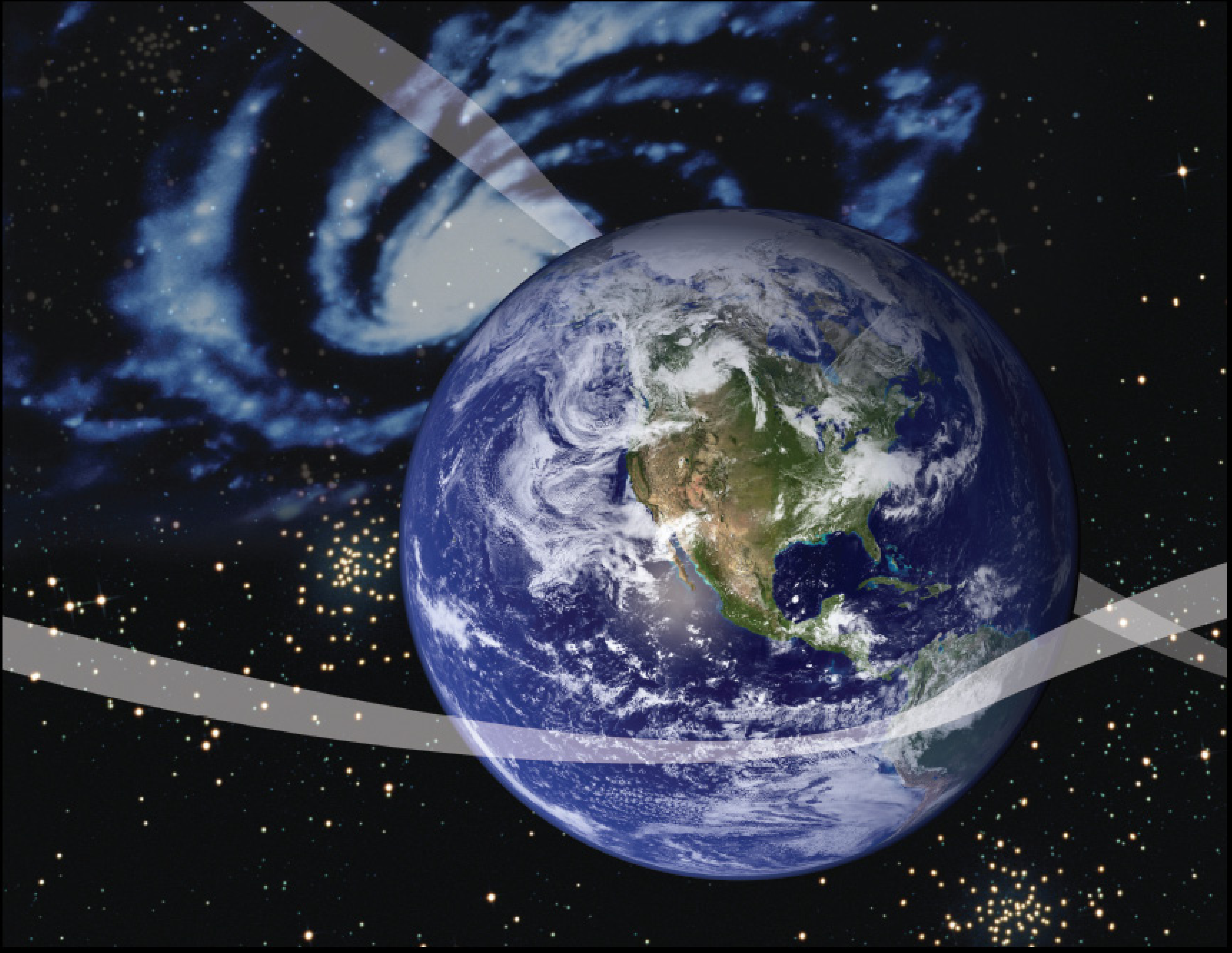
Journey
Into the Heart of Matter

The Department of Energy's Office of Science Office of Nuclear Physics