grant to understand neutron capture reactions and properties of atomic nuclei at high excitation energies.

For nuclei away from closed neutron shells, the capture of neutrons and subsequent gamma-ray decay of the final compound nucleus follows a statistical process that cannot be reliably modeled. Therefore, techniques for surrogate reactions for neutron capture have been developed by scientists at Lawrence Livermore National Laboratory. The work over the past decade has focused on heavy, stable targets bombarded by light ion beams. Current efforts are developing the techniques to study surrogate reactions in inverse kinematics, where a heavy, short-lived beam interacts with a light target, such as deuterated plastic. Surrogate reaction studies now include universities and other national laboratories. Surrogate reactions for fission and  $(n,2n)$  reactions with high energy neutrons have also been validated. In addition to informing the synthesis of elements in stars and their explosions, surrogate reactions and direct studies of neutron-induced reactions

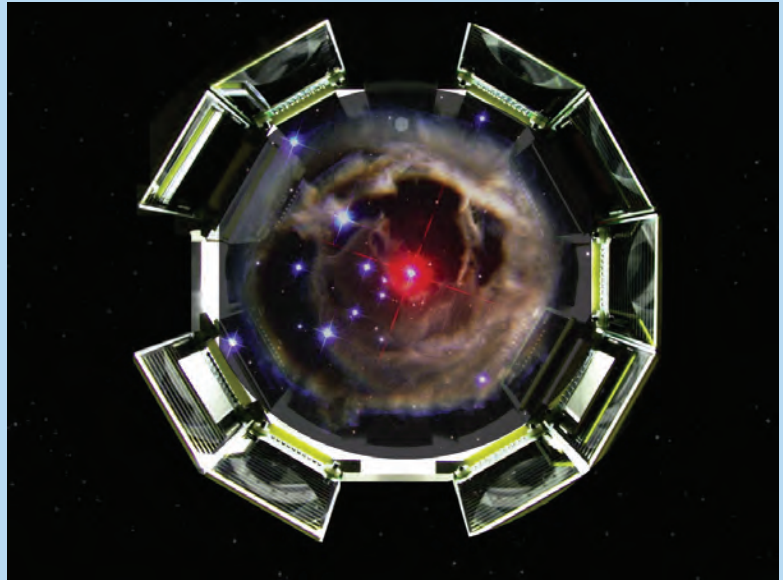


Figure 3. The ORRUBA of position-sensitive silicon strip detectors was developed by the SSAA-supported Center for Radioactive Ion Beam Studies for Stewardship Science for experiments with radioactive ion beams. ORRUBA is superimposed on an image of the explosion in V838 Monocerotis.



Figure 4. Graduate student Erin Gantz of the University of California at Berkeley is shown working inside a plutonium containment glovebox. Berkeley provides hands-on training in actinide and fission product separation techniques which are essential to the NNSA mission.

are important for stockpile stewardship (understanding neutron-induced reactions for radiochemistry applications). Many of these surrogate and direct studies of neutron-induced reactions require actinide targets. As highlighted in Figure 4, mastery of actinide and radio chemistry is, therefore, a critical skill for both basic and applied nuclear science, and next generation reactors (understanding fission of minor actinides).

Current research with radioactive ion beams is focused in the U.S. at the National Superconducting Cyclotron Laboratory at Michigan State University (MSU). The community is developing the tools and educating future leaders in nuclear science in anticipation of the next generation world-class Facility for Rare Isotope Beams that will be commissioned later this decade at MSU.

In summary, low energy nuclear science is a vibrant enterprise that is bringing together teams of scientists from national laboratories and universities, teams that include students and postdoctorates, to answer some of the most important questions in physics and astrophysics. Answering these questions requires development of new experimental tools and theoretical methods and engaging early career scientists to realize these developments and scientific results. At the same time, the research, tools, and people help to address the outstanding challenges in national and homeland security and nuclear energy.

For more information, read *Designer Nuclei—Making Atoms that Barely Exist*, Kate L. Jones and Witold Nazarewicz, *The Physics Teacher*, Volume 48, page 381 (2010).

## Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

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## Introduction

Low energy nuclear physics is one of the forefront areas of modern science. The fundamental questions that low energy nuclear physics can help to answer include: *What is the origin of the elements in the cosmos?* and *What is the origin of simple patterns in complex nuclei?* At the same time, low energy nuclear science can help provide solutions to some of the most challenging problems facing our nation, for example, by developing passive and active nuclear detection systems for homeland security. Research activities in low energy nuclear science provide the training ground for the next generation of leaders in basic research and in applications of low energy nuclear science, from nuclear forensics to homeland security to nuclear energy.

The Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSS) has worked to answer some of these questions, as well as attract and train early career scientists. The focus has been to use radioactive ion beams of fission fragments and other rare isotopes to study the reactions on and structure and decay of atomic nuclei far from stability. Studies with many of these short-lived isotopes can help us understand the origin of the elements. For example, the rapid neutron capture r-process is responsible for about one half of the elements heavier than iron. With fission fragment beams, the decay of some of these r-process isotopes, as well as reactions on these nuclei far from stability, can be studied. To realize these efforts requires new theoretical approaches, new experimental tools and new rare isotope beams. The RIBSS Center is currently developing the Versatile Array of Neutron Detectors at Low Energy (VANDLE) that will first be deployed to study neutron emission following beta decay of very neutron rich nuclei. Realization of these research efforts requires a highly talented team that includes graduate students and postdoctoral scholars.

### Research Highlight: Probing nuclear structure and nucleosynthesis with fission fragments

Observations of abundances of the elements in our Sun that are produced by the r-process of nucleosynthesis cannot be reproduced with standard solar models and the shell model of nuclear structure first

developed by Mayer and Jensen in 1949 and displayed in Figure 1. One solution: the nuclear shell structure changes when many more neutrons are added to atomic nuclei. Figure 1 shows a region of the chart of the nuclei that RIBSS Center scientists are investigating now to probe the properties of neutron-rich nuclei near the r-process path.

The RIBSS Center made the first measurement of a transfer reaction on an r-process nucleus to study the single-neutron structure of  $^{83}\text{Ge}$ , with 32 protons and one neutron beyond the  $N=50$  shell closure. This work showed that the  $3s_{1/2}$  orbital had come down in energy, approaching the ground  $2d_{5/2}$  configuration. A more precise measurement of the excitation energy of the  $1/2+ 3s_{1/2}$  state was determined by beta-decay studies. The next question is: *What happens in other  $N=51$  isotones when the proton number approaches the shell closure at  $Z=28$ ?*

The RIBSS Center, and University of Tennessee-Knoxville graduate student Stephen Padgett and postdoctoral scholar Miguel Madurga, led the effort to study the beta decay of  $^{81}\text{Zn}$ , with 51 neutrons and 30 protons. As displayed in Figure 2, the relatively strong beta decay to the  $J\pi=5/2-$  ground state of  $^{81}\text{Ga}$ , with 31 protons, was only consistent with a  $J\pi=5/2+$  ground state spin for  $^{81}\text{Zn}$ . Therefore, the  $1/2+ 3s_{1/2}$  state is not the  $^{81}\text{Zn}$  ground state. Subsequent shell model calculations predict that this  $1/2+$  state should increase in energy for  $Z<32$ , approaching the values observed in  $N=51$  isotones near stability, such as  $^{91}\text{Zr}$  and  $^{89}\text{Sr}$ , with 40 and 38 protons, respectively.

That the ground state of  $^{81}\text{Zn}$  is not  $1/2+$  and the subsequent predictions that the only bound excited state in  $^{79}\text{Ni}$ , with 28 protons, is a relatively high-lying  $1/2+$  state, has important implications for r-process nucleosynthesis. The probability of direct capture of neutrons in

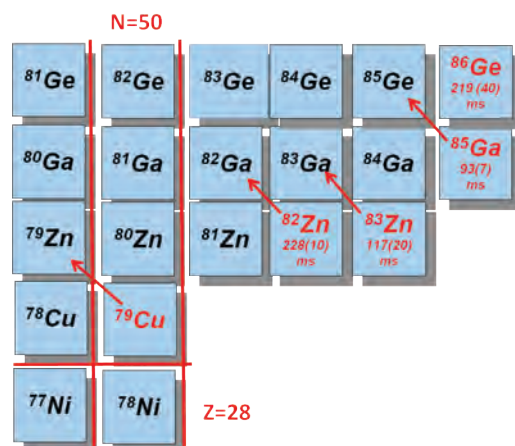
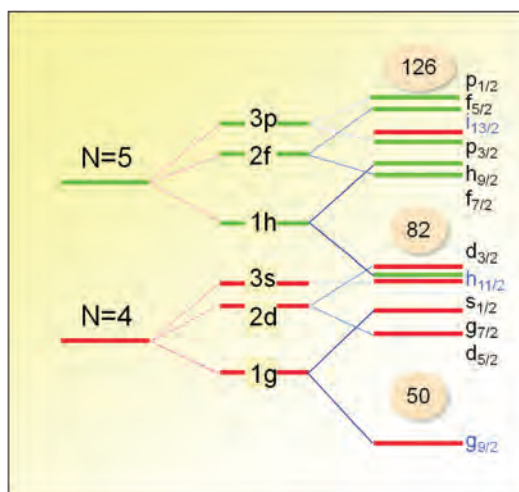


Figure 1. The shell structure of atomic nuclei can be modeled as a modified three-dimensional harmonic oscillator. This shell structure gives rise to gaps in the energy spectra for neutrons and protons at *magic numbers* of 50, 82 and 126. The orbitals are labeled by  $n\ell j$ , where  $n$  is the number of nodes in the wave function,  $\ell$  is the orbital angular momentum, and  $j$  is the vector sum of  $\ell$  and spin.  $^{78}\text{Ni}$ , with 14 neutrons beyond stability, is a doubly-magic nucleus with shell closures at proton number 28 and neutron number 50. To understand the shell structure of these neutron-rich nuclei, the RIBSS Center has played a leadership role in nuclear reaction studies with accelerated beams of  $^{82}\text{Ge}$  and beta decay studies of  $^{86}\text{Ge}$ ,  $^{83,84,85}\text{Ga}$ ,  $^{81,82,83}\text{Zn}$ , and  $^{79}\text{Cu}$ .

r-process nucleosynthesis, and subsequent freeze-out from the r-process, is reduced when the  $3s_{1/2}$  orbital is higher in energy. Another important input for r-process nucleosynthesis network calculations is the lifetimes of the unstable nuclei. The beta-decay group recently measured the lifetimes of  $^{82,83}\text{Zn}$ ,  $^{85}\text{Ga}$ , and  $^{86}\text{Ge}$  and determined that they are shorter than values used in theoretical r-process network calculations. If lifetimes being shorter than standard calculation predictions in this mass region turns out to be a common feature, it will impact r-process network

predictions of abundances of heavier nuclei, with mass greater than 140.

Beta decay half-lives can be reduced when the beta decay proceeds through allowed transitions to highly excited states that subsequently decay by neutron emission, a process known as beta-delayed neutron decay. The neutron detector array VANDLE, shown in Figure 3, is being commissioned to enable energy-resolved studies of the emitted neutrons, with detection efficiency as low as 150 keV in energy.

### Connecting Early Career Scientists to NNSA Laboratories

On May 24, 2011, RIBSS Center graduate students and postdoctoral scholars toured the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL) (Figure 4). This was part of a 1.5-day workshop hosted by the LLNL Physics Division, where students and postdoctorates made oral and poster presentations and learned about basic and applied research opportunities at LLNL.

Figure 2. The beta decay of  $^{81}\text{Zn}$  populates low and higher lying excitations in  $^{81}\text{Ga}$ . The relatively strong population of the  $J\pi=5/2^-$   $^{81}\text{Ga}$  ground state implies a  $J\pi=5/2^+$  ground state for  $^{81}\text{Zn}$ . Therefore, the  $1/2^+$   $3s_{1/2}$  state is an excited state in all  $N=51$  isotones, as predicted by nuclear shell model calculations (black squares) with realistic nucleon-nucleon interactions. Adopted from S. Padgett et al., Phys. Rev. C 82, 064314 (2010).

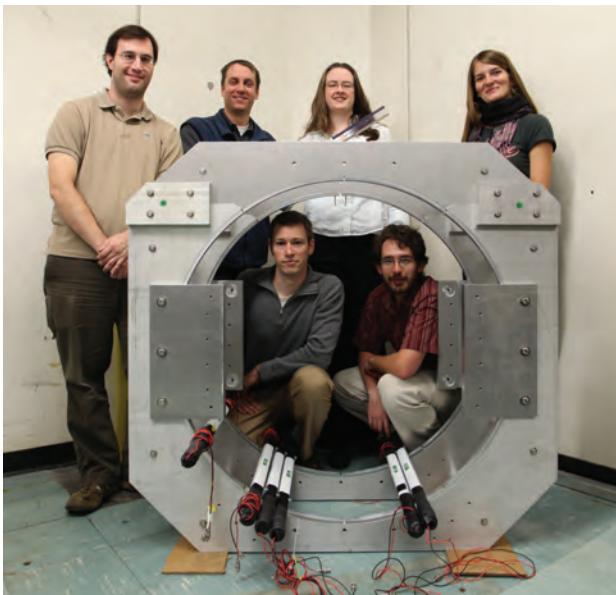
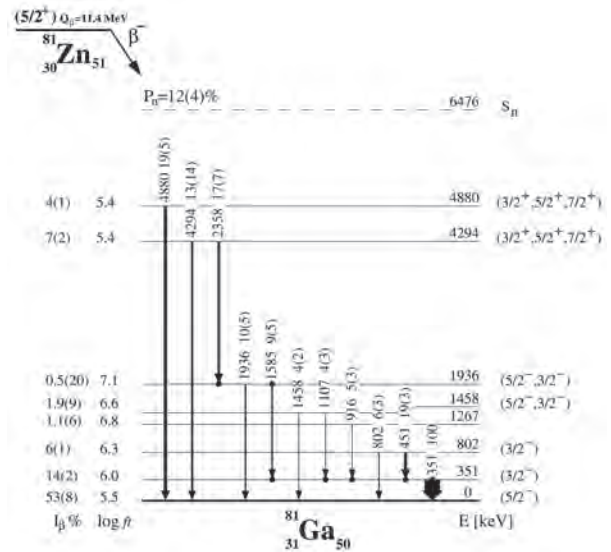
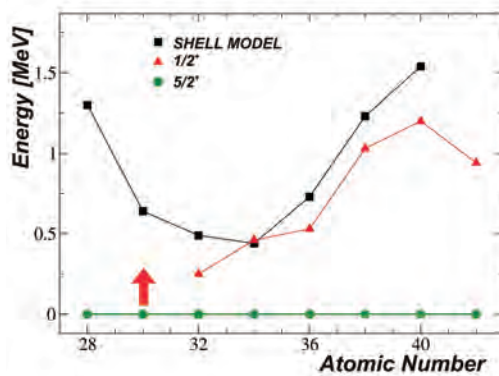


Figure 3. Graduate students and postdoctorates play key roles in the RIBSS Center team constructing the Versatile Array of Neutron Detectors at Low Energy. VANDLE will include a barrel of 100 60-cm bars of plastic scintillators with photomultiplier tubes at both ends to measure neutrons following beta decay of very neutron-rich atomic nuclei. Center: graduate students Brett Manning and Stanley Paulauskas; Top: postdoctorates Miguel Madurga, William Peters, Meredith Howard and graduate student Aleksandra Kuzniak.

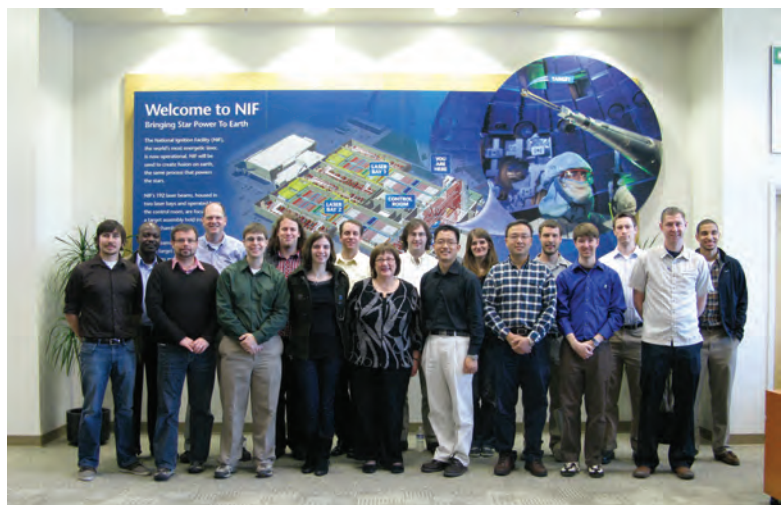


Figure 4. RIBSS Center graduate students and post-doctoral scholars visited the National Ignition Facility in May 2011 during a 1.5-day workshop hosted by the Physics Division at Lawrence Livermore National Laboratory.

## Digital Waveform Sampling of Neutron and Gamma Ray Signals from Scintillation Detectors for Pulse Shape Discrimination and Pulse Height Analysis

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New systems for the measurement of neutron and gamma-ray emissions from fissile material are required to ensure the safety, reliability, and performance of the U. S. nuclear stockpile. The detection, identification, and characterization of nuclear materials rely on the measurement of neutrons and gamma rays emitted by the materials in passive or active-interrogation scenarios. In particular, the neutron emission strength and energy spectrum is characteristic of the type and composition of the material under assay, and can be used for characterization. The development of new instruments to assay nuclear materials is the subject of extensive investigations at the national laboratories, in academia, and in the private industry. The current shortage of He-3 gas has motivated the search for new, alternative detection technologies. Among these, organic scintillators have shown much promise.

The University of Michigan was funded by the Stewardship Science Academic Alliances program to develop new algorithms to analyze the detected neutron and gamma ray pulses from organic scintillation detectors. Specifically, we are developing new algorithms for the neutron and gamma ray pulse shape discrimination (PSD) for digitized pulses from organic liquid scintillators. Figure 1a shows a photograph of our University of Michigan (UM) laboratory where benchtop experiments are performed to calibrate detectors and obtain data for the development of analysis algorithms. Figure 1b shows a photograph of measurements performed on pressurized water reactor fuel at the Joint Research Centre in Ispra, Italy. Graduate and undergraduate students assist in all research activities.

The PSD algorithms are crucial for distinguishing neutron pulses from gamma ray pulses when the deposited neutron energy is below 1 MeV, which is the energy threshold applied in many currently available systems. The current effort aims at lowering this energy threshold to well below 500 keV. This lower range of neutron energies is important in the fission neutron energy spectrum, which peaks around 800 keV. In addition, it is important to detect neutrons that may be down-scattered in moderating materials

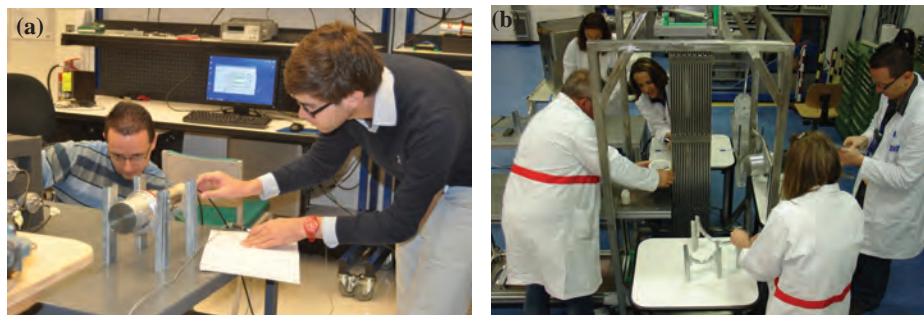


Figure 1. (a) UM intern Guillaume Chaud and Assistant Research Scientist Marek Flaska perform measurements with an organic liquid scintillator (Ann Arbor, September 2011); (b) Liquid scintillation detectors employed in measurements on pressurized water reactor fuel assembly at the Joint Research Centre in Ispra, Italy (May, 2011); Pictured from the bottom, counterclockwise: Jennifer Dolan, UM graduate student, Marek Flaska, UM Assistant Research Scientist, Sara Pozzi, UM Associate Professor, and JRC collaborators Alice Tomanin, graduate student, and Santino Frison.

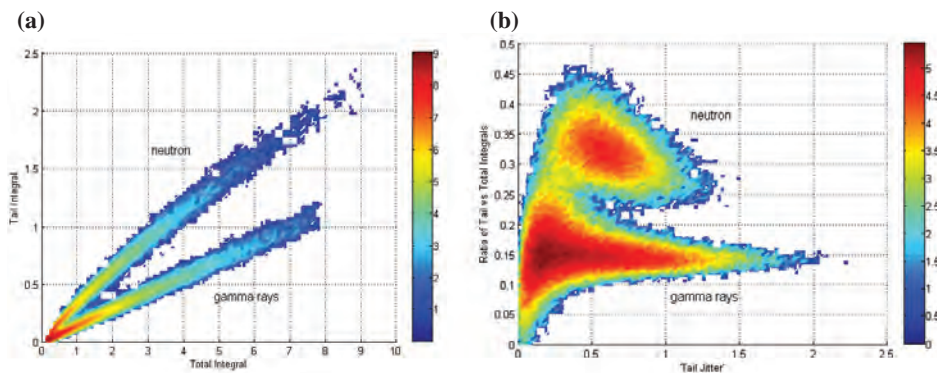


Figure 2. (a) Tail versus total integral PSD for neutron and gamma ray pulses from  $^{252}\text{Cf}$  spontaneous fission obtained with an EJ-309 liquid scintillator; (b) Same pulse data as (a) using the new PSD approach based on tail jitter analysis.

present within the nuclear material (for example plutonium-oxide compounds) or surrounding it (for example special nuclear material that is shielded with low-Z materials). Figure 2 shows the result of PSD algorithms applied to measured neutron and gamma ray pulses from a  $^{252}\text{Cf}$  source with a 40 keV threshold, corresponding to approximately 400 keV neutron energy deposited on a single scattering event on hydrogen. Figure 2a shows a traditional PSD approach based on pulse integration (tail vs. total pulse integral). Figure 2b shows a promising new approach based on the analysis of jitter that is more pronounced in the tail of the digitized neutron pulses when compared to the tail of digitized gamma

ray pulses. This effect is directly related to the increased excitation of scintillator triplet states when compared to singlet states with increasing mass of the recoil charged particle (electrons for gamma rays and protons for neutrons). This work was performed by UM graduate student Brian Wieger in collaboration with UM postdoctoral fellow Andreas Enqvist.

The new PSD algorithms developed at UM will allow a lower detection threshold in measurement systems that make use of liquid scintillation detectors. This approach will result in faster and more robust measurement systems for the detection and characterization of nuclear materials.



## Separation Procedure for the Isolation of Americium from Proton-Irradiated Plutonium

University of California, Berkeley

PI: Heino Nitsche (hnitsche@berkeley.edu)

Our work has the following two immediate goals: (1) Develop and test a radiochemical procedure necessary to perform a nuclear measurement important for stockpile stewardship and nuclear forensics, and (2) Train the next generation of radiochemists necessary for stockpile stewardship, nuclear forensics, nuclear power generation, and radiopharmaceutical industries.

Measuring the neutron-induced fission probability of the rare isotope  $^{240}\text{Am}$  is important for stockpile stewardship and nuclear forensics. However, performing this measurement is technically difficult due to the short half-life (about 51 hours) of  $^{240}\text{Am}$  and the complication that laboratory-source  $^{240}\text{Am}$  must be produced in a particle accelerator. Our previous work has shown that the most promising method for the production of  $^{240}\text{Am}$  is through the proton irradiation of  $^{242}\text{Pu}$ .<sup>1</sup> To produce enough material for a neutron-induced fission measurement, about 500 milligrams of  $^{242}\text{Pu}$  must be irradiated with protons from a particle accelerator. After such an irradiation, the irradiation target will be chemically processed to isolate approximately 100 nanograms of  $^{240}\text{Am}$  from the irradiated bulk  $^{242}\text{Pu}$  and several hundred nanograms of proton-induced fission products. These fission products produce a significant radiation dose field, which necessitates their removal from the americium. The development of such a separation procedure is complicated because of the large plutonium/americium mass ratio, the similar chemistry of americium and other nuclear reaction products, and the high radioactivity of the material.

We have developed a four-step separation procedure for isolating  $^{240}\text{Am}$  from proton-irradiated  $^{242}\text{Pu}$ . The procedure utilizes two anion exchange columns and two extraction chromatography columns to achieve the necessary separation of americium from plutonium and other reaction products. Undergraduate students, graduate students, and postdoctoral fellows have performed experiments with small quantities of  $^{239}\text{Pu}$  and  $^{241}\text{Am}$  to verify the efficacy of this procedure in isolating very small amounts of americium from large amounts of plutonium. Figure 1 shows an anion exchange column that has been loaded with a solution of plutonium and americium. The green band of plutonium

Figure 1. Anion exchange column loaded with an americium / plutonium solution. The plutonium, which forms anionic complexes in the acid solution, sticks to the column, as visible in the green band at the top of the yellow resin bed.



stays on the column while the americium (colorless) elutes to achieve separation.

Recently, we have focused on examining the behavior of the proton-induced fission products on our developed americium/plutonium separation procedure. Using measured cross section values for the proton-induced fission of  $^{242}\text{Pu}$ ,<sup>2</sup> it is evident that the most troublesome high dose-emitting fission products are  $^{97}\text{Zr}$ ,  $^{97}\text{Nb}$ ,  $^{99}\text{Mo}$ ,  $^{126,129}\text{Sb}$ ,  $^{140}\text{La}$ , and  $^{143}\text{Ce}$ . Thus, it is important to understand the behavior of these elements on the developed americium/plutonium separation procedure. Over the past year, we have examined the behavior of zirconium, niobium, antimony, and europium (europium models lanthanum and cerium behavior) on the separation procedure under a variety of experimental conditions. The best separation of these elements from americium was achieved when loading the anion exchange and extraction chromatography columns with

10 M hydrochloric acid, as shown in the elution curves shown in Figure 2. Under these conditions, americium, europium, and a fraction of zirconium are observed to elute from the column in the concentrated acid loading solution. Plutonium, niobium and a fraction of the zirconium are removed from the column under the reductive conditions containing hydriodic acid. Antimony was

not observed to elute from the column in either of these conditions. With the exception of zirconium, which has the tendency to form polynuclear hydrolysis products complicating its separation, these conditions provide a good separation of americium from high dose proton-induced fission products. The plot shown in Figure 2 is the first of four steps of the separation. During the next three steps, the americium will be rendered pure enough to allow for an accurate neutron-induced fission cross section measurement.

The Heavy Element Nuclear and Radiochemistry group at the University of California, Berkeley, led by Department of Chemistry Professor Heino Nitsche, has a long history of training students and postdoctoral fellows in low energy nuclear sciences essential to the NNSA mission. Second year PhD student Erin Gantz is shown working inside a plutonium containment glove box (see Figure 4 of the *Low Energy Nuclear Science Overview* on page 17). Students receive hands-on training in nuclear irradiation studies, nuclear decay spectroscopy, and actinide and fission product separation methods. These skills, techniques, and their underlying science are essential to the fields of nuclear forensics and stockpile stewardship science.

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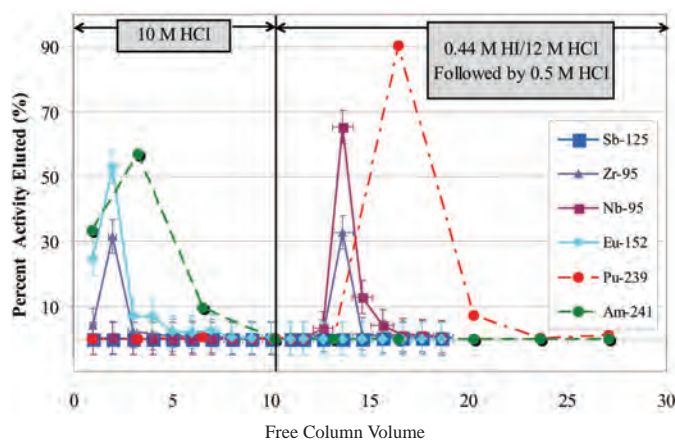


Figure 2. Elution curve of americium, plutonium, and model fission products from anion exchange resin columns in acidic media. Americium, which elutes immediately from the column, is effectively separated from niobium, antimony, and plutonium.

## Stewardship Science at the University of Richmond

University of Richmond

PI: Con Beausang (CBeausan@richmond.edu)

Authors: C. Beausang, R.O. Hughes, T.J. Ross, and A. Sharpe

The Richmond group, together with Lawrence Livermore National Laboratory collaborators, has been involved in the ongoing efforts to develop and benchmark the surrogate technique as a tool to measure neutron induced cross sections, both  $(n, f)$  and  $(n, \gamma)$ , on short lived nuclei. The surrogate technique utilizes a light charged particle transfer reaction and stable or long-lived target combination to populate the same compound system as the neutron-induced reaction of interest. Studying that system combined with nuclear theory allows us to obtain cross-section information on a reaction that would otherwise require a difficult or unfeasible measurement with a radioactive target and high neutron flux. The surrogate method has been shown to give excellent agreement with direct neutron induced fission measurements to within 5-10% over a wide energy range for several different light ion reactions on actinide targets.

In the last year, our group spent a significant amount of time based at Lawrence Berkeley National Laboratory. During this period, we performed several experiments using the STARS-LIBERACE detector arrays (Silicon Telescope Array for Reaction Studies – Livermore Berkeley Array for Collaborative Experiments) to benchmark the surrogate technique. In particular, we led an experiment investigating the efficacy of  $(p, d)$  and  $(p, t)$  light ion reactions as surrogates in the actinide region. By tagging on outgoing deuterons and tritons in coincidence with gamma rays or fission fragments, various  $(n, f)$  and  $(n, \gamma)$  cross-section measurements are obtainable. One preliminary result from this work is shown in Figure 1. Plotted is the ratio of  $N[{}^{236}\text{U}(p, df)] / N[{}^{238}\text{U}(p, df)]$  (points with error bars) compared to the accepted values for the  $[{}^{234}\text{U}(n, f)] / [{}^{236}\text{U}(n, f)]$  cross section ratio.<sup>1,2</sup>

In addition to surrogate measurements, we have recently shown that the combination of particle and gamma ray detection can be a very powerful tool for low-energy nuclear structure studies.<sup>3</sup> Graduate student Timothy Ross's PhD thesis project focuses on the change in structure of Gd isotopes with the onset of nuclear deformation. As a side product of our recent surrogate experiment studying

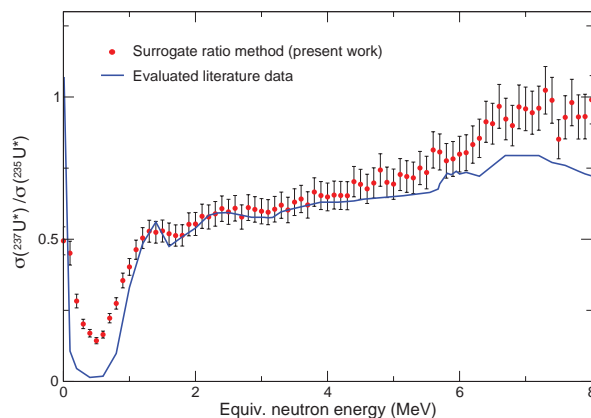


Figure 1. The ratio of the  ${}^{237}\text{U}$  and  ${}^{235}\text{U}$  neutron-induced fission cross sections. Results of our recent  $(p, df)$  surrogate measurement (data points) are compared to the ENDF VII neutron data (solid line).

Uranium isotopes, the structure of these nuclei can be studied in a similar vein. A brief analysis has revealed several new states and numerous new gamma rays in  ${}^{235}\text{U}$  and  ${}^{237}\text{U}$ .

While in Berkeley, the group was also able to partake in the commissioning of the next generation gamma ray spectroscopy array Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA). GRETINA is an array of seven quad module detectors, each containing four Germanium crystals. Each crystal is further segmented both longitudinally and transversely into 36 segments. The segmentation, coupled with sophisticated digital signal processing techniques, enables the interaction points for each gamma-ray interaction to be localized to  $\sim 1$ -2 mm in each direction leading to orders of magnitude improvement in resolving power, superb Doppler correction, improved peak-to-total and higher solid angle coverage, when compared with the best of the current generation of gamma-ray detection

arrays, e.g., Gammasphere. A picture of the group with the new array is shown in Figure 2. Masters student Aaron Sharpe will write his thesis on the response of the GRETINA detectors to high gamma-ray multiplicity events. Danyi Chen, a University of Richmond summer student, worked with us on a problem related to calibrating the energy response of GRETINA. The first science campaign utilizing GRETINA began in September 2011 with Richmond as a collaborating institution. The science aim is to perform the most detailed spectroscopy to date on very heavy elements in the vicinity of  ${}^{254}\text{No}$ .

## Reference

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<sup>2</sup>R.O. Hughes et al., submitted to *Physica Review C* (2011).

<sup>3</sup>J.M. Allmond et al., *Physical Review C* 81, 064316 (2010).

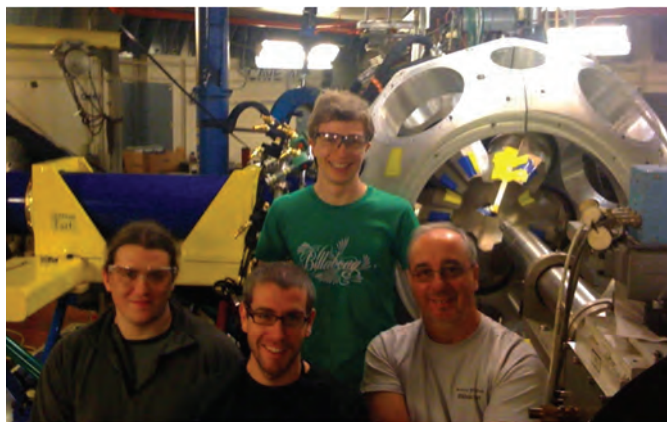


Figure 2. The Richmond group with the next generation gamma ray detection array, GRETINA. L-R: Aaron Sharpe, Richard Hughes, Timothy Ross and Con Beausang.

**Studies in Low Energy Nuclear Science**

Department of Physics and Astronomy, Ohio University

PI: Carl Brune (brune@ohio.edu)

Authors: Andreas Schiller, Carl Brune, Steve Grimes, and Tom Massey

Located in the hilly, southeastern corner of the state, Athens is host to Ohio University, Ohio's oldest institute for higher education. Here, the Department of Physics and Astronomy has run the Edwards Accelerator Laboratory for the last 40 years. The laboratory has specialized in nuclear astrophysics measurements, level density measurements, and other studies with neutrons.

**Boiling Nuclei**

Atomic nuclei share many similarities with liquid drops. Heating a nucleus will lead to protons and neutrons boiling off, just like steam from a boiling kettle. Just as higher temperatures will make steam production more prolific, heating nuclei more boils off more energetic nucleons.

Heating nuclei is not easy. It requires the nucleus to be struck by an energetic microparticle such as a proton. In our laboratory, an electric terminal that can be charged to +4 MV attracts negatively charged particles, which gain kinetic energy in the process (see Figure 1). Once they reach the terminal, they traverse a thin carbon foil or gas under reduced pressure. Contact with carbon or gas atoms will make the particles lose electrons, thus reversing their charge. The already energetic particles will now be repelled from the +4 MV terminal. They leave the accelerator and gain more kinetic energy along the way. The terminal voltage of +4 MV is utilized twice to transfer energy to beam particles; this acceleration concept is known as a tandem accelerator. The charging system of the terminal will soon be upgraded from a belt-driven Van de Graaff system to a Pelletron system.

The beam is directed to target nuclei, which are heated by reactions. We measure the number and energies of emitted nucleons to determine the temperature of the target nuclei. However, we also need to know the energy to heat nuclei to the measured temperatures in the first place. This is calculated from the beam energy, which is set by adjusting the terminal voltage, and the reaction Q-value which is tabulated. When both the energy and temperature of a nucleus are known, a third quantity, the entropy, can be determined.

Entropy is an important concept throughout physics. Colloquially speaking, it measures disorder. More specifically, it

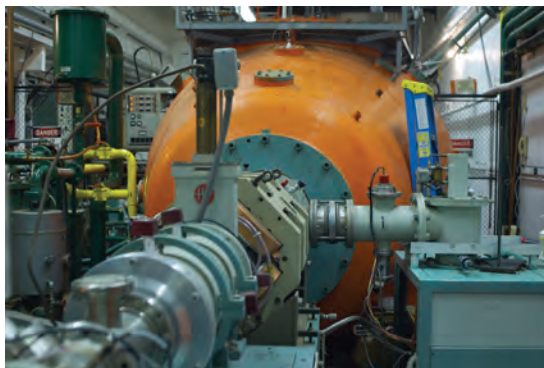


Figure 1. The orange tank (seen from the high-energy end) contains the +4 MV terminal and electron stripping system of the tandem accelerator.

measures the number of ways a given energy can be distributed across the degrees of freedom of a system. In a quantum system, entropy is connected to the level density. Level density is the result of our investigation of heated nuclei. Analysis of the angular distribution of the emitted particles yields the average spin of the excited levels. Theoreticians require knowledge of the nuclear level density of many nuclei to model diverse systems such as nucleosynthesis in stars, transmutation of elements in a reactor, and behavior of tracers in a National Ignition Facility shot.

**Detecting Neutrons**

Neutrons are neutral and hardly interact with electrons. This makes it difficult to develop a good neutron detection device.

To get detected, neutrons first transfer their energy to protons, which then knock electrons out of their orbits to produce a charge pulse, or a flash of light, which is electronically processed and analyzed. This process causes several problems. Neutrons rarely transfer all their energy to protons in the detection material. Therefore, unlike charged particles, which produce a signal in proportion to their energy, this connection gets lost for neutrons. Instead, the velocity of a neutron on its path between emission and detection is measured.

Also, the transfer of energy from a neutron to a proton requires the two particles to get close together (1 fm). Since such encounters are rare, large detection volumes are employed. This makes neutron detectors sensitive to background radiation, in particular gamma radiation. The problem with neutrons now turns into an advantage. Since neutrons transfer their energies to protons and not electrons as gamma rays do and since protons



Figure 2. Three neutron detectors sitting in the 30 m time-of-flight tunnel of the Edwards Accelerator Laboratory.

and electrons produce light flashes with different time structure, analysis of this time structure allows for differentiation between neutrons and gamma rays.

We have focused on characterizing neutron detectors as precisely as possible. The techniques we have developed are fast and allow calibration with energy steps and resolution typical for time-of-flight spectrometers. Our detector located in a 30 m long tunnel (see Figure 2), might be the best-calibrated neutron detector found anywhere. Groups from other institutions visit to calibrate their detectors against ours. We welcome researchers to make use of our facilities and interact with our students. For more information, visit <http://edwards1.phy.ohiou.edu/~oual/>.

# MATERIALS

## *Properties of Materials Under Extremem Conditions*

### Introduction

The Office of Stockpile Stewardship is responsible for ensuring that the laboratories can assess the condition of the U.S. nuclear stockpile using the best available scientific tools. The ability of the nuclear weapons complex to assess and certify weapon performance depends upon the experience and data from historic full scale nuclear tests and the development of capabilities to predict, via physical models, the weapons' operation. In addition to supporting maintenance of the stockpile, predictive capability is used for modeling of security options, resolving any concerns with regard to function of weapons if their condition goes beyond their original design space, and to avoid technological surprise. This mission requires accurate, validated and verified models. These models in turn require understanding the dynamic behavior of weapon materials over multiple time scales spanning conditions from ambient to extremes in pressure, temperature, and strain rate found only in nuclear weapons and the cores of planets.

Prediction, therefore, depends upon experimental data-based models of materials performance. Materials in an operating nuclear weapon are subjected to the most extreme of conditions, conditions that change at very high rates and also vary, as the materials themselves couple and feedback to their changing environment. The result is a dynamic situation that is highly non-linear, complicating attempts to unravel the inner workings that couple the scale of a nucleus to the engineering scale of the weapon. Physical processes include materials crystal structure and density, which are modeled by equations of state (EOS) to inform engineering hydrodynamic models; constitutive properties such as strength and the moduli that describe elastic and plastic behavior; damage and failure, which depend on microscopic processes that manifest themselves as macroscopic effects such as spall or fracture; and the complex kinetics and dynamics that carry matter from solid to high-temperature plasma. In addition, high explosives provide chemical energy, which dynamically couples with materials' response and must be well understood to enable predictive modeling.

Consider material response under dynamic, high-pressure loading. At a



Figure 1. EBSD through thickness map of a section taken from a flyer plate-driven, shock-loaded copper specimen. The polycrystalline material in the bottom portion of the image is the flyer plate. The dark spots in the image across the target are voids.

fundamental level, very few materials demonstrate homogenous isotropic behavior. Variability on a microstructural (approximately 1 to 100 micrometer) or even atomic scale influences bulk behavior. The effects of defect generation, chemical composition, shock-induced chemistry, grain boundaries, grain orientation and phase transformations within a material will often influence its dynamic behavior. A core part of weapons material research is dedicated to testing materials at discrete states to piece together the puzzle, which governs the dynamic behavior in a fully integrated configuration.

### Spall

One manifestation of damage under shock-loading is spall. In this mechanism, a material is shocked on one side and the shock wave propagates through the material. This shock is characterized by the material being very compressed at the front of the wave. The shock front reaches the other side of the material and a release wave is launched back into the material. This wave is characterized by a front that pulls material, rather than pushing it together. This release wave can interact with another release wave propagating in the opposite direction to create a strong region of tension at their intersection. Small gaps or voids may open up in the material. If there is enough energy in the tension, the material can be torn asunder when the voids connect to one another, forming a spall plane. The details of how and where the voids form (nucleate),

connect to one another, and ultimately form the spall plane has been an active area of research for many years.<sup>1</sup>

Figure 1 illustrates the complexity of formation of a spall plane in a metal.<sup>2</sup> In this example, a copper specimen was shock-loaded at a pressure below which a complete spall plane would form but high enough to generate voids in the specimen. This condition is called incipient spall. The figure shows the Electron Backscattering Diffraction (EBSD) map of a slice of the specimen post-shot. The colors denote the crystallographic orientation in the direction of shock propagation: blue is [111], green is [101] and red is [001]. Voids formed both within individual grains of the specimen and form along a grain boundary. In a hydrodynamic sense, the spall plane would form a horizontal line across the slice as this is the point of greatest tension in the specimen during the unloading of the material. Note, however, that the voids can form away from the general plane as shown by the voids formed along the grain boundary in the left hand side of the image. Also, grains of different orientation have different numbers of voids within them. Clearly, details of overall material strength depend on strength of grain boundaries, the anisotropy due to grain orientation (and other factors such as loading rate, duration and dynamic form).

Figure 2 shows a comparison of another specimen's cross-section with a model that captures some of these effects. The

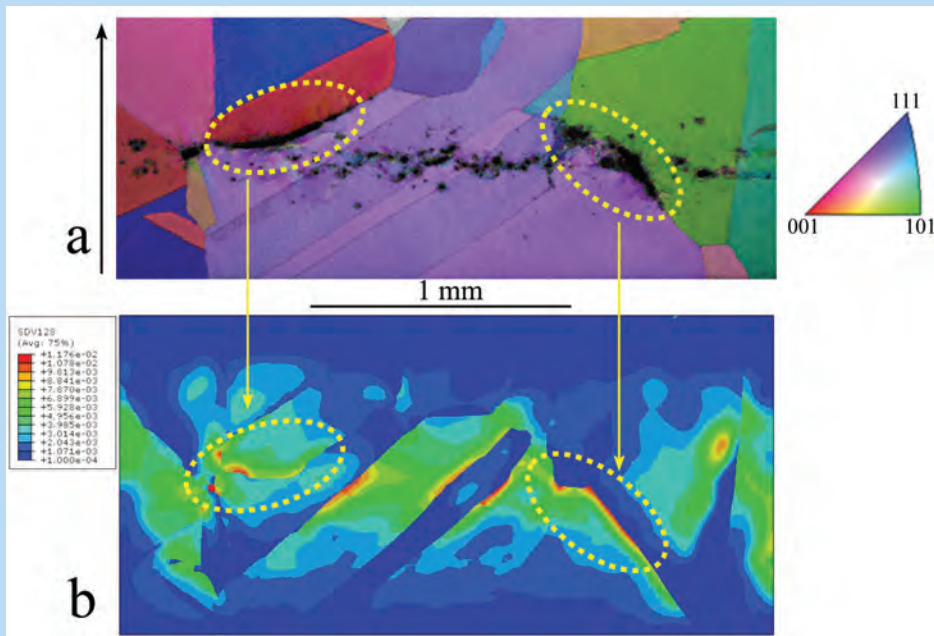


Figure 2. (a) Cross-section of an actual microstructure showing how spall damage (black areas) changes along different grains and GBs (interfaces). Shock direction is indicated by the arrow. (b) FE results for the same microstructure showing the evolution of damage along GBs.

complete discussion can be found in *3-D Characterization and Modeling of Spall Damage Sites* on page 30. Also discussed is a recent paper by Peralta et al. that shows both the distribution of grain boundaries as well as the relative misorientations between grains at the boundaries are important in understanding the development of spall.

### Phase Change and Structural Deformation

A material's response to high pressure can be manifested in ways other than failure. For example, the crystal structure can become unstable and the atoms of the material rearrange to form a new structure or phase. The physical rearrangement of the atoms can take the form of a new solid phase or the material may melt. Under very extreme conditions of energy deposition, the material may transform to what is known as warm dense matter (WDM). In this state, the matter has the density of a solid but is so hot that it is a plasma. WDM is difficult to create and even more difficult to probe but is important for inertial confinement fusion and astrophysical phenomena. One means of investigating the EOS and other properties of WDM is through ultrashort pulse x-ray methods. This is discussed in the article entitled *X-ray Spectroscopy of Warm and Hot Dense Matter* on page 33.

The phase of a material at a given temperature and pressure depends on

the atomic level details of the material. Details such as bond strengths, intrinsic defects, kinetic barriers to atomic motion, the coupling between electronic structure and thermal motion are just some of the variables that determine a material's phase and how it changes phase. There are many ways to probe phase transformation through measuring the dynamics of variables such as those listed. Discussions of the various methods and what they tell us about phase change can be found in the articles by the Carnegie-DOE Alliance Center (CDAC) (see Figures 3 and 4), High Pressure Science and Engineering Center (HiPSEC) at the University of Las Vegas, Nevada, and the University of Alabama at Birmingham (see Figure 5), all of which are presented in this section.

Structural deformation of a material also depends on the microscopic to mesoscopic scales. Yield strength, flow due to creep, structural strength and hardness of a material all depend on atomic scale structure, intergranular orientation, grain size, etc. Grain boundaries in particular can impede transmission of deformation through the bulk material, or on a more macroscopic level, boundaries between layers in a multilayer specimen can exhibit an analogous effect. These topics are discussed in greater detail in the articles from HiPSEC and the University of Illinois at Urbana-Champaign.

### References

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- <sup>3</sup>*Statistics of Weak Grain Boundaries for Spall Damage in Polycrystalline Copper*, Scripta Materialia, 63, 1065-68, (2010).

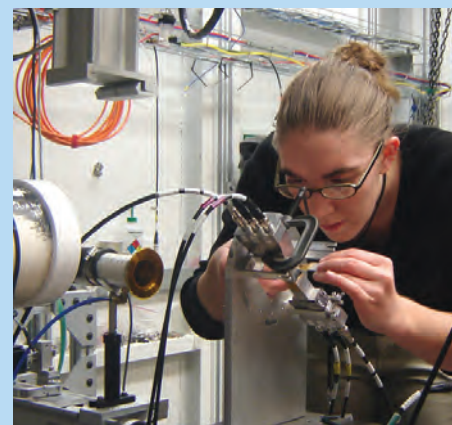


Figure 3. Lisa Mauger (California Institute of Technology) makes final adjustments on the NRIXS instrument prior to data collection at HPCAT.

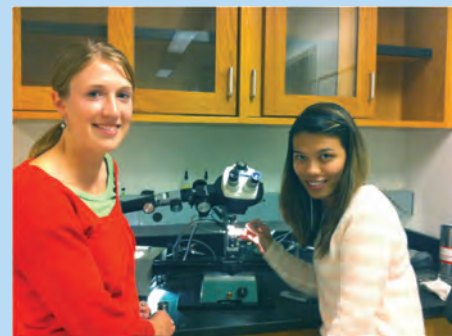


Figure 4. Pamela Kaercher (left) and Jane Kanitpanyacharoen (right) load a sample into a diamond anvil cell in the lab at Berkeley.



Figure 5. Physics graduate student Jeffrey Montgomery (right) and undergraduate student John Owens (left) studying electrical conductivity of heavy rare earth metals under high pressures using designer diamonds.

## Condensed Matter Dynamics at Extreme Conditions

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Dynamic compression experiments subject materials to large compressions, deformations, and high temperatures on very short time scales (ps to  $\mu$ s) resulting in a rich array of physical and chemical changes. These experiments are ideal for achieving a fundamental understanding of condensed matter dynamics at extreme conditions and are central to NNSA's Stockpile Stewardship Program (SSP) mission.

Scientific activities at the Institute for Shock Physics (ISP), a multidisciplinary research organization, are focused on a continuum-to-atomic scale understanding of the following shock wave induced condensed matter phenomena: structural transformations, deformation and fracture, and chemical reactions.

The shock physics effort at Washington State University (WSU) has a 55 year history of research innovations and educational excellence. The American Physical Society's Shock Compression Science Award has been awarded to WSU graduates and faculty on six occasions among the thirteen awards to date. The Institute, established by the DOE/Defense Programs in 1997, supports the SSP mission through the following activities:

- Conduct innovative and exciting research;
- Educate and train the next generation of scientists; and
- Develop meaningful collaborations with the NNSA Laboratories.

### Research and Education Highlights

The Institute's research activities emphasize real time, multiscale measurements and related analysis and provide students and postdoctorates with strong hands-on training in shock wave and static high pressure research. During 2010-2011, five ISP graduate students and postdoctorates moved on to employment at one of the NNSA Laboratories. Representative research activities include:

#### *Measurements of the Refractive Index of Shocked Diamond Crystals*

John Lang (Figure 2), as a part of his PhD work, measured refractive index changes in diamond crystals shocked along the [100] and [111] orientations to 90 GPa. The refractive index changes along [111] showed good agreement with linear photoelasticity. In contrast,



Figure 1. Many of the ISP Graduate Students and Research Associates.

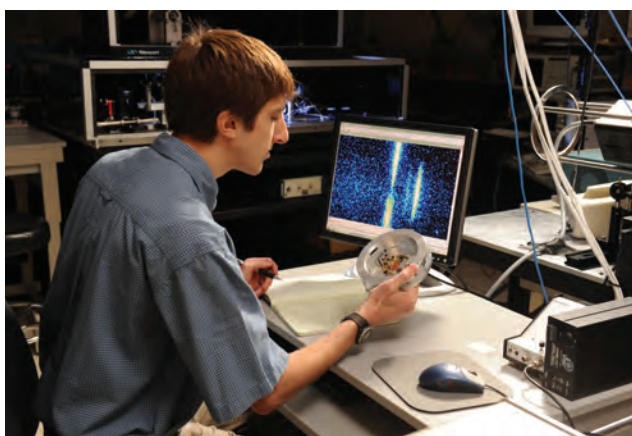


Figure 2. John Lang's research has focused on the mechanical and optical response of shocked diamond crystals.

the refractive index changes measured along [100] required the use of nonlinear photoelasticity. Apart from photoelasticity studies, this work has provided the results to use [100] and [111] diamonds as high-impedance optical windows in shock experiments. John Lang, Graduate Student.

#### *Shockless and Shock Compression of Brittle Single Crystals*

For his PhD Thesis, Brandon LaLone conducted shockless and shock compression experiments on x-cut and z-cut quartz crystals and showed that the shockless elastic limit of both quartz crystals was higher than the shock wave elastic limit. This elastic limit increase, with a decrease in loading rate, is contrary to the expected loading rate dependence of strength, and cannot be explained using current inelastic deformation models. A strain energy localization model was developed to explain the observed loading rate dependence for the quartz elastic limit. Shock wave experiments on gadolinium gallium garnet crystals showed that the measured elastic limits depend on the impact stresses. Brandon LaLone, PhD (June 2011).

#### *Dynamic Response of Aluminum (Al) Single Crystals*

Deep Choudhuri investigated the dynamic response of Al single crystals to examine material anisotropy at high shock stresses. Single crystals were shocked along [100], [110], and [111] orientations to peak stresses ranging from 42 - 70 GPa. Although the Hugoniot curves were comparable for all three orientations, the longitudinal sound speeds (and the corresponding elastic moduli) displayed anisotropy over this stress range. Deep Choudhuri, Postdoc

#### *Acoustic Properties of Polymers at High Pressures*

To gain insight into the mechanical response of polymers under high pressure, the acoustic properties of four polymers compressed to more than 5 GPa in diamond anvil cells were determined using the impulsive stimulated light scattering method. The longitudinal acoustic velocities for all four polymers displayed nonlinear pressure dependence. The acoustic velocities converged above 2.5 GPa due to the reduction of free volume in the polymers. These findings are important for understanding and

modeling the response of polymers at extreme conditions. Zbigniew Dreger, Senior Scientist, Jufei Zhou, former postdoctorate, and Nhan Dang, former postdoctorate (now at Los Alamos National Laboratory [LANL.]

#### Dynamic Tensile Response of Zirconium-based Bulk Amorphous Alloys

Pablo Escobedo conducted plate impact experiments to examine the dynamic tensile response of Zirconium-based bulk amorphous alloys (BAA) at high strain rates ( $\sim 10^5$ - $10^6$  / s). Tensile damage in the soft-recovered BAA samples showed both a brittle response and a ductile response. The fracture response and resulting fracture morphologies were related to three key features of dynamic uniaxial strain tension, and changes in the free volume of the BAAs. J.P. Escobedo, former Postdoc, now at LANL.

#### Carrier Lifetime Measurements in Shock-Compressed Gallium Arsenide

Carrier dynamics, an important characteristic of semiconductor devices, was examined in GaAs: Te shocked along [100] to 4 GPa, using time-resolved photoluminescence (PL). (See Figure 3) PL signals extending over five orders of magnitude and comprising several recombination mechanisms were detected in single-event experiments. In marked contrast to hydrostatic pressure results, a linear lifetime reduction was observed under uniaxial strain. Significant loss of carrier lifetimes suggests a decrease in quantum efficiency at high strains. Paulius Grivickas, Research Associate.

#### Material Strength of Shocked Crystals from Real-time, X-ray Diffraction (XRD)

Stefan Turneaure, Research Scientist, has developed a new approach using real time, XRD measurements to determine the material strength in the shocked state. Figure 4a shows ambient and shocked diffraction peaks. The horizontal peak shift provides the volume averaged longitudinal elastic lattice strain, which is related to strength. The strength results for Al[100] are in good agreement with the strength obtained from continuum measurements. Because of the non-contact aspect of the XRD approach, it will have broad applicability at extreme conditions. Stefan Turneaure, Research Scientist.

#### Collaborations and Outreach

Collaborations with scientists at the NNSA Laboratories provide a valuable research experience for ISP students and researchers. For example, the shockless compression activities at the Institute

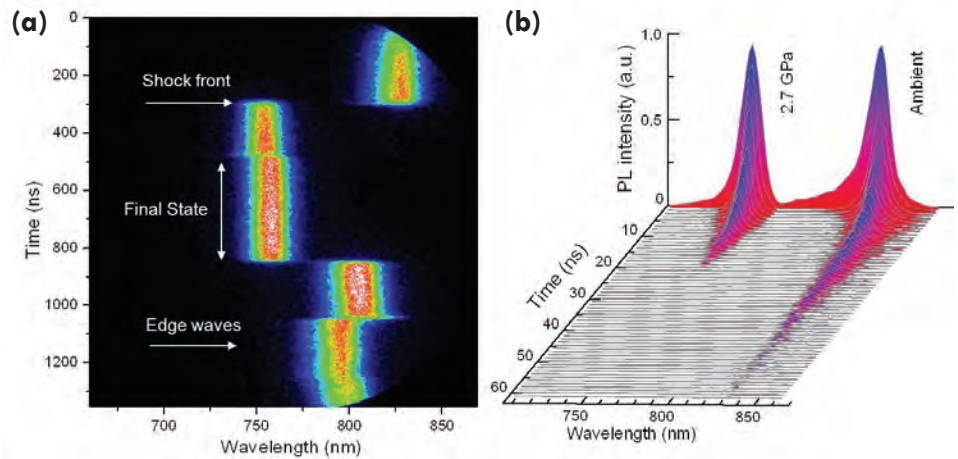


Figure 3. PL data from 2.7 GPa experiments. (a) Band gap shifts. (b) Carrier dynamics.

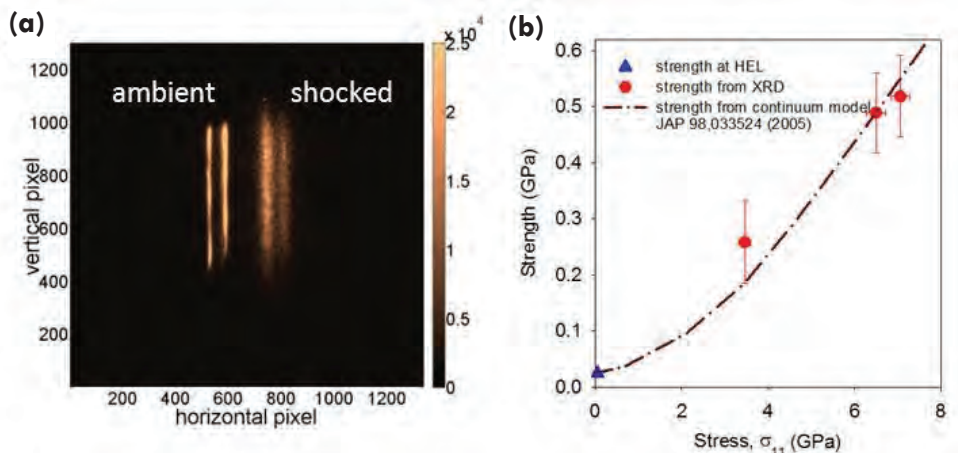


Figure 4. (a) Diffraction peaks for Al[100]. (b) Strength results for Al[100].

resulted from the strong interactions with the Pulsed Power Sciences Center at Sandia National Laboratories (SNL). Brandon LaLone, the first graduate student with significant experience in shockless compression research, completed his PhD in June, 2011. Extending a previous collaboration with Dr. Alison Kubota (LLNL), a modeling/simulation collaboration with Dr. Jon Zimmerman (SNL) resulted in a publication linking molecular dynamics simulations to continuum calculations. In 2011,  $\sim 45$  scientists from the NNSA Laboratories completed Professor Gupta's shock wave course via video conferencing. As in previous years, the course received excellent reviews.

To create a new paradigm for dynamic materials research, the Institute is partnering with the Advanced Photon Source (APS) to establish a DOE/NNSA-supported user facility: Dynamic Compression Sector (DCS@APS) to focus on time-resolved x-ray diffraction and imaging measurements in dynamically compressed materials.

The energies (hard x-rays) and the time-structure (ns-separated pulses) of the APS x-rays are uniquely suited to examine time-dependent changes in materials subjected to a broad range of peak stresses ( $\sim 5$  GPa to above 100 GPa) and time-durations (tens to several hundred ns). DCS@APS, with its emphasis on materials science activities using a variety of dynamic compression platforms, will be an excellent complement to other user facilities that emphasize static pressure materials response, warm dense matter response, and dense plasma response.

For additional information, please visit [www.shock.wsu.edu](http://www.shock.wsu.edu).

## Carnegie-DOE Alliance Center Students Advance Extreme Conditions Science

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Graduate students in the Carnegie-DOE Alliance Center (CDAC) are taking advantage of cutting-edge experimental techniques to address key questions in extreme conditions science that were intractable only a few years ago. In recent work carried out at Sector 16 (High Pressure Collaborative Access Team (HPCAT)) at the Advanced Photon Source (APS), CDAC graduate students Jorge Munoz and Lisa Mauger (see *Materials Overview*, Figure 3, page 25), from the research group of CDAC academic partner Brent Fultz at Caltech, observed for the first time how vibrations of atoms in a crystal lattice (phonons) can stabilize an ordered phase more than a disordered phase. This is opposite to what has been exclusively observed until now; usually the stronger chemical bonds of an ordered phase cause its atoms to vibrate less at a given temperature, giving it the lower vibrational entropy. Munoz and Mauger collaborated on the project with Matt Lucas and Mike Winterrose, former CDAC graduate students also from Caltech.

The higher vibrational entropy of the ordered phase in the equiatomic alloy FeV, which has a body-centered cubic parent lattice, was determined by combining measurements from inelastic neutron scattering performed at the ARCS instrument at the Spallation Neutron Source and nuclear resonant inelastic x-ray scattering measurements performed at HPCAT. This combination of measurements allowed for an accurate determination of the phonon density of states (DOS) and the opportunity to study the iron and vanadium motions separately through their partial DOS (pDOS) curves, as shown in Figure 1. All the lattice vibrations shift to lower energies and have higher entropy upon ordering, but the effect is more prominent for low-energy transverse vibrations than for longitudinal vibrations. The effect is also stronger for vanadium atoms than for iron atoms. Computational studies using first-principles calculations indicate that this effect originates at the electronic level. The ordered alloy has more electrons available to screen the displacements of moving atoms, especially the vanadium atoms.

This new correlation between the change in the electronic structure of a particular

atom in a system and the shift in energy of the pDOS of that atom appears to be quite general and can potentially be used to study other systems. A fundamental understanding of the vibrational entropy and the interaction of phonons and electrons at moderate temperatures could lead to more accurate predictions of stable phases in all systems. This work has shown that changes in the electronic structure of a system, even when the coordination number and the bond length remain unchanged, can have important and unexpected effects on the phonon DOS and the overall thermodynamics.

Diffraction techniques are widely used in extreme conditions research, and CDAC graduate students Pamela Kaercher and Jane Kanitpanyacharoen (see the *Materials Overview*, Figure 4,

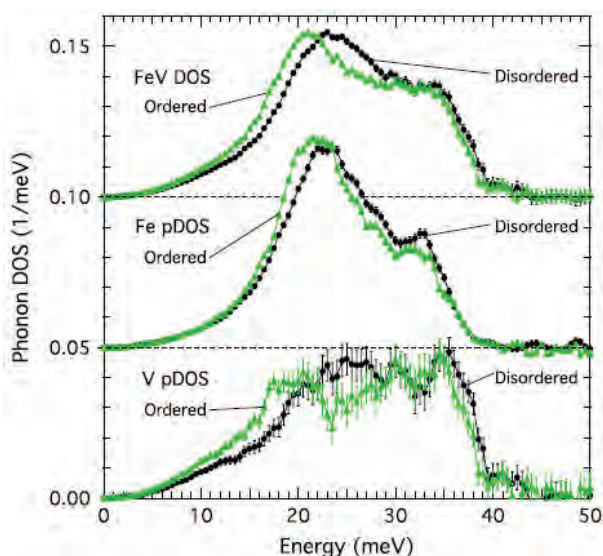


Figure 1. Neutron-weight corrected phonon DOS curve of FeV samples (top), along with Fe pDOS (middle), and V pDOS (bottom) curves. The Fe pDOS curves were determined directly with x-ray scattering, while the total FeV DOS curves and the V pDOS curves were determined with neutron scattering. [Munoz, et al. *Phys. Rev. Lett.* 107, 115101 (2011).]



Figure 2. Powder diffraction patterns of polycrystalline hafnium metal at various conditions. More homogeneous diffraction rings in the pattern on the right show that higher temperatures reduce twinning activity at high pressures. [Kanitpanyacharoen et al., *Acta Mater.*, in press]

page 25) from CDAC academic partner Rudy Wenk's group at Berkeley are now using neutron diffraction to study texture development in metals at high pressure and temperature.

At the Los Alamos Neutron Science Center, the group has been able to use the unique capabilities of the high pressure preferred orientation diffractometer to measure the change in texture in situ during hcp-bcc-hcp phase transformations in the hexagonal metals titanium and zirconium. A finding of regular variant selection during the phase transformation sequence suggested further work on uranium, a low-symmetry metal. Currently, the Wenk group is exploring whether an orthorhombic structure will retain a memory of its orientation after transforming to a cubic structure.

Experiments on the alloy U-0.7Ti show that at high pressure and under applied stress, this brittle material becomes ductile, and a very strong texture develops at 4 GPa and room temperature, with texture memory and regular variant selection, but without excessive grain growth.

Various metals even within the same chemical family display quite different behaviors under pressure and stress, and developing a systematic picture of texture development at high pressure has been a goal of the Wenk group for some time. A very important recent observation with hafnium metal, which is a Group 4 metal along with Ti and Zr, shows that increasing temperature at high pressure reduces twinning activity, even under applied stress (see Figure 2).



## High Pressure Science and Engineering Center (HiPSEC)

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## Revealing the Creep Mechanism and Phase Transition in Superhard Materials

The University of Nevada, Las Vegas (UNLV) HiPSEC researchers led by Professor Changfeng Chen recently performed first-principles calculations that reveal boron's unique ability to form both two- and three-center bonds under strain, which opens up new channels for structural deformation and transformation. These three-center covalent bonds become less rigid and directional, which gives rise to metallic-like creeping behavior along selected soft-bond deformation paths in superhard  $\gamma$ -B<sub>28</sub>. Figure 1 shows the theoretical tensile stress as a function of tensile strain. In most directions, we see typical steep rise followed by abrupt drop of the stress past the elastic limit. However, in the [011] direction, the stress stays within a narrow range over a large range of strain, which is atypical for strong covalent materials. These results have important implications for mechanical properties of other boron systems where three-center bonds are vital in forming the stable structures. In another recent work, Chen's group also studied cold-compressed graphite using *ab initio* calculations. The results revealed that the phase transformation initiates and proceeds along the pathways with lowest enthalpy toward a newly identified sp<sup>3</sup>-orthorhombic W-carbon phase or the previously proposed monoclinic M-carbon phase. These results offer key insights for understanding the graphite-to-diamond transition. (W. Zhou, H. Sun and C. F. Chen, *Phys. Rev. Lett.* 105, 215503 (2010); J. T. Wang, C. F. Chen, and Y. Kawazoe, *Phys. Rev. Lett.* 106, 075501 (2011). Contact: chen@physics.unlv.edu)

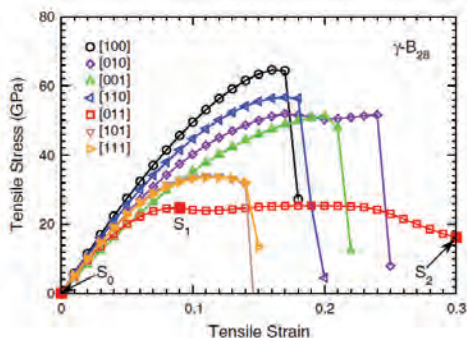


Figure 1. Calculated stress-strain relations of  $\gamma$ -B<sub>28</sub> in various tensile deformation directions. Under the [011] tensile strain,  $\gamma$ -B<sub>28</sub> exhibits creep-like behavior.

New Compound in the Fe-O System: Fe<sub>4</sub>O<sub>5</sub>

The peculiar properties of iron oxides have triggered scientific curiosity for thousands of years. In spite of extensive investigation, only three compounds have been reported so far: FeO, Fe<sub>3</sub>O<sub>4</sub> and Fe<sub>2</sub>O<sub>3</sub>, often showing large degrees of non-stoichiometry. Professor Barbara Lavina and coworkers show that extreme conditions of high pressure and temperature stabilize a new compound, Fe<sub>4</sub>O<sub>5</sub>, retrievable to ambient conditions. The atomic ordering at Fe/O=0.8 changes with pressure from a mixture of cubic oxides with 4 and 6-coordinated iron, typically showing extensive defects and coherent clusters of ordered vacancies and interstitials, to a layered structure, represented in Figure 2, where iron is 6-coordinated in edge sharing octahedra and trigonal prisms.

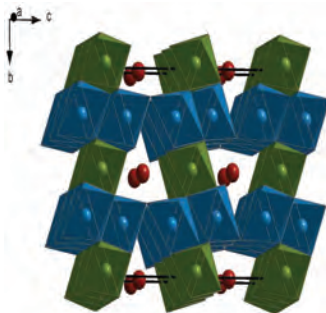


Figure 2. Crystal structure of the new iron oxide compound, Fe<sub>4</sub>O<sub>5</sub>, formed at high P-T conditions. In blue and green are represented edge-sharing FeO<sub>6</sub> octahedra in two distinct crystallographic positions, red spheres represent iron in a larger trigonal prism coordination. Black lines are the edges of the unit cell.

The finding has a broad significance, spanning planetary science, physics, and materials science. A recoverable, magnetic iron oxide might find technological applications as well. Being a relatively reduced phase, we infer that Fe<sub>4</sub>O<sub>5</sub> is a plausible accessory phase of the deep Earth's interior, a phase that would affect redox equilibria and the behavior of iron in the mantle. (Lavina et al., *Proc. Nat. Acad. Sci.*, 1107573108, (2011). Contact: lavina@physics.unlv.edu)

## The Observation of a Pressure-Induced Spin Transition in FeSe Superconductor

Professor Ravhi Kumar and his team have observed the Fe K- $\beta$  emission spectra as a function of pressure up to 16 GPa at

room temperature (RT) and up to 8 GPa at low temperature (8K). A main peak (K $\beta$  1, 3) at 7058 eV, and a satellite peak (K $\beta$ ') around 7045 eV were observed due to the 3p and 3d shell interaction in FeSe (see Figure 3). The K $\beta$  emission spectra corresponding to FeO in which Fe is in the high spin state and FeS<sub>2</sub> in which Fe is in the low spin state.

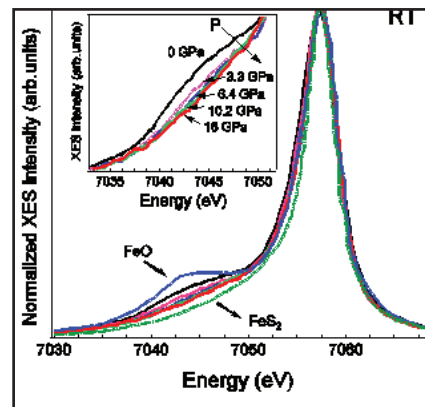


Figure 3. X-ray emission spectra collected for FeSe at room temperature at various pressures. The inset shows the changes observed in the satellite peak intensity as a function of pressure.

Around 16 GPa, the satellite peak intensity is considerably reduced and the emission spectrum tends to become a single peak structure and closely resembles the x-ray emission (XES) spectrum of low spin Fe in FeS<sub>2</sub>. The team also observed similar changes in the XES spectra obtained at the low-temperature (8K) at high pressures up to 8 GPa, where the suppression of the XES intensity of the satellite peak at low temperature and high pressure is gradual in comparison with RT. In both cases, a high spin-low spin transition for Fe on application of pressure was observed. These results are consistent with the results of spin-lattice relaxation measurements in the nuclear magnetic resonance experiments which reveal enhanced spin fluctuations with pressure and show competing antiferromagnetic (AF) spin fluctuations with superconductivity. The experiments further indicate that the observed spin transition and spin fluctuations are mainly caused by the Fe d-electrons in the conduction band since the s-electron density is reported to be less sensitive with applied pressure. (Ravhi Kumar et al., *Appl. Phys. Lett.* 99, 061913 (2011); doi:10.1063/1.3621859. Contact: ravhi@physics.unlv.edu)

### 3-D Characterization and Modeling of Spall Damage Sites

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Correlations between spall damage and local microstructure were investigated using polycrystalline copper samples via laser-driven plate impacts at low pressures (2-6 GPa). Electron backscattering diffraction was used to relate the presence of porosity to microstructural features such as grain boundaries (GBs). Preferred void-nucleation sites were identified in terms of their crystallography via statistical sampling in serial sectioned specimens, for as-received (AR), heat treated (HT), and fully recrystallized (FR) microstructures. Results indicate that terminated twins and GBs with misorientations between 25° and 50° are preferred for damage localization in AR specimens, whereas the tendency for damage in this misorientation range, although still present, is less pronounced in FR microstructures, as shown in Figure 1. The HT microstructure (not shown) produced results similar

This indicates that pre-strain removal from AR material via heat treatment decreases the strength of the bulk, which then competes effectively with GBs to localize damage. This decreases the dominance of intergranular damage nucleation and allows for a mix of intergranular and transgranular voids, while reducing the preference for damage localization for misorientations between 25° and 50° seen in the AR microstructure. The spall voids in the samples were reconstructed using x-ray tomography, and it was found that damage on the spall plane contained a uniform spatial distribution of pores, indicating one-dimensional loading conditions. Preliminary results obtained from fitting the individual voids to a best-fit ellipsoid are shown in Figure 2. Results indicate that transgranular damage (spherical) is pronounced in the FR samples, whereas intergranular damage and void coalescence (disc and needle shapes) are dominant in the AR sample, matching the results obtained from the crystallographic statistics. The trend for samples with HT microstructure (not shown) was similar to that for FR samples. This indicates a strong effect of microstructure and initial material condition on spall void nucleation and growth.

Finite element (FE) analysis of the experiments has been performed to study damage evolution as affected by local

geometry and crystallography. The flyer is modeled as a single crystal and the target is sub-divided into grains with different orientations. A crystal plasticity model that includes an equation of state is used along with void nucleation and growth criteria (the Gurson - Tvergaard - Needleman model) to predict initiation and evolution of damage. The experimental results and the predicted fraction of voids are shown in the *Materials Overview* on page 25, Figure 2. In Figure 2a below, grain colors represent their crystal orientations parallel to the shock direction, with orientations given in the stereographic triangle to the right. In Figure 2b, sites with a low volume

fraction of voids are blue, whereas regions with high volume fractions are red. The model predicts microstructural sites with significant damage localization; however, the extent of the damage is not always predicted correctly and there are instances of predicted damage concentrations that are not observed experimentally. Most of the discrepancies correspond to intergranular sites, which suggests a model for the intrinsic strength of GBs needs to be added to the simulation to improve the qualitative agreement with experiments. This work is currently in progress.

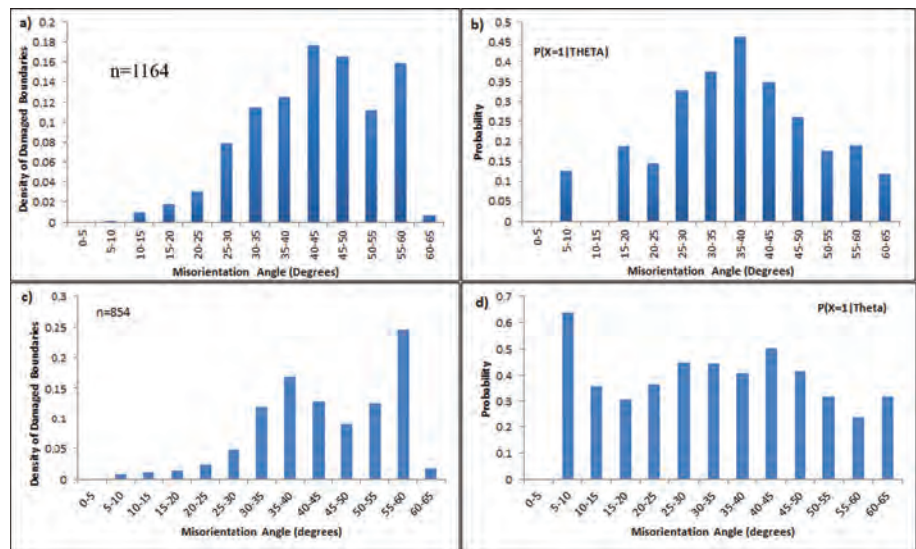


Figure 1. Statistics of weak GBs (a, c) Distribution of damaged boundaries in AR and FR samples, respectively. (b, d) Probability of a misorientation angle  $\theta$  present in the microstructure having damage in AR and FR microstructures, respectively.

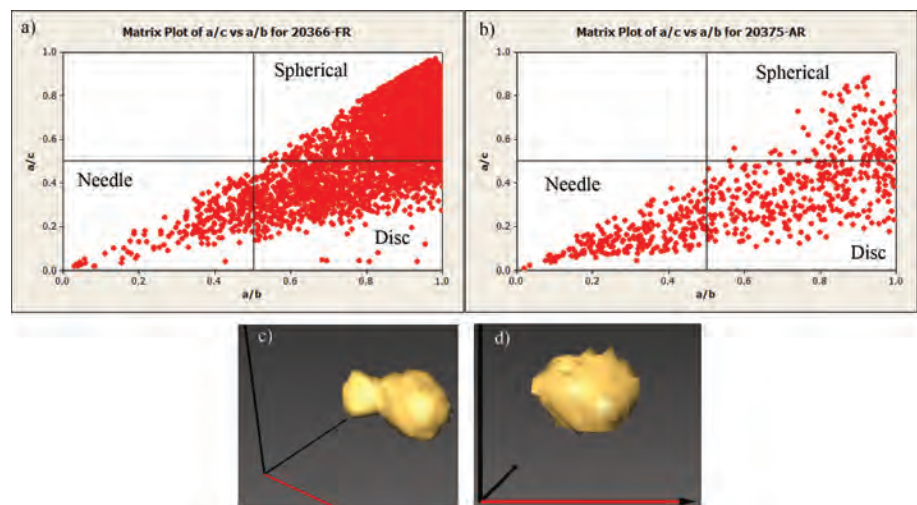


Figure 2. Distribution of void shapes based on best fit ellipsoids (semi-axes  $c \geq b \geq a$ ) of the experimentally measured voids for (a) FR and (b) AR microstructures. (c) 3D reconstruction of a needle-like void (two voids coalescing), and (d) 3D view of a spherical void.

**Dynamic Response of Nanostructured, Single and Multi-layered Materials**

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Interfaces are used to enhance mechanical properties of multilayered metallic systems. For example, in the Cu-Ag system, produced by deposition, the hardness increased with decreasing layer thickness with a lower rate of increase for layer thicknesses between 50 and 25 nm. Below this layer thickness range the hardness saturates to 4.5 GPa. To put this in perspective, this increase is about three times higher than anticipated by the simple rule-of-mixtures. This indicates a gap in our understanding of how deformation processes interact with, and are influenced by, interfaces at the nanoscale. One challenge is to understand if the collective, as opposed to the individual, response of the interfaces is responsible for this enhancement. Another challenge is to establish if similar improvements occur when these multilayered systems are subjected to different loading conditions; for example, high strain rate loading ( $10^3$  –  $10^6$  s<sup>-1</sup>) conditions at high stresses. This effort seeks to address these questions through a synergistic combination of modeling and multi-scale experiments.

The overall goal is to determine the mesoscale response of the interfaces and build the salient features into a modeling effort to determine how these responses *average* to determine the macroscale behavior. To achieve this goal, experiments will be conducted on samples at two different length scales, micro/nanoscale and macroscale, with both containing nanoscale sized interfaces. These multiscale experiments will span strain rates from  $10^3$  s<sup>-1</sup> to  $10^6$  s<sup>-1</sup>, in order to characterize the strength of the nanolayered materials, and to generate controllable microstructures for subsequent examination by transmission electron microscopy (TEM). The macroscale samples possessing nanoscale interfaces are produced as a cast eutectic Cu-Ag material system and the Cu-Ag or Cu-Au multi-layered nanoscale systems by deposition methods. The results from the macroscopic tests and characterization will be used as input to finite element simulations in which the high strength normal to the interfaces and low shear resistance along the interface are included; deformation twinning will be included in subsequent models.

Samples of a cast Ag-Cu eutectic alloy have been subjected to compressive

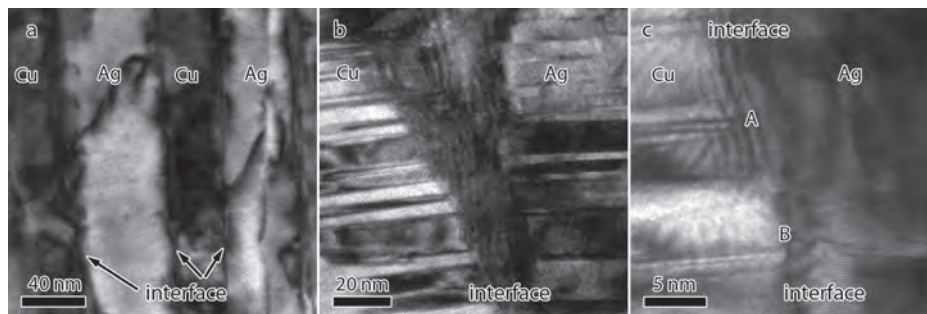


Figure 1. Comparison of the microstructure in a cast Ag-Cu alloy following compressive loading at a strain rate of  $10^3$  s<sup>-1</sup>, a stress of 350 MPa and 4% strain. Compare A and B to see distortion.

loading and the evolved microstructure determined by TEM. A series of electron micrographs, Figure 1, illustrate the different deformation microstructures that have been observed following a test at a strain rate of  $10^3$  s<sup>-1</sup>, a stress of 350 MPa and a strain of 4%. Figure 1a shows the underformed structure with distinct interfaces seen between the copper and silver layers. In this condition, the two layers appear to be compositionally distinct as determined from the profile of the energy dispersive spectroscopy signals. Figures 1b and 1c show the change in the microstructure and the interface following loading. Both layers show evidence of deforming by twinning rather than by dislocation slip, which at least for the copper layer is unexpected. Note the distortion of the interface as evidenced by the width of the interface in Figure 1b and the stepped and varying width interface seen in the high resolution image shown in Figure 1c, compare regions A and B. This interface distortion and rotation

may provide insight as to how the texture evolves during severe deformation. To address the former issue, samples are being deformed in-situ in the transmission electron microscope; this approach allows the response to be observed in real time and at appropriate spatial resolution.

These studies were performed on samples in which the interfaces were oriented randomly with respect to the loading condition, which makes correlating the structure to loading condition challenging. The undergraduate student who initiated the characterization study spent this past summer at Los Alamos National Laboratory preparing a set of alloys, including ones in which the interface direction is constant. These samples will be used for his graduate studies, and now the samples are being characterized and prepared for testing under different loading conditions. The results from these samples will be compared and contrasted with those obtained from multi-layered deposited films.

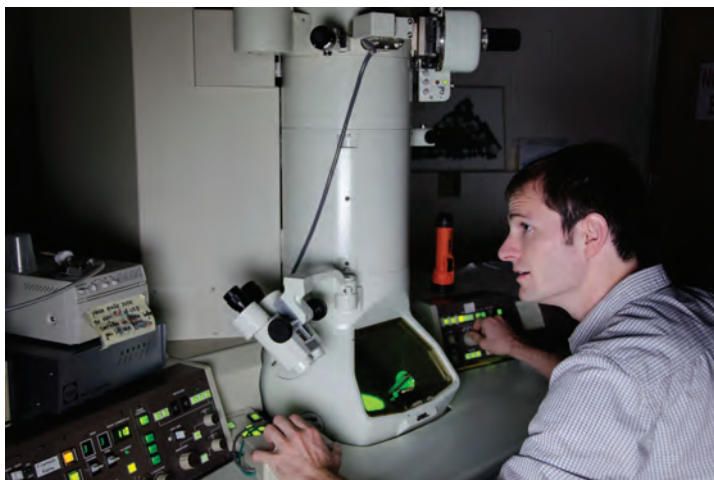


Figure 2. Graduate student Ben Eftink using the electron microscope to investigate the deformation microstructure in a Cu-Au eutectic alloy.

## Structural and Magnetic Studies on Heavy Rare Earth Metals at High Pressures Using Designer Diamonds in Support of the Stockpile Stewardship Program

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### Prototype Large Culet Designer Diamonds for Nuclear Magnetic Resonance Experiments

In collaboration with Dr. Samuel T. Weir of Lawrence Livermore National Laboratory, we have launched a new effort in the fabrication of large millimeter size culet designer diamonds for high pressure research. There is a need in high pressure experiments like Nuclear Magnetic Resonance (NMR) of large sample volumes and hence larger diamond culet size of millimeter or higher are needed. Figure 1 shows the results of our first attempt to grow designer diamond with a culet size of 1 mm.

Figure 1(a) shows the photolithography deposited tungsten microcircuit for NMR experiments on a diamond culet of 1 mm in diameter. Figure 1(b) shows the same diamond after chemical vapor deposited (CVD) diamond growth with a darker region showing presence of diamond twins that are formed above the probe pattern. The diamond twins are easily removed during the polishing step, and the diamond culet after polishing is shown in Figure 1(c). It is clear from the scales indicated that the diamond culet is considerably enlarged after CVD growth and the NMR coil is completely encapsulated in CVD diamond film. It is interesting to note from Figure 1(c) that there is a formation of a pit in the centre of the diamond anvil during the growth process due to lower growth rate in that region. This pit which forms on large culets can be utilized in future experiments for containment of high pressure samples with these anvils.

### Heavy Rare Earth Metals Under Extreme Conditions of Multi-megabar Pressures

The high pressure behavior of 4f rare earth metals is of fundamental interest because of electronic transfer of electrons from one band to another under pressure as well as delocalization of 4f-shell under extreme conditions. In addition, there are similarities with ambient pressure and high pressure crystal structures between 4f-rare earth metals and 5-f actinide metals. The light rare earth metals have been studied extensively due to relatively accessible pressures of 50 GPa for most phase transitions, however, for heavy rare earth metals megabar pressures (100 GPa

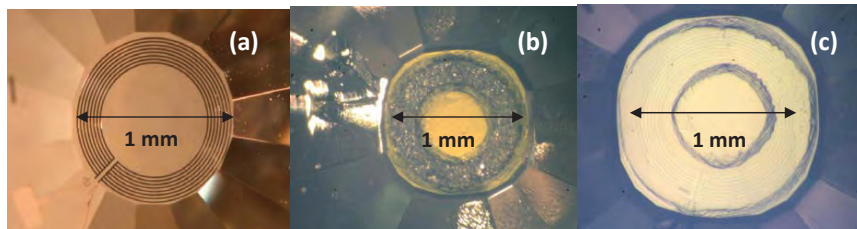


Figure 1. (a) Prototype designer diamond with a NMR coil deposited by photolithography technique on a diamond anvil cell with a culet size of 1 mm. (b) The same designer diamond after CVD diamond growth, shown the dark region is due to occurrence of diamond twins on top of the coil. (c) Diamond after polishing shows an enlarged culet with encapsulated NMR coil and a pit in the centre.

and above) are needed. Under this SSAA program, the focus is on heavy rare earth metals (Terbium to Lutetium).

In our experiments, dysprosium has been compressed to 35% of its initial volume at 210 GPa, holmium has been compressed to 41% of its initial volume at 137 GPa, erbium has been compressed to 40% of its initial volume at 151 GPa and thulium has been compressed to 38% of its initial volume at 195 GPa.

Detailed discussions on the phase transitions of holmium, erbium and thulium could be found under SSAA supported publications.<sup>1-3</sup> At ambient conditions, dysprosium is in hexagonal close packed structure and the *hcp* → *Sm-type* phase transition is observed starting at 7 GPa at ambient temperature. This is followed by a phase transformation from *Sm type* → *dhcp* starting at 18 GPa. The *dhcp* phase is observed between 18 GPa till 41 GPa. Above 42 GPa, *dhcp* phase transformed to the distorted fcc phase (*dfcc*, hR24 phase).<sup>4</sup> The *dfcc* phase is observed between 42 and 80 GPa. Beyond  $82 \pm 2$  GPa, a new yet unreported phase transition was observed that was attributed to a monoclinic (*C2/m* phase). Figure 2 shows the distorted fcc to monoclinic phase transition pressures for rare earth metals that have been shown to adapt this structure at high pressures.

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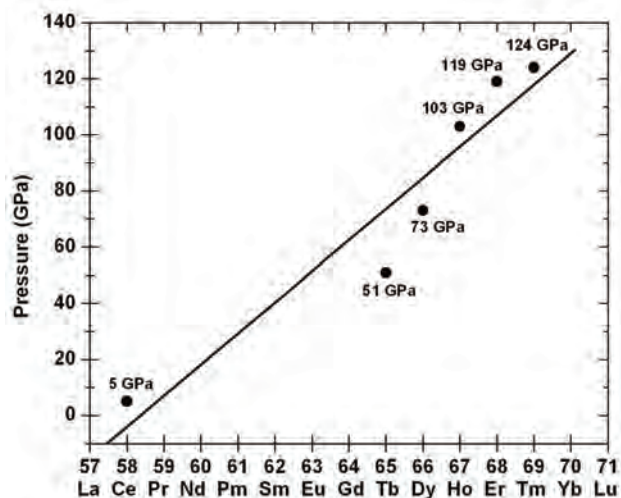


Figure 2. The pressure at which a post-dfcc phase *C2/m* is observed to occur in rare earth metals is plotted against the atomic number for elements. The pressure increases from 5 GPa for cerium to the highest pressure of 124 GPa for thulium. The solid line is merely a guide to the eye.

## X-ray Spectroscopy of Warm and Hot Dense Matter

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Understanding warm dense matter (WDM) and hot dense matter (HDM) is important for inertial confinement fusion research, as well as in the fields of astrophysics and materials performance under extreme conditions. However, measurements of thermodynamic and transport properties of these states of matter are challenging, due to both the difficulty of creating well-defined macroscopic samples, as well as the transient nature of extreme states in accessible geometries. Ultrafast probe techniques are therefore essential to the quantitative study of warm and hot dense matter.

In two different types of experiments we investigated the properties of (1) WDM using ultrafast optical laser pulses and x-ray absorption spectroscopy (XAS)<sup>1</sup> and (2) HDM using ultrafast x-ray free electron laser pulses and x-ray emission spectroscopy.<sup>2</sup>

Ultrafast XAS of warm dense copper was performed at the Advanced Light Source (ALS) in Lawrence Berkeley National Laboratory. Cu foil (70 nm) was heated by a femtosecond (fs) optical laser pulse to create high energy density condition ( $> 10^6$  J/kg). The broadband x-ray probe from ALS was tuned to Cu *L*-edge. Because it is necessary to probe a band of x-ray absorption spectrum before the sample expands, an ultrafast x-ray streak camera developed at the ALS<sup>3</sup> was fielded, and the evolution of XAS could be captured with 2 picosecond (ps) resolution.

We observed that the shift and broadening of the absorption edge is a sensitive temperature sensor and the electron temperature,  $T_e$  can be determined in the eV-range by comparing the XAS measurements with calculations based on density functional theory molecular dynamics simulations (Figure 1, Left). The evolution of  $T_e$  showed the temperature reaches equilibrium faster than predicted by a theoretical electron-phonon coupling constant (Figure 2, Right). In this warm dense regime, the energy exchange rate between electron energy and atomic vibration is expected to be temperature dependent, and is about 3 to 6 times faster than previously assumed.

In a second set of experiments, we utilized the new Linac Coherent Light Source at SLAC National Accelerator Laboratory, where ultrafast high intensity x-ray pulses

Figure 1. Left - X-ray absorption of warm dense copper with 1eV temperature and solid density. Right - The temporal evolution of electron temperature of warm dense copper. Experimental-derived temperatures are shown as squares. For electron-phonon coupling constant,  $G_0$  and temperature dependent electron-phonon coupling,  $G(T_e)$ , solid lines are temperatures calculated by the two-temperature model. The shaded curves include the experimental accuracies. A temperature dependent electron-phonon coupling provides a better description of dynamics.<sup>1</sup>

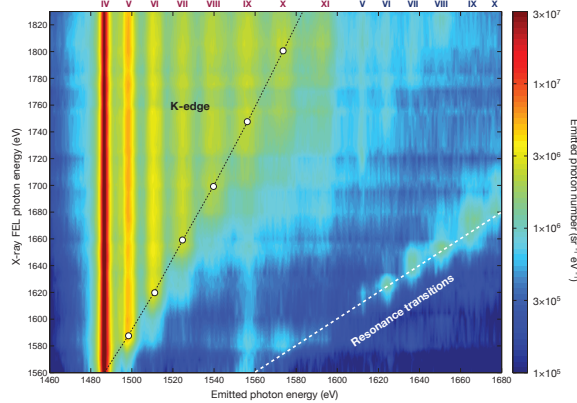
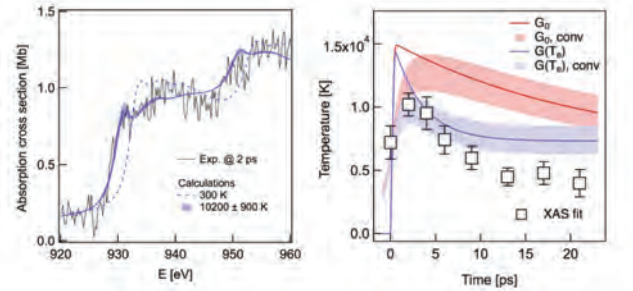


Figure 2. Experimental spectra as a function of the emitted photon energy (x-axis) and the x-ray excitation photon energy (y-axis). The K-edges for the various charge states are indicated as circles. Emission peaks around the resonance line correspond to K-L resonant emission.<sup>2</sup>

(100 fs,  $10^{17}$  W/cm<sup>2</sup>), can be obtained. The heating of a solid with such x-rays has been proposed as an ideal way to create macroscopic high energy density samples without temperature and density gradients during timescales sufficiently long for quantitative study; this is due to the long penetration depth and short duration of x-ray pulses. We performed one of the first experiments at that facility to create HDM with this scheme. Intense x-ray pulses, in a spectral range around the Al *K*-edge, were focused on a 1  $\mu$ m Al foil and *K*-alpha emission spectra were observed.

Observed *K*-shell emission spectra are shown in Figure 2. Here the major ionization processes are direct photoionization of *K*-shell electrons followed by Auger decay. The relatively uniform intensity of *K*-alpha emission from different ionization states indicates the charge distribution is mainly determined by collisions. The important role of collisions is also supported by emission corresponding to resonantly pumped single and double-core-hole states, for which direct photo-excitation with given x-ray photon energies is not possible.

By comparing this with the spectral simulation using the population kinetic code, the temperature of such a system would be above 100 eV. During the x-ray pulse (100 fs), electron heating, photoionization and Auger decay are all rapid compared with the time scales for both hydrodynamic expansion ( $\sim 20$  ps) and electron-ion relaxation ( $\sim 10$  ps). These results bode well for the concept of creating a bulk of HDM with a uniform density and temperature.

In conclusion, these x-ray spectroscopic techniques provide not only new methodologies to create and probe various properties of WDM and HDM, but also benchmarks for theoretical modeling in these regimes. Such results can be applied to further investigation of plasmas for fusion, astrophysics, planetary science, and materials performance under controlled environments.

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# NLUF

National Laser Users' Facility

The National Laser Users' Facility (NLUF) was established in 1979 at the University of Rochester's Laboratory for Laser Energetics (LLE) to provide unique opportunities for university and business users to conduct basic high energy density research on the Omega Laser Facility. All NLUF proposals are independently peer reviewed by highly qualified scientists. DOE/NNSA provides annual funding support directly to NLUF users for non-facility costs related to their experiments and funds NLUF target fabrication through the DOE/NNSA target support contractor. DOE/NNSA funds operation of the facility through its Cooperative Agreement with LLE. To date, the NLUF has received 306 proposals to use the facility and 165 have been approved. More than 120 graduate students and postdoctoral fellows have participated in the NLUF program. Fifteen percent of the OMEGA Laser Facility time is currently allotted to the NLUF.

Approved NLUF high energy density physics experiments are conducted by investigators from U.S. universities, non-NNSA government laboratories, and industry in a variety of areas, including inertial fusion, laboratory astrophysics, radiation hydrodynamics, plasma nuclear physics, hydrodynamic instabilities, studies of the equation of state of materials under ultra-high pressures, plasma physics, extreme ultraviolet spectroscopy, and high-temperature and high-density plasma diagnostic development.

The Omega Laser Facility includes two of the most powerful lasers in the world: OMEGA—a 60-beam ultraviolet Nd:glass laser capable of producing ultraviolet laser pulses with total peak power of approximately 30 trillion watts and a total energy up to 30,000 Joules (Figure 1) and OMEGA EP (Figure 2)—a four-beam Nd:glass laser capable of producing ultraviolet pulses with total energy in the range of 10,000 to 30,000 Joules. Two of the OMEGA EP laser beams can be configured as high energy Petawatt (HEPW) laser beams that produce infrared laser pulses with peak power in excess of a thousand trillion watts (Petawatt). The HEPW beams can be directed to either the OMEGA or OMEGA EP target chambers. Key to facility's scientific productivity is an extensive array of plasma and laser

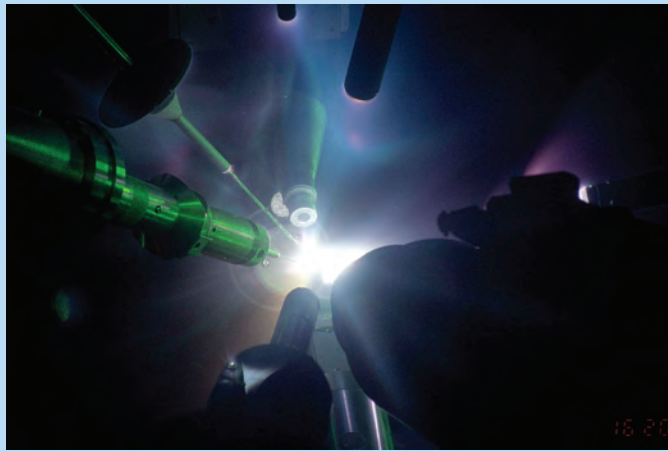


Figure 1. The June 2010 issue of *Physics Today* highlighted the NLUF laboratory astrophysics experiments of a University of Michigan team led by Paul Drake. The front cover features an image taken for his experiment from inside the OMEGA target chamber. (Cover photo of *Physics Today*, June 2010)



Figure 2. Photograph of the four OMEGA EP laser beams during a test shot.



Figure 3. Attendees of the 2011 OLUG Workshop sponsored by UR/LLE. Many of the attendees are students and post-doctorates.

diagnostics. More than 200 state-of-the-art optical, particle, x-ray and nuclear diagnostic systems are currently available for experiments at the facility.

Eleven different principal investigators were awarded Omega Facility time for the FY 2011-2012 period. It is anticipated that a NLUF solicitation for the FY 2013-2014 period will be issued in the second quarter of FY 2012.

The Omega Laser Users Group (OLUG), established in 2008, is open to anyone who uses the Omega Laser Facility or

aspires to use it, or wants to collaborate with current users. OLUG includes over 270 academics and researchers from 32 universities, 28 centers, and 5 national laboratories. OLUG conducts an annual workshop at LLE with the following goals: (1) define improvements to the capabilities and operation of the facility that would advance research opportunities for all users, and (2) provide an opportunity for young researchers to present their research in a very interactive yet informal setting.

## Exploring Planetary Materials Using Ramp Compression at the Omega Laser Facility

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Authors: Thomas Duffy, Jue Wang (Princeton University); Ray Smith and Jon Eggert (LLNL)

We are developing new techniques to study geological materials at deep planetary interior conditions using laser-driven ramp compression. Ramp compression is a method in which materials are compressed dynamically along a quasi-isentropic path at relatively modest temperatures. It can be used to explore the equation of state and to study solid-solid phase transitions. An important attribute of ramp compression is that it provides the capability to study materials in the solid state to higher pressures than can be achieved with more traditional approaches involving diamond anvil cell (DAC) or shock wave methods.

Laser-based ramp compression of planetary materials has applications to understanding the structure and dynamics of the interiors of planets both within and outside our solar system. Iron (Fe) and magnesium oxide (MgO) are geologically important materials in one of the two major interior regions (core and mantle) of terrestrial planets. The composition of planetary cores, for example, is central to understanding planetary formation mechanisms and the thermal history of planets. The discovery of hundreds of extra-solar planets in the last decade has raised intriguing questions about the existence of large terrestrial planets and their interior characteristics. As observational capabilities improve in the coming years, it is expected that a wide range of planetary types will be identified and characterized with high accuracy. For a plausible 10-Earth-mass terrestrial-type planet, the central pressure and temperature conditions are predicted to be approximately 3500 GPa and 7500 K. This is far beyond the regime that can be accessed with current static (DAC) compression methods. Existing models of the interior of extra-solar planets are based on extrapolations of experimental data and theoretical calculations well beyond where the data was taken. Better experimental equation of state data at multi-megabar pressures is needed to improve and test these models. Ramp compression experiments are potentially well-suited to this task as they can reach higher pressures than DAC experiments (which are presently limited to about 3 Mbar) and they avoid the melting that commonly occurs in shock experiments above 1 Mbar.

Working with colleagues at Lawrence Livermore National Laboratory and the

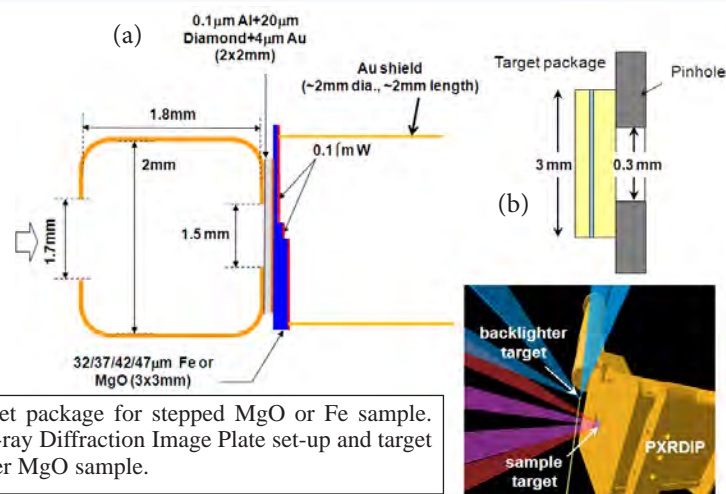


Figure 1. (a) Target package for stepped MgO or Fe sample. (b) The Powder X-ray Diffraction Image Plate set-up and target package for powder MgO sample.

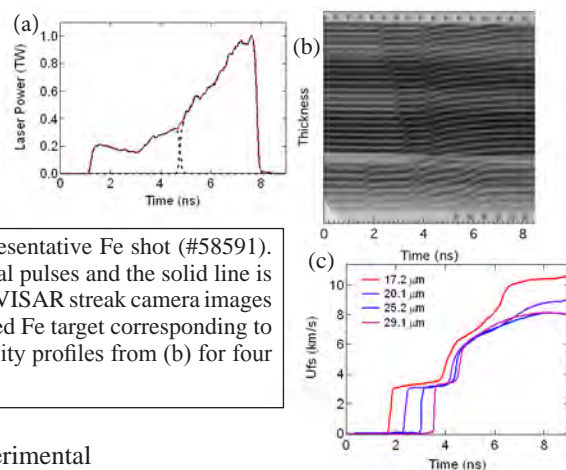


Figure 2. (a) Laser pulse for a representative Fe shot (#58591). The dashed lines show the individual pulses and the solid line is the composite pulse shape. (b) Line VISAR streak camera images from ramp compressed multi-stepped Fe target corresponding to (a). (c) Extracted free-surface velocity profiles from (b) for four different step thickness.

University of Rochester, an experimental platform for ramp loading of Fe and MgO, has been developed and tested in experiments at the Omega Laser Facility. Target packages consist of stepped samples of Fe or MgO obtained through vapor deposition and lithographic etching. Each sample is glued to a diamond ablator and attached to a Au hohlraum (see Figure 1). The targets had four steps that were approximately 5-7  $\mu\text{m}$  in thickness. A composite ramped laser pulse of about 7 ns in duration with typically 15 beams with total energy of 2.6-3.3 kJ was used. The ramped laser drive generates a time-dependent radiation temperature within the Au cavity. X-ray ablation of the diamond surface leads to propagation of a ramp compression wave through the diamond ablator and subsequently into the sample. Detection of the ramp wave arrival and its velocity at the free surface of each step was made using a line-imaging VISAR velocity interferometer. Figure 2 shows examples of the input pulse, VISAR signal, and resultant wave profiles obtained for a typical iron ramp

compression experiment. Through a series of shots, we systematically changed the laser pulse to assess the effect on the wave profile and the ability to maintain ramp compression.

To analyze the data, Lagrangian sound velocities were calculated from the free surface velocity histories. Through the use of Lagrangian analysis of the measured wave profiles, stress-density states in iron and magnesium oxide were determined to pressures of 291 GPa and 260 GPa respectively. For Fe, the  $\alpha$ - $\epsilon$  transition of iron is overdriven by an initial shock pulse of  $\sim 90$  GPa followed by ramp compression to the peak pressure. Our results for iron are broadly consistent with previous experiments from shock and static data. The ramp data above 1 Mbar appear to lie closer to static data than Hugoniot data, which indicates a low shear strength of iron under these experimental conditions. It is expected that these measurements will be extended to much higher pressures in future experimental work at Omega and the National Ignition Facility.

## Laboratory Experiments of Supersonic Astrophysical Flows Interacting with Clumpy Environments

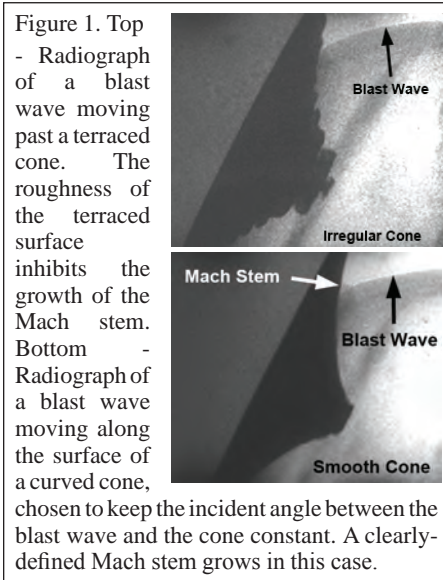
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PI: Patrick Hartigan (hartigan@rice.edu)

The NLUF program is designed to explore plasma hydrodynamic phenomena observed in stellar jets and star-forming regions. Both areas use laboratory experiments and numerical simulations to motivate new astronomical observations, and to explain features observed within existing astronomical images and spectra. The laboratory work is done at the Laboratory for Laser Energetics (LLE) at the University of Rochester under the guidance of scientists from the Atomic Weapons Establishment (AWE) in the UK, Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), General Atomics (GA), Rice University, and the University of Rochester (UR). New astronomical observations have been taken with a variety of world-class ground-based telescopes on mountains in Arizona and in Chile, and with the Hubble Space Telescope. Numerical simulations use codes developed at LLNL, AWE, and UR. One team member, Kris Yirak, recently began a postdoctoral position at LANL, and the program has produced several MS and PhD theses over the past few years.

The work with stellar jets has focused on the shock waves that form within these flows as they are launched from accretion disks around young stars. As part of this program we obtained multiple-epoch Hubble Space Telescope images of several jets that revealed anomalous pattern motions at the intersection between overlapping bow shocks. It is possible that these structures represent hot spots produced as material flows through narrow normal shocks (Mach stems). Several aspects of the physics of Mach stems are poorly understood, including how the critical angles of formation vary with the polytropic index of the gas, how easily the structures can be disrupted by instabilities, the growth rate of the structures, and differences between the critical intersection angles where the stems are created and destroyed (hysteresis). These are the main subjects of the current project.

The laser experiments within the last year have focused on a few key target designs. First, a Mach stem was created as a blast wave moving over a cone-like target, where the cone was shaped in such a way as to keep the angle between the blast wave and the surface of the cone constant



(Figure 1, bottom). Backlit images at different times quantify how the Mach stem growth rates vary for a given incident angle. They are compared with predictions from the Radiation Adaptive Grid Eulerian (RAGE) code, and also from AstroBear, an astrophysical magnetohydrodynamic code. A second design (Figure 1, top) introduced 'terraces' along the cone's surface to quantify how fragile the Mach stems were to destruction by flow irregularities. In future shots the shape of the cones will be changed to create systems where the incident angle either increases or decreases through the critical angle to explore hysteresis. Another goal is to explore the possibility of gas-filled targets in order to reduce the polytropic index to the theoretical stability limit of 1.2 to simulate more closely the radiative cooling present in the astrophysical cases.

In the last year, we began to explore a new research direction focused on the hydrodynamics within star-forming regions. In areas where young massive stars exist, one often sees dense globules being altered by intense ionizing radiation from the massive stars. This process reveals itself particularly well at near-infrared wavelengths as ultraviolet radiation from the stars undergoes fluorescence with molecular hydrogen present in the globules to create a layer of infrared line radiation that traces the surface of the interaction. Because infrared radiation largely penetrates through obscuring dust, images of this process reveal how the



Figure 2. A color composite (red=H<sub>2</sub>, green=HI, blue=OIII) of a small portion of Carina shows the spectacular structures that result when radiation from massive stars interacts with molecular globules that harbour newborn stars. (SSAA Annual 2012 cover photo.)

interfaces between the radiation and the molecular cloud behave.

Using a new, very large-format imager at telescopes in Arizona and Chile, we recently imaged large areas of massive star formation located in the constellations Carina and Cygnus in the light of H<sub>2</sub> and H<sub>I</sub> (Figure 2). The results show a fascinating array of hydrodynamic phenomenon, including shocks, evaporating flows, shadowing, and fluid dynamic instabilities. These processes also commonly occur in various laboratory situations where radiation is important in the overall dynamics. Motivated by these images, we are now considering various experimental analogues that might help to clarify the tremendous variety and complexity that Nature has created in these regions.

Our ongoing NLUF work continues to produce a series of publications in the primary refereed journals of the field, including the *Astrophysical Journal* and *Physics of Plasmas*, and we have given numerous contributed and invited talks at recent conferences. Our 2011 paper in the *Astrophysical Journal* on the Hubble movies generated a great deal of interest in the community, as well as press coverage for Omega. An earlier *Astrophysical Journal* paper about deflected jets combined new astrophysical spectra with laboratory experiments from Omega and was well-received by the community. A paper summarizing the previous multiple clump work is now in preparation, as are papers on the irradiated globules in Cygnus and Carina.



## Systematic Study of Fast Electron Transport in Solid and Warm Dense Plasmas

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Understanding of relativistic electron generation and transport in a solid and warm dense plasma is a fundamental issue pertinent to relativistic high energy density plasmas and intense particle beams as outlined in the recent Research Needs Workshop (RENEW).<sup>1</sup> We have performed two experiments on the OMEGA EP laser to address this important issue. The goals of the experiments were:

i) to characterize plasma to be used as the transport medium using the x-ray line absorption spectroscopy,<sup>2</sup> and ii) to study the fast electron transport in the pre-characterized plasma. In the first experiment, a shock-wave-heated foam target was used to create warm dense plasma. The foam target package consisted of 200 mg/cm<sup>3</sup> plastic foam doped with aluminum inside a solid plastic container (Figure 1a). A long pulse laser (1.2 kJ/3.5 ns in UV) irradiated a plastic foil to launch a shock wave into the foam target as shown in Figure 1b. The other three lasers were focused onto a samarium (Sm) dot target to produce an x-ray point source for the absorption spectroscopy. The Sm x-ray spectrum (1.4 – 1.6 keV) was transmitted through the Al-doped foam target and recorded with an x-ray streak camera. Figure 2 shows a measured streak image of Al 1s-2p absorption spectra. The spectral analyses using a detailed atomic physics code Prism SPECT<sup>3</sup> show the electron temperature of  $40 \pm 5$  eV and the mass density of  $30 \pm 10$  mg/cm<sup>3</sup> at 7 ns after the drive laser. The presence of the lower charge state features (i.e. O-like and F-like) later in time indicates a decrease of electron temperature. The experimental results are consistent with a two-dimensional DRACO simulation<sup>4</sup> that shows the foam plasma peak temperature of 30 - 50 eV at about 7 – 8 ns.

In the second experiment, fast electrons generated by an OMEGA EP short pulse beam were transported into the characterized foam plasma. The EP beam interacted with a gold foil on one side of the package target to generate the fast electrons (Figure 1c). The electron transport was studied by measuring 8.0 keV K<sub>α</sub> x-ray from a Cu foil attached to the other side. The K<sub>α</sub> x-rays induced by the electrons were recorded with an x-ray spectrometer and a spherical crystal imager. Figure 3 shows the K<sub>α</sub> images from the three transport media: (a) a solid

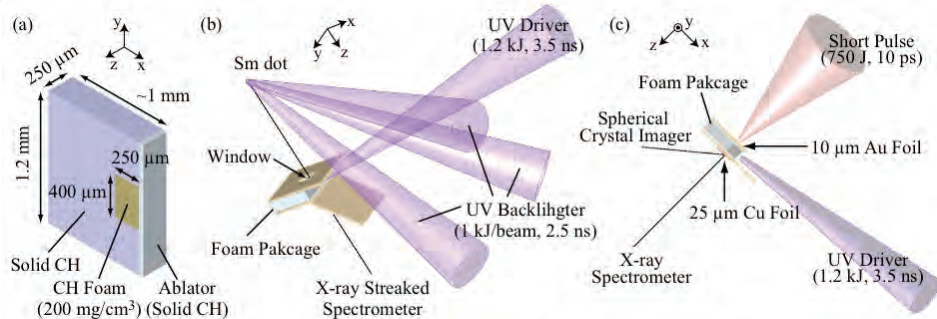


Figure 1. Schematics of (a) the foam package target, (b) plasma characterization experiment and (c) fast electron transport experiment. Plastic-coated gold foils on both sides were added for both experiments. The foils had an aperture to transmit backlighter x-rays for the characterization experiment.

plastic, (b) an un-driven foam, and (c) the laser-driven foam plasma. A small K<sub>α</sub> spot was observed in the cold plastic target; however, no clear structure was found in the foam targets, indicating a large divergence of the relativistic electron beam in both driven and un-driven foam. The comparison of the total K<sub>α</sub> yields in the foam targets shows a reduction of the yield by factor of 20 in the driven foam

(Figure 3d). The large divergence in the warm foam target could be attributed to interface field effects and relativistic electron beam instability exiting the gold layer into warm dense plasma. Modeling to understand the underlying physics using LSP and Osiris codes is underway. The work described above facilitated an excellent platform for training and teaching of post-doctoral fellows Toshi Yabuuchi and Hiroshi Sawada.

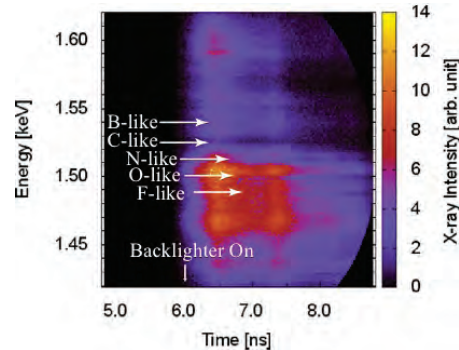


Figure 2. Streaked 1s-2p Al absorption spectrum from the Al-doped CH foam target. Several Al absorption lines are indicated by arrows.

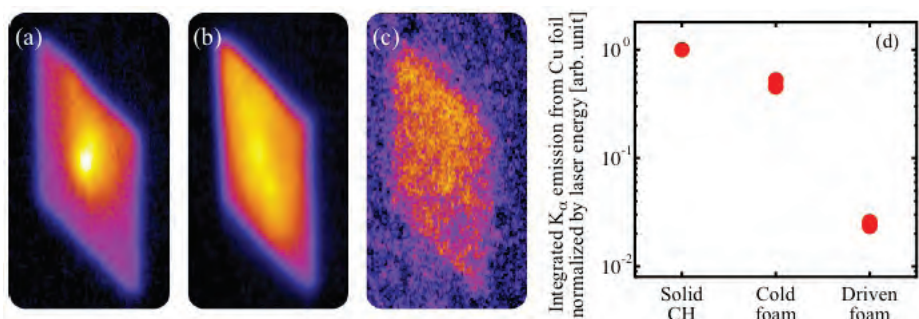


Figure 3. Cu K<sub>α</sub> images observed with spherical crystal imager when the transport medium was: (a) 50 μm solid CH, (b) 250 μm cold foam, and (c) 360 μm driven foam. (d) Integrated K<sub>α</sub> x-ray yield measured with the x-ray spectrometer for three cases.

## Bulk and Shear Moduli of Osmium at High Pressure from Ultrasonic Measurements and First Principles Calculation; Stony Brook University; Baosheng Li (bli@notes.cc.stonybrook.edu)

Osmium (Os), a hexagonal close packed 5d transition metal, has the highest density (22.598 g/cm<sup>3</sup>) and bulk modulus among all the metal elements at ambient conditions. Static compression studies suggest that Os at ambient pressure may be less compressible than diamond and, thus, a rival candidate for various industrial applications under extreme conditions. Unfortunately, the wide range for the bulk modulus reported in previous studies (390-471 GPa) makes the comparison between Os and diamond less conclusive. In addition, the shear modulus, a parameter that is closely related to a material's performance and yield strength, cannot be evaluated from these compression studies. In this study, ultrasonic velocity measurements were conducted using a transfer function method of ultrasonic interferometry (Dual-mode LiNbO<sub>3</sub>, 30-60MHz) in conjunction with in-situ x-radiography in a multi-anvil apparatus installed at beamline X17B2 of the National Synchrotron Light Source at Brookhaven National Laboratory. Combining travel times ( $t_p, t_s$ ) from ultrasonic measurement and sample length ( $L$ ) from x-ray imaging, compressional ( $V_p = L/t_p$ ) and shear ( $V_s = L/t_s$ ) velocities as well as the bulk [ $K = \rho(V_p^2 - 4V_s^2)/3$ ] and shear moduli [ $G = rV_s^2$ ] at high pressures are obtained. Fitting the

velocity data to finite strain equations yields  $K_s = 407(1)$  GPa,  $G = 274(1)$  GPa,  $\partial K/\partial P = 5.7(2)$ , and  $\partial G/\partial P = 1.8(1)$  for the bulk and shear moduli and their respective pressure derivatives. For the first time, the pressure derivatives  $\partial K/\partial P$  and  $\partial G/\partial P$  for Os are directly determined using acoustic velocity measurements. Plane wave pseudopotential density functional theory (DFT) calculations were also performed on Os and diamond for comparison. Excellent agreement in

both  $V_p$  and  $V_s$  can be found between the current measurements and those from our DFT calculations for Os (Figure 1). From this study, we conclude that (1) the bulk modulus of Os at ambient conditions is ~9% less than diamond, so Os is more compressible at low pressures; (2) above 35GPa, Os becomes less compressible than diamond due to its larger  $\partial K/\partial P$  than diamond; and (3) the  $G$  of Os is ~49% lower than diamond with  $\partial G/\partial P$  similar to that of diamond (Figure 1b).

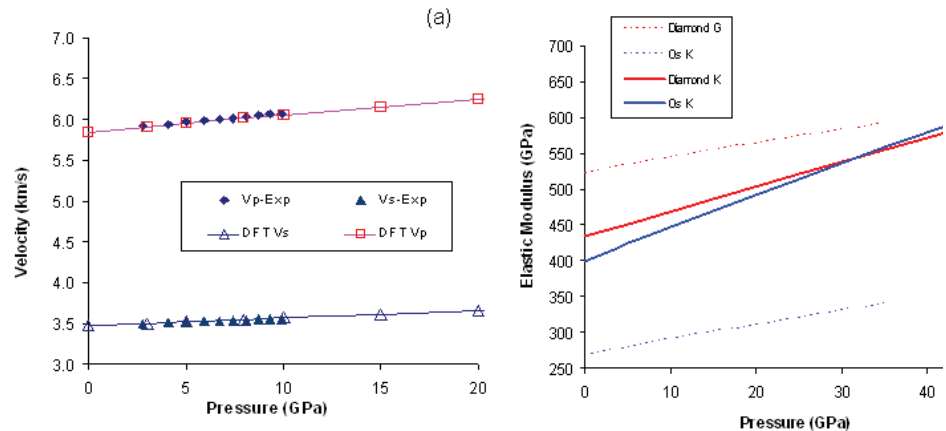


Figure 1. (a) Compressional and shear wave velocities from the current experiment (solid symbols) and DFT calculation (empty symbols). (b) Comparison of bulk and shear moduli of Osmium and diamond as a function of pressure from current DFT calculations. Thick lines: bulk modulus; dashed lines: shear modulus.

## Pressure Dependence of the Spin-Density-Wave Transition in the High Temperature Superconductor Parent Compound LaFeAsO; University of California, San Diego; M. Brian Maple (mbmaple@ucsd.edu)

The so-called 1111 ZrCuSiAs-type materials were the first of the new iron based superconductors to be discovered, and they remain the class that displays the highest superconducting critical temperatures ( $T_c$ ), with  $T_c$  reaching ~55 K in, e.g.,  $\text{SmFeAsO}_{1-x}\text{F}_x$  and  $\text{Gd}_{1-x}\text{Th}_x\text{FeAsO}$ . Despite having the highest values of  $T_c$ , focus has largely shifted away from 1111 materials towards other classes of iron-based superconductors, e.g., the 122  $\text{ThCr}_2\text{Si}_2$ -type materials such as  $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ , which are more straightforward to prepare in single crystal form. Because of the significant anisotropies in these iron-based materials and the fact that measurements on polycrystalline samples generally yield physical properties that are averaged

over different crystallite directions, understanding of the 1111 compounds has been impeded by the scarcity of single crystal specimens. We have synthesized several members of the 1111 family of iron-based materials in single crystal form and are involved in a systematic effort to characterize their properties as a function of pressure. Figure 1 presents some of our recent results on single crystals of LaFeAsO, where the signature of the spin-density-wave remains clear and sharp under applied pressure. Such experiments will help to clarify the pressure-temperature phase diagrams of 1111 Fe-pnictide materials, which were obscured by the broad transitions reported in previous studies of polycrystalline samples.

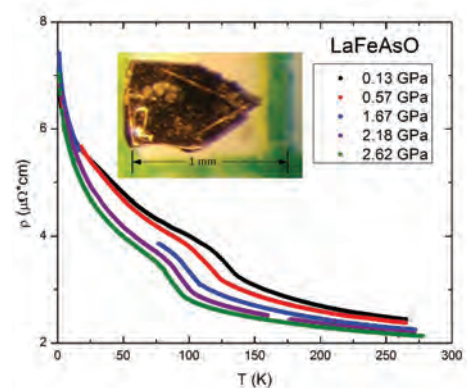


Figure 1. Results from recent research on single crystals of LaFeAsO.

## Detailed Measurements of Turbulent Rayleigh-Taylor Mixing at Large and Small Atwood Numbers

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Our current SSAA project involves collection of statistical turbulence data from a high Atwood ( $A_t$ ) number Rayleigh-Taylor (RT) mixing facility that can achieve Atwood numbers up to 0.75. The experiment investigates buoyancy driven RT mixing that is relevant to ICF implosion. The data has been, and will continue to be, provided to Alliance members (specifically LLNL and LANL) for code validation and turbulence model formulation/testing. This facility is a convective type system that uses air and air helium mixture separated by a splitter plate initially. In the last one year, we have been able to study the effect of shear on RTI at  $A_t \sim 0.04$  by creating a velocity difference between the two streams. A flow visualization technique (Banerjee et al., *Detailed Measurements of a Statistically Steady Rayleigh-Taylor Mixing Layer from Small to High Atwood Numbers*, JFM 659(1), 2010) is used to obtain the mixing growth rate. The comparison between the images taken with buoyancy, shear and compound shear and buoyancy are shown in Figure 1.

Spanwise vortical structures are characteristic of shear instability and vertical plumes from shear between vertically moving fluids are the characteristic of RT instability. For the compound case, spanwise vortical structures are still observed close to the splitter plate and the flow resembles RT like behavior far away from the splitter plate indicating that buoyancy eventually takes over shear at later times.

Figure 1d shows the variation of mixing width variation with time  $x/U$ ,  $x$  is the downstream distance from the splitter plate for different cases and  $U$  is the density weighted average velocity. The pure RT case shows a parabolic variation with time, whereas case KHRT3, which is close to pure shear, shows a linear variation. Case KHRT1 shows a linear variation at the start, and eventually becomes parabolic at later times. KHRT2 shows a similar variation. Late times could not be achieved for KHRT3 case because of larger values of  $U$  and fixed channel

length. For RTI, Youngs (1984) proposed  $h_b = \alpha A_t g t^2$ ;  $h_b$  is the penetration distance of lighter density fluid to heavier fluid;  $g$  is the acceleration due to gravity;  $t$  is time and  $\alpha$  is mixing growth constant. Although this relation is not valid for all cases at all times,  $\alpha$  is found to be in the range of 0.07-0.1 irrespective of amount of shear present at the splitter plate. We are in the process of implementing a new diagnostic capable of simultaneous measurements of velocity and density fields.

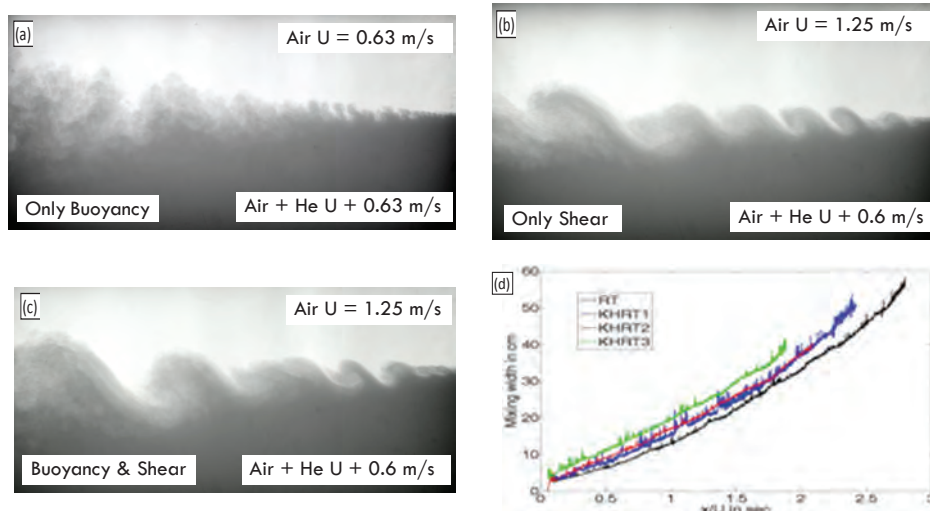


Figure 1. Typical images taken during mixing layer visualization experiments (a) with buoyancy  $At \sim 0.04$ , (b) only shear, (c) compound shear and buoyancy, and (d) mixing width variation with time for different cases with different values of shear at  $At \sim 0.04$  with KHRT1  $\Delta U = 0.23$  m/s, KHRT2  $\Delta U = 0.40$  m/s, KHRT3  $\Delta U = 0.62$  m/s.

## Modernizing the Fission Basis

Duke University; Werner Tornow (tornow@tunl.duke.edu)

In a collaborative effort between Triangle Universities Nuclear Laboratory (TUNL), Los Alamos National Laboratory, and Lawrence Livermore National Laboratory, our first high-precision measurement of the neutron-induced fission product yield was successfully performed. The associated activation measurements on  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and  $^{239}\text{Pu}$  were performed with mono-energetic 9 MeV neutrons produced via the  $^2\text{H}(d,n)^3\text{He}$  reaction at TUNL. A dual fission chamber was used to obtain absolute fission fragment yields by measuring off-line the characteristic  $\gamma$ -rays from the fission products of interest produced in the thick target. The future measurements will cover the energy range between 1 and 15 MeV.

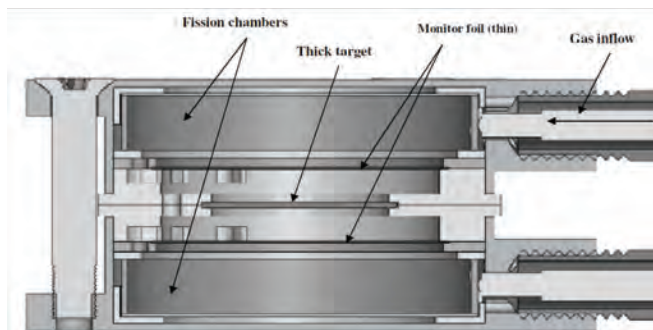


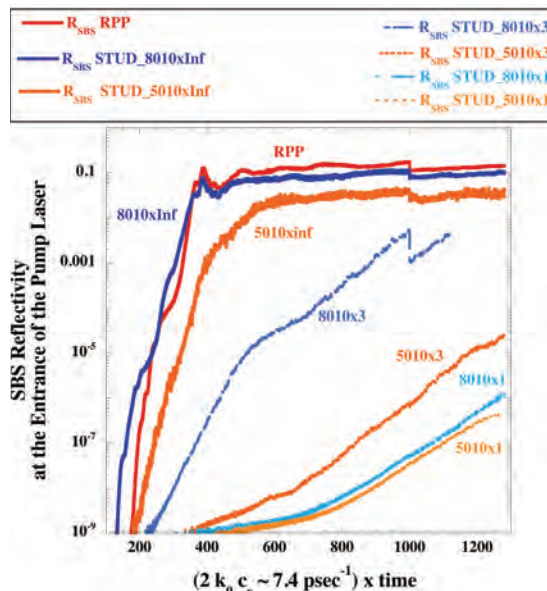
Figure 1. Schematic of dual fission chamber.

## Optical Mixing Techniques for Taming Laser Plasma Instabilities in High Energy Density Laboratory Plasmas

Polymath Research Inc.; Bedros Afeyan (bedros@polymath-usa.com)

We devised new methods of laser-plasma instability control by strong space-time modulations of the laser. The new laser profiles fall under the name of STUD pulses, which stands for Spike Trains of Uneven Duration and Delay. We demonstrated that over thousands of hot spots in a distribution obeying Gaussian statistics, we can reduce stimulated scattering reflectivities by orders of magnitude when compared to random phase plate (RPP), smoothing by spectral dispersion (SSD), smoothing by induced spatial incoherence (ISI) beams. These latter have been the poster children of beam smoothing in the past. Simulations that included the effects of strong coupling, pump depletion and diffraction, all beyond the paraxial wave equation or rate equation type models, confirmed our theoretical picture on optimal ways of taming parametric instabilities in laser produced plasmas. We also established a new way of measuring the fast time scale evolution of velocity distribution functions due to instabilities by using STUD pulses to tame the amplification of a pump-probe pair and to record by

Figure 1. The instability reflectivity levels are plotted versus time for a conventional RPP or SSD beam smoothing techniques (dubbed RPP), as well as pure time modulation without speckle pattern changes between spikes, dubbed STUD 5010xinf, and down to speckle pattern changes with every spike, dubbed STUD 5010x1. Note that the ISI technique is very close to the STUD8010x3 pulse which is much worse than STUD 5010x3. Orders of magnitude less reflectivity is computed using STUD 5010x1 pulses than with any other. Future laser designs should adopt adaptive STUD pulse capability in their principle objectives.



time-lens technology, the evolving (time dilated) small signal gains of controlled instabilities from which the slope of the velocity distribution functions locally, one frequency at a time, can be extracted. This should revolutionize what we can measure in high energy density plasmas

(HEDP) and open many new vistas from the infrared to the x-ray regime where coherent x-ray optical sources will allow crucial HEDP measurements of burning plasmas, their temperature evolution, their mix, and their temporal histories.

## Innovation, Discoveries, and Education to Understand Materials at Extreme Conditions, Dynamic Compression Sector at the Advanced Photon Source; Washington State University; Yogendra M. Gupta (ymgupta@wsu.edu)

Understanding the response of materials under dynamic compression is at the heart of NNSA's Stockpile Stewardship Program. Scientifically, dynamic compression experiments have two unique attributes: (1) the ability to achieve extreme thermo-mechanical states of matter, and (2) the opportunity to probe the temporal evolution of these states, or materials dynamics, in real time.

To develop a fundamental understanding of the materials phenomena under dynamic compression (structural changes and phase transformations; deformation and fracture; and chemical reactions) and their relationship to the evolving atomistic structure, it is necessary to examine the time-dependent response of materials at microscopic length scales with nanosecond time resolution. Such measurements are essential for gaining scientific insights and for evaluating multi-scale simulations of key phenomena under dynamic compression.

To address the overarching scientific need indicated above, the DOE/NNSA is establishing a first-of-a-kind user facility at the Advanced Photon Source (APS).

Washington State University (WSU) is partnering with the APS to establish the Dynamic Compression Sector (DCS), an experimental capability dedicated to multi-scale measurements under dynamic compression. DCS will couple a variety of dynamic compression platforms to a state-of-the-art synchrotron beamline to routinely obtain time-resolved x-ray measurements with nanosecond resolution. DCS will permit a range of tunable incident energies (hard x-rays) and time-structures (ns-separated pulses) to observe time-dependent changes in materials subjected to a broad range of peak stresses (~5 GPa to above 100 GPa) and time-durations (tens to several hundred nanoseconds). Additionally, DCS will provide a rapid turnaround of experiments to optimize scientific throughput for the users. The NNSA-sponsored user facility represents a new para-

digm to undertake scientific discovery challenges related to dynamic compression of materials, and to train the next generation of scientists.

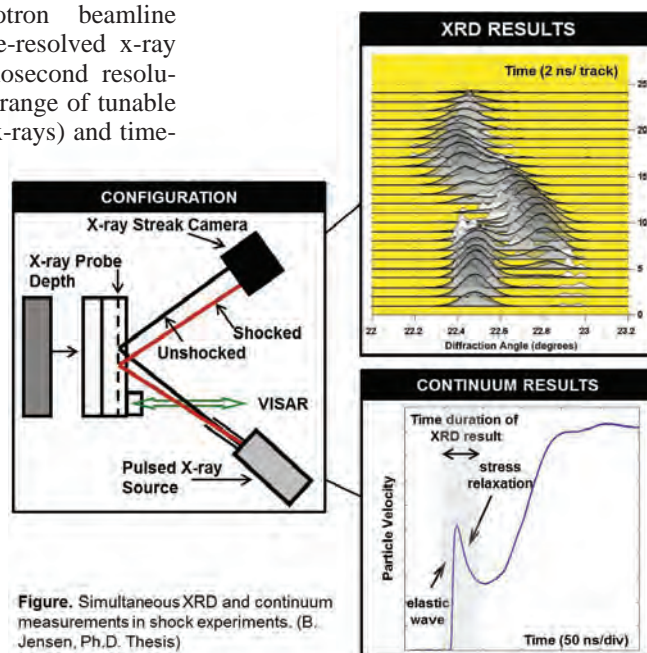


Figure. Simultaneous XRD and continuum measurements in shock experiments. (B. Jensen, Ph.D. Thesis)

## Radiation from High Energy Density Plasmas Workshop

University of Nevada, Reno; Alla Safronova (alla@unr.edu)

The International Workshop on Radiation from High Energy Density Plasmas (RHEDP) was held from March 15 to 18, 2011 at the University of Nevada, Reno (UNR). The workshop was co-chaired by Prof. Alla Safronova (UNR) and Dr. John Giuliani (Naval Research Laboratory). The subject of radiation from high energy density plasmas is an important and interdisciplinary topic combining aspects of atomic structure, population kinetics and reaction processes, photon transport, and spectroscopic diagnostics. In addition to the scientific challenges addressed within the SSAA program, there is also an interest to maintain a long-term recruiting pipeline to the National Laboratories so that NNSA's stewardship mission can be sustained into the future. The purpose of the workshop was to bring together in a colloquial setting a small group of leading researchers and their students working on theoretical and/or experimental studies of RHEDP. The attendees were limited to those whose research is primarily supported by DOE/NNSA. The main objectives of the meeting were to highlight progress in the field, while identifying

current issues and conferring on future directions. The framework consisted of invited oral presentations of 20 or 30 minutes, one poster session, and several discussion sessions among the attendees led by co-chairs. The international workshop hosted 61 attendees from three DOE/NNSA laboratories, six universities, one DoD laboratory, and one scientific company (see Figures 1 and 2). The scientific topics included the study of radiation from laboratory plasmas, such as wire-array or gas-puff pinches and high-intensity, short-pulse laser interactions, as well as radiation from astrophysical systems. The focus was on emission and absorption spectroscopy, radiative shocks, radiation MHD simulations, non-LTE atomic kinetics, radiation transfer, detailed x-ray and EUV synthetic spectra, *cold* characteristic lines, x-ray line polarization, line broadening, diagnostic interpretation of spectroscopic data, and efficiency/development of new x-ray K- and L-shell sources of radiation. All oral and poster presentations highlighted the tremendous progress in Radiation Physics of HED plasmas, both in experimental and



Figure 1

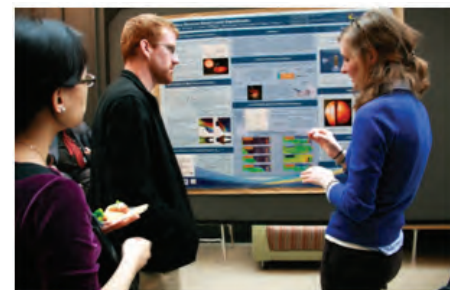


Figure 2

theoretical work. The discussion sessions identified the current issues in the area of Radiation Physics of high energy density plasmas and formulated the questions related to enhanced collaboration between the national laboratories and universities.

## Searching for Efficient X-ray Radiators for Wire Array Z-pinch Plasmas on Zebra at UNR

University of Nevada, Reno; Alla Safronova (alla@unr.edu)

The K- and L-shell radiation sources provide excellent opportunities for studying Z-pinch plasmas through radiated output in broad photon energy regimes, spectroscopy, and imaging. Though the K-shell x-ray sources were extensively studied at the Z accelerator at Sandia National Laboratories (SNL) [see, for example, C.A. Coverdale *et al.*, HEDP 6, 143 (2010)], there is much less research concerning L-shell radiators. To find more efficient x-ray radiators on University-scale Z-pinch Zebra generator at UNR, we have recently studied the radiative and implosion characteristics of mid-atomic-number Single Planar Wire Arrays (SPWA) [A.S. Safronova *et al.*, HEDP 7, 252 (2011)]. The general features of the SPWA implosion dynamics are illustrated in Figures 1 and 2: the wires are involved in a cascade-type implosion starting with the outermost wires and ending with the innermost wires (Figure 1); implosions result in the formation of a Z-pinch at the geometrical center of the load that is manifested by the appearance of soft and hard x-ray radiation, which can be observed on x-ray time-gated pinhole images and by the sharp increase of the photo conducting detector (PCD) signal

(Figure 2); formation of a hot, dense and highly-radiating Z-pinch is followed by stagnation, characterized by multiple x-ray bursts traceable with the PCD signal. After a few tens of ns, the pinch is destroyed by magnetohydrodynamic instabilities, the intensity of the PCD signal quickly subsides to zero, and the last phase begins. We have studied all phases of implosion, and in particular have demonstrated that the Ag (silver) radiator is the best so far of all mid-atomic-

number wire materials that we tested on Zebra, with a total radiation yield of up to 30 kJ, bright-spot generation, the small size of the x-ray source, and a maximum L-shell plasma electron temperature that reaches the highest values of 1.9 keV and larger. These results have much broader applications, not only for SPWAs on Zebra, but for development of L-shell radiators on Z at SNL as well as for other high energy density plasmas with mid-atomic-number ions.

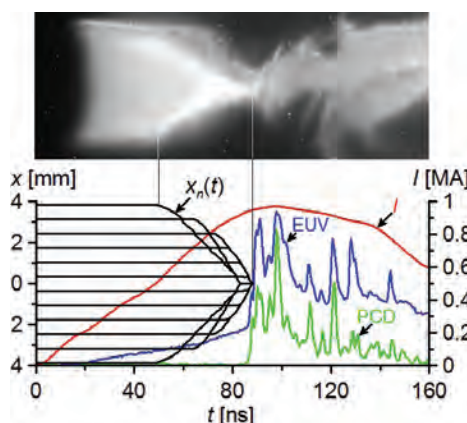


Figure 1

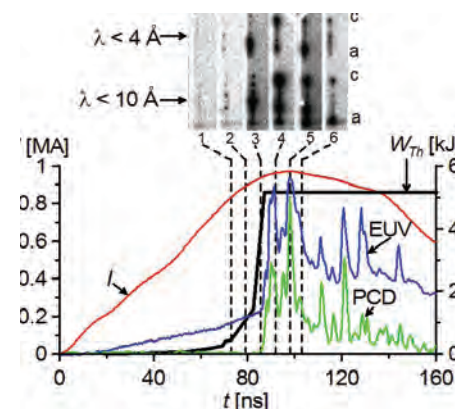


Figure 2

## Study of a Prototype of New Hohraum Configuration with Planar Wire Array X-ray Sources

University of Nevada, Reno; Victor Kantsyrev (victor@unr.edu)

An indirect drive configuration for inertial confinement fusion (ICF) was recently jointly proposed by Sandia National Laboratories and the University of Nevada, Reno (UNR), where multiple compact Z-pinch planar wire array x-ray sources surround a hohlraum [B. Jones *et al.*, PRL, v.104, 125001 (2010)]. Planar compact wire array sources (mm-scale size) allow reduced primary hohlraum surface area. Such geometry could significantly reduce the hohlraum surface and potentially provide a hotter hohlraum x-ray environment for ICF than well-studied double-ended cylindrical arrays. The increase in peak current on the UNR Zebra from 0.9 to 1.7 MA without changing generator architecture by application of new Load Current Multiplier technology and extensive experience with planar wire arrays during the last 5 years has allowed us to start development and testing of a prototype of a new compact double-source hohlraum configuration for ICF and radiation physics on Zebra. During experiments, the current redistribution in two magnetically decoupled compact

planar array Z-pinches was demonstrated without significant loss of radiation yields and power. It was shown that plasma might dissipate the magnetic energy at stagnation, acting as a resistor. First experiments were performed recently with a prototype hohlraum placed between two

compact planar array sources. Extreme ultraviolet (EUV) diagnostics that registered only the radiation from inside the hohlraum volume demonstrate the presence of a strong output signal. This research is in progress.

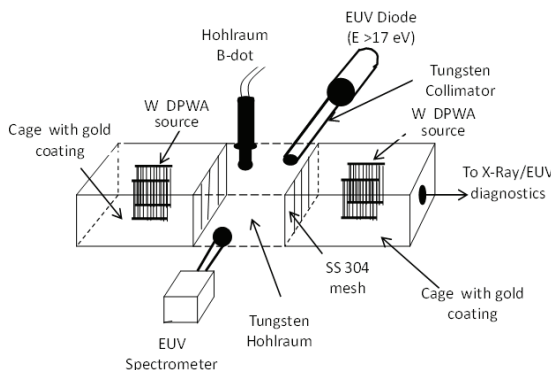


Figure 1. Experiment schematic with hohlraum placed between two magnetically insulated double planar wire array x-ray sources. EUV diagnostics (registered photons with energy > 17 eV) observed only radiation from inside hohlraum volume.

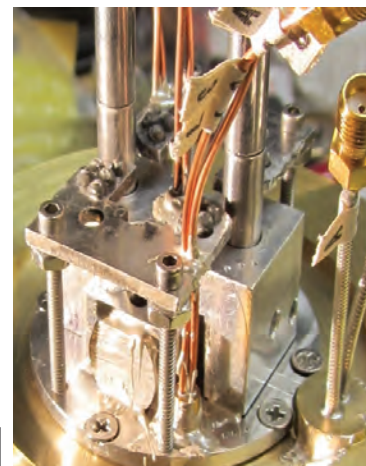


Figure 2. Hohraum installation with B-dots, wires, and diagnostics holders.

## Surface Symmetry Energy of Nuclear Energy Density Functionals

University of Tennessee; Witold Nazarewicz (witek@utk.edu)

Precise simulations of nuclei are required for different purposes. For example, the National Nuclear Security Administration Stockpile Stewardship Program requires them to assess the safety and functionality of the weapons in the U.S. nuclear stockpile. This in turn requires a coherent framework for nuclear structure and reactions based on a well-founded microscopic theory. For heavy nuclei, density functional theory (DFT) is used, where the energy density functional (EDF) is an integral of a function of various proton and neutron densities. The theory includes variables, or coupling constants, that must be adjusted to selected data. Different optimization strategies to determine the coupling constants then lead to different results.

Calculations by Nikolai Nikolov and collaborators (N. Nikolov *et al.*, Phys. Review C 83, 034305, 2011) shown in Figure 1 show that in deformed neutron-rich nuclei, a poorly constrained surface-

symmetry parameter could be instrumental for determining the stability of the nucleus. This observation suggests that including experimental data pertaining to very elongated systems in the EDF optimization process could help pin down deformation properties of the functional. In the highlighted paper, we validated the commonly used EDF parametrizations against the data on excitation energies of superdeformed band-heads in Hg and Pb isotopes, and fission isomers in actinide nuclei. The results indicate that unlike in nuclei close to the stability valley, whose macroscopic deformability hangs on the balance of surface and Coulomb terms, the deformability of neutron-rich nuclei strongly depends on the surface-symmetry energy; hence, its proper determination is crucial for the stability of deformed phases of the neutron-rich matter and description of fission rates for r-process nucleosynthesis.

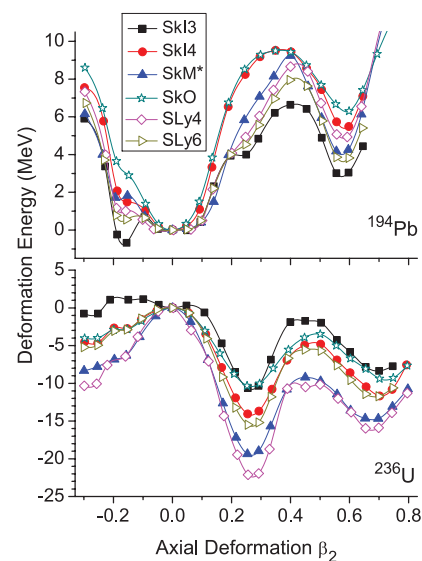


Figure 1. Potential energy curves for  $^{194}\text{Pb}$  (top) and  $^{236}\text{U}$  (bottom) versus quadrupole deformation calculated with SkI3, SkI4, SkM\*, SkO, SLy4, and SLy6 Skyrme EDFs. All curves are normalized to the spherical point.



**SSAA Program Years:**

2003-2007, Graduate Student at University of Wisconsin-Madison

**Years at Los Alamos National Laboratory:**

2008 as a Director's Postdoctoral Fellow

**Years at TAMU:**

January 2009 to present, Principal Investigator of SSAA funded grant at TAMU since September 2009

**Awards:**

- Morris E. Foster Faculty Fellowship, Department of Mechanical Engineering, TAMU, 2010
- TAMU Student Led Award for Teaching Excellence (SLATE), 2009
- Director's Research Fellow, Los Alamos National Laboratory, 2008
- Alexander von Humboldt Fellowship for Postdoctoral Research, 2007 (International Fellowship)
- Best Student Contribution (co-authored by John Niederhaus), 16<sup>th</sup> American Nuclear Society Topical Meeting on the Technology of Fusion Energy, September 2004

I attended the University of Wisconsin-Madison from 2003-2007 with funding from a SSAA grant. My faculty advisor was Professor Riccardo Bonazza, and my PhD thesis title was *Experimental Investigation of the Shock-Induced Distortion of a Spherical Gas Inhomogeneity*. I found that a transition exists in the growth rate of these instabilities when the post shock flow becomes supersonic (See Ranjan et al., PRL 94, 2005 and PRL 98, 2007, and Annual Rev. Fluid Mech. 43, 2011). I also developed a new scaling law that can be

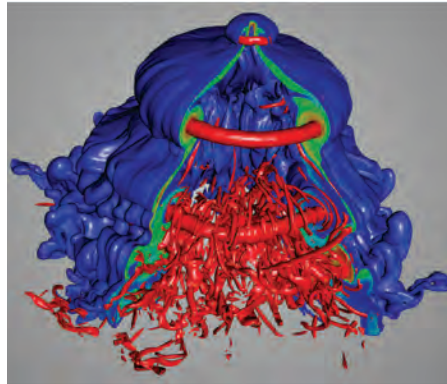


Figure 1.3-D rendered plot showing multiple vortex rings and complex 3-D structure evolving in Mach 2.88 accelerated Argon bubble in air. Blue: Ar vol. fraction=0.1, Red: vorticity magnitude, Green: film material plotted on cuts.

used to scale the laser driven experiments to the shock-tube experiments.

The support from the SSAA Program allowed Professor Bonazza to maintain a very dynamic research staff to work on shock-driven mixing problems. The funding from the SSAA Program gave me access to state-of-the-art laser diagnostics tools such as three high power Excimer lasers, fast framing cameras, etc. The support was also instrumental in allowing us to acquire the high quality data used for code validation. The funding from NNSA allowed me to attend various conferences and meetings like the American Physical Society-Division of Fluid Dynamics (APS-DFD) annual meeting, the Shock Wave Symposium, and the Topical Meeting on the Technology of Fusion Energy (TOFE). The research work we presented at the 16<sup>th</sup> TOFE meeting was judged as the best student contribution.

Through the SSAA program, I had a unique opportunity to work in close collaboration with researchers from Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratories (LLNL). I had access to a research code that was under active development at LLNL. We had monthly meetings with LLNL's Dr. Greenough, and this close interaction really helped in shaping the experimental program at the University of Wisconsin. Apart from that, it motivated me to work at a national laboratory after my PhD.

The annual SSAA Symposium provided me an ideal platform to showcase my research work. I had an opportunity to meet and discuss my future research ideas with Dr. Prestridge from LANL. In January 2008, after finishing my PhD, I joined Dr. Prestridge's group at LANL. My main focus at the laboratory was on understanding material mixing under extreme conditions, where I was able to work with the scientists at the Proton Radiography Facility (pRad). Our team performed experiments to measure the turbulent mixing between materials at high pressure-temperature environments. At pRad I had many people helping me with the experimental setup and data analysis. This assistance allowed me to work on several different projects during my tenure at LANL.

I am currently directing a SSAA-funded research program at TAMU. This is the first grant I received after joining TAMU in Spring 2009. The research funds from the SSAA Program allowed me to negotiate matching funds from the department to buy a state-of-the-art simultaneous velocity-density measurement system. The department also supported one graduate student to work on this project for two years. Such support from the department came as a direct result of support of my research program from SSAA. My group's main focus currently is to acquire high quality turbulence data for Rayleigh-Taylor driven systems. The research funds from the SSAA Program, and the matching funds from the department, are currently being used to support two domestic graduate students. Without the support from the SSAA Program, I would not have been able to develop a dynamic research program at TAMU in such a short amount of time. Three students from the group had the privilege to spend summers at LANL and LLNL. I have also been able to introduce undergraduate students to high energy density research. One of the undergraduate students, after working in our group, decided to pursue doctoral work after graduation (currently at Stanford University). For these reasons, I sincerely believe that the support from the NNSA-SSAA program has been pivotal in shaping my career. I cherish the feeling that the work performed in our group has a direct impact on the national security of this country.

**Ryan McBride, Physicist & Senior Member of the Technical Staff**  
High Energy Density Experiments, Sandia National Laboratories



**Employment at National Lab:** I've been working at Sandia for almost three years.

**SSAA Program Years:** I was supported by the SSAA program for a little over 4 years (September 2004 – October 2008).

**University Attended During Program Years:** I attended Cornell University and my advisor was David Hammer.

**PhD Research Topic:** My PhD dissertation was titled *Implosion Dynamics, Radiation Characteristics, and Spectroscopic Measurements of Wire-array Z-pinches on the Cornell Beam Research Accelerator (COBRA)*, and I received my PhD from Cornell University in January 2009.

**Responsibilities at the Lab:** My responsibilities include conducting large integrated experiments on the Z pulsed-power accelerator at Sandia. Recently, I have been the principal investigator on Z experiments that used radiography to measure the growth of the magneto-Rayleigh-Taylor instability during the implosion of initially solid beryllium tubes (also referred to as beryllium liners). These experiments are part of my group's overall investigation into the possibilities of magnetically-driven liner implosions for inertial confinement fusion. I have also worked with colleagues from the dynamic materials group at Sandia, where I was the principal experimenter (co-investigator) on Z experiments that used radiography to make equation-of-state measurements of both shock- and ramp-compressed beryllium liners. The ramp-compression experiments have extended the measured isentrope for beryllium out to about 5.5 Mbar.

**Specific Opportunities Provided by the SSAA Program:** The SSAA program provided the funding that supported my

*...I was exposed to the exciting work being done at the national laboratories. I was also able to meet and interact with many of the scientists involved with this work.*

dissertation research, including tuition and stipend support, as well as support for new diagnostic instruments, accelerator time at the COBRA pulsed-power facility, and travel to many scientific conferences to present my research. At these conferences, I was exposed to the exciting work being done at the national laboratories. I was also able to meet and interact with many of the scientists involved with this work. Through this exposure, it became clear to me that I wanted to pursue a career within the national laboratories. None of this would have been possible without the support from the SSAA program.

**Miguel Morales, Staff Scientist**

Condensed Matter and Materials Division/EOS and Materials Theory Group, Lawrence Livermore National Laboratory



**Employment at National Lab:** I have been working at Lawrence Livermore National Laboratory for one year.

**SSAA Program Years:** I was involved with the SSAA Program from 2006-2009.

**University Attended During Program Years:** I attended the University of Illinois at Urbana-Champaign from 2004-2009 and my advisor was David M. Ceperley.

**PhD Research Topic:** My graduate research was centered on the development and application of novel first-principles computer simulation methods. In particular, we focused on the use of quantum Monte Carlo methods to study materials at

extreme conditions, including high pressures and high temperatures. I obtained my PhD from the University of Illinois at Urbana-Champaign in 2009, with a thesis titled *First Principles Simulations of Hydrogen and Helium at High Pressures*.

*I was very fortunate to be part of the first generation of students in the SSGF program, through which I developed a strong connection with researchers at LLNL.*

**Responsibilities at the Lab:** Currently, my research is focused on the development and application of advanced first-principles simulation methods to study materials at high pressure and temperature. The goal is to create reliable and predictive methods that can be used, for example, to study materials in regimes inaccessible to experiments. In addition, I am also involved in the development of novel

quantum Monte Carlo methods used to study strongly correlated materials and system containing heavy elements.

**Specific Opportunities Provided by the SSAA Program:** The SSAA program provided me with many opportunities that helped shape my career. It was through the SSAA program that I learned about the Stewardship Science Graduate Fellowship (SSGF) program. I was very fortunate to be part of the first generation of students in the SSGF program, through which I developed a strong connection with researchers at LLNL. Those connections eventually lead me to my current position and career path. In addition, the SSAA Program provided me with an incredible opportunity to meet and interact with world experts in my field through the annual SSAA Symposium and to learn about their research.



## SSAA Program Research Grants

### Stewardship Science Academic Alliances

#### *High Energy Density Physics*

##### **Cornell University**

Bruce Kusse and D. Hammer

Center for the Study of Pulsed-Power-Driven High Energy Density Plasmas

##### **Princeton University**

Nathaniel Fisch

Fundamental Issues in the Interaction of Intense Lasers with Plasma

##### **University of Arizona**

Jeffrey Jacobs

An Experimental Study of the Turbulent Development of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

##### **University of Nevada, Reno**

Aaron Covington

High Energy Density Research

##### **University of Nevada, Reno**

Victor Kantsyrev

Experimental Studies of Implosion Characteristics and Radiation Properties of Planar and Cylindrical Wire Arrays and X-pinch

##### **University of Nevada, Reno**

Alla Safranova

Theoretical X-ray/EUV Spectroscopy and Imaging Studies of Wire Array and X-pinch Plasmas

##### **University of Texas at Austin**

Todd Ditmire

The Texas Center for High Intensity Laser Science

##### **University of Wisconsin**

Ricardo Bonazza

Investigation of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

#### *Low Energy Nuclear Science*

##### **Brigham Young University**

Lawrence Rees

Development and Testing of an Inexpensive Capture-Gated Neutron Spectrometer

##### **Colorado School of Mines**

Uwe Greife

Fission Fragment Distribution Measurements at the ALEXIS Facility of LLNL

##### **Duke University**

Anton Tonchev

Precision Photo-Induced Cross-Section Measurements Using the Monoenergetic and Polarized Gamma Beams at H<sub>17</sub>S

##### **Duke University**

Werner Tornow

Neutron Induced Reaction on Specific Nuclei

##### **North Carolina State University**

Gary Mitchell

Cross Sections, Level Densities and Strength Functions

##### **Ohio University**

Carl Brune

Studies in Low Energy Nuclear Science

##### **Rensselaer Polytechnic Institute**

Yaron Danon

Experiments with a Lead Slowing-Down Spectrometer and Fission Neutrons

##### **Rutgers University**

Jolie Cizewski

Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

##### **Texas A&M University**

Robert Tribble

Development of New Techniques to Determine Neutron Induced Reaction Rates

##### **University of California, Berkeley**

Heino Nitsche

Neutron-Induced Fission Cross Section Measurements on Rare Actinide Isotopes: Americium-240 and Uranium-237

##### **University of Cincinnati**

Henry Spitz

Design and Fabrication of a Novel, Multi-Element Scintillation Detector Exhibiting Enhanced Energy and Spatial Resolution for Measuring Low Energy Photons

##### **University of Kentucky**

Michael Kovash

Measurements of Low-Energy Neutrons from Neutron-Induced Fission

##### **University of Michigan**

Sara Pozzi

Digital Waveform Sampling of Neutron and Gamma Ray Signals from Scintillation Detectors for Pulse Shape Discrimination and Pulse Height Analysis

##### **University of Nevada, Las Vegas**

Ralf Sudowe

Neutron Capture Measurements on <sup>171</sup>Tm and <sup>147</sup>Pm

##### **University of Richmond**

Con Beausang

Nuclear Stewardship Research at the University of Richmond

##### **University of Tennessee**

Witold Nazarewicz

Microscopic Description of the Fission Process

#### *Properties of Materials Under Extreme Conditions*

##### **Arizona State University**

Pedro Peralta

Incipient Spall in Metallic Materials: A Three Dimensional Study of the Microstructural Characteristics of Damage Nucleation Sites

##### **Carnegie Institution of Washington**

Russell Hemley

Center of Excellence for High Pressure Science and Technology

##### **Florida State University**

Stan Tozer

Electron Interactions in Actinides and Related Systems under Extreme Conditions

##### **Harvard University**

Stein Jacobsen

Soft X-Ray Shock Loading and Momentum Coupling in Meteorite and Planetary Material

##### **Harvard University**

Isaac Silvera

Hydrogen and Its Isotopes at High Pressure

##### **Stony Brook University**

Baosheng Li

Thermoelasticity of SSP Materials: An Integrated Acoustic and Diffraction Study at High-P and High-T

##### **Texas A&M University**

Devesh Ranjan

Detailed Measurements of Turbulent Rayleigh-Taylor Mixing at Large and Small Atwood Numbers

##### **University of Alabama**

Yogesh Vohra

Structural and Magnetic Studies on Heavy Rare Earth Metals at High Pressures using Designer Diamonds in Support of the Stockpile Stewardship Program

##### **University of California, Berkeley**

Roger Falcone

Structure and Dynamics of Materials under Extreme Conditions

##### **University of California, Davis**

Nigel Browning

Enhanced Functionality for Materials Analysis in the DTEM

##### **University of California, Davis**

Richard Scalettar

Magnetic and Structural Properties of f-Electron Systems at High Pressure: Experiments and Theory

##### **University of California, San Diego**

Brian Maple

Novel-d and f-Electron Materials under Extreme Conditions of Pressure, Temperature, and Magnetic Field

##### **University of Illinois, Urbana-Champaign**

David Ceperley

Quantum Simulations for Dense Matter

## SSAA Program Research Grants (continued)

### *Properties of Materials Under Extreme Conditions (continued)*

**University of Illinois, Urbana-Champaign**  
Ian Robertson

Dynamic Response of Nanostructured Single and Multilayer Metals

**University of New Mexico**

Peter Vorobieff

Shock-Driven Multiphase Hydrodynamics Experiments for Hydrocode Validation

**University of Nevada, Las Vegas**

Zhao Yusheng

Science Based Stockpile Stewardship Collaborative Research Development

**University of Washington**

Evan Abramson

Viscosities of Highly Compressed Fluids

**Washington State University**

Yogendra M. Gupta

Institute of Shock Physics at WSU

**High Energy Density Laboratory Plasmas (NNSA Sponsored)**

**Harvard University**

Stein B. Jacobsen

Planetary Science and Astrophysical Applications of Experimental Studies with the SNL Z Facilities

**Massachusetts Institute of Technology**

Richard D. Petrasso

Studying Fields and Matter in HED Plasmas, Hohlräume and ICF Implosions, Using Monoenergetic Proton and Alpha Radiography and Fusion-Product Spectrometry

**Ohio State University**

Anil Pradhan

Laboratory Tests of Stellar Interior Opacity Models

**Polymath Research Inc.**

Bedros Afeyan

Optical Mixing Techniques for Taming Laser Plasma Instabilities in High Energy Density Laboratory Plasmas

**University of California, Los Angeles**

Warren Mori

Parallel PIC Simulations to Laser and Electron Transport Through Plasmas Under Conditions Relevant to ICF and HEDS

**University of California, San Diego**

Hoanh Vu

Study of Laser Plasma Instabilities Generation of Hot Electrons That Adversely Affect Fusion Target Compression

**University of Colorado**

Henry Kapteyn

Coherent Imaging Studies of High Density Femtosecond Laser Plasmas

**University of Michigan**

R. Paul Drake

Center for Laser Experimental Astrophysics Research (CLEAR)

**University of Nevada, Reno**

Roberto Mancini

Experiments and Modeling of Photoionized Plasmas at Z

**University of Nevada, Reno**

Yasuhiko Sentoku

Enabling Numerical Modeling of Extreme-Intensity Laser-Produced Hot Dense Plasma

**University of Texas at Austin**

Todd Ditmore

Experimental Study of the Equation-of-State in Dense, Strongly-Coupled Plasma

**National Laser Users' Facility (FY 2011-2012)**

**General Atomics**

Rich Stephens

Investigation of Laser to Electron Energy Coupling Dependence on Laser Pulse Duration and Material Composition

**Massachusetts Institute of Technology**

Richard D. Petrasso

Charged Particle Probing of Inertial Confinement Fusion Implosions and High Energy Density Plasmas

**Princeton University**

Thomas S. Duffy

Ramp Compression for Studying Equations of State, Phase Transformations, and Kinetics on OMEGA

**Princeton University**

Anatoly Spitkovsky

Collisionless Shocks in Laboratory High Energy Density Plasmas

**Rice University**

Patrick Hartigan

Clumpy Environments and Interacting Shock Waves: Realistic Laboratory Analogs of Astrophysical

**University of California, Berkeley**

Roger Falcone

Detailed In Situ Diagnostics of Higher Z Shots

**University of California, Berkeley**

Raymond Jeanloz

Recreating Planetary Core Conditions on OMEGA

**University of California, San Diego**

Farhat Beg

Systematic Study of Fast Electron Transport in Imploded Plasmas

**University of Michigan**

Paul Drake

Experimental Astrophysics on the OMEGA Laser

**University of Michigan**

Karl Krushelnick

Intense Laser Interactions with Low Density Plasma Using OMEGA EP

**University of Nevada, Reno**

Roberto Mancini

Investigation of Hydrodynamic Stability and Shock Dynamics in OMEGA Direct-drive Implosions using Spectrally Resolved Imaging



The High Pressure Collaborative Access Team (HPCAT) Sector at the Advanced Photon Source is dedicated to advancing the state of the art in high pressure-temperature science and technology. With four separate beamlines and the capability to operate all four simultaneously around the clock, HPCAT provides critical resources for the high pressure research community.



Department of Energy National Nuclear Security Administration

# Stewardship Science Graduate Fellowship

The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) program provides outstanding benefits and opportunities to students pursuing a PhD in areas of interest to stewardship science, such as **properties of materials under extreme conditions and hydrodynamics, nuclear science, high energy density physics**. The fellowship includes a 12-week research experience at either Lawrence Livermore National Laboratory, Los Alamos National Laboratory or Sandia National Laboratories.

## BENEFITS

- \$36,000 yearly stipend
- Payment of all tuition and fees
- \$1,000 yearly academic allowance
- Yearly conferences
- 12-week research practicum
- Renewable up to four years

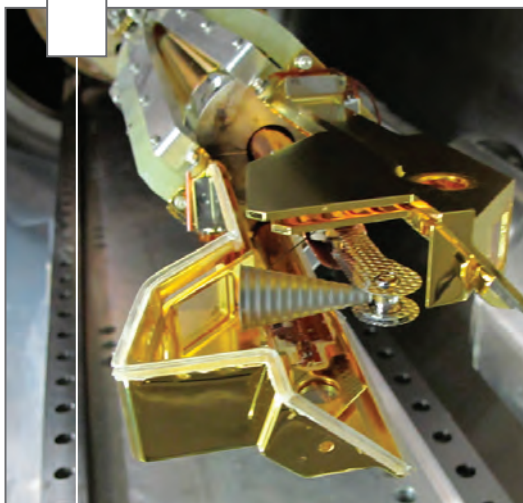
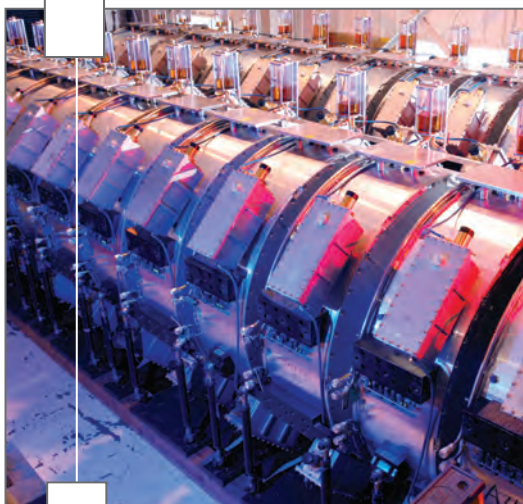
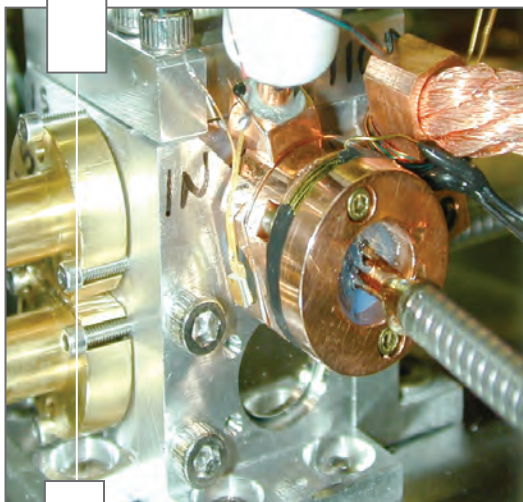
## APPLY ONLINE

The DOE NNSA SSGF program is open to senior undergraduates or students in their first or second year of graduate study. Access application materials and additional information at:

[www.krellinst.org/ssgf](http://www.krellinst.org/ssgf)

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### IMAGES

TOP: At Sandia National Laboratories, high magnetic fields on the aluminum side of this magnetically launched aluminum/copper flyer drive it into diamond targets at tens of kilometers per second, generating enormous pressures and shock waves in the diamond. MIDDLE: Circular aluminum structures create magnetic fields in Los Alamos National Laboratory's Dual Axis Radiographic Hydrodynamic Test accelerator, focusing and steering a stream of electrons.

BOTTOM: A "keyhole" target for a shock timing experiment is positioned on the ignition target insertion cryostat in the cryogenic target positioning system of the National Ignition Facility at Lawrence Livermore National Laboratory.

Images courtesy of respective laboratories.

This is an equal opportunity program and is open to all qualified persons without regard to race, gender, religion, age, physical disability or national origin.



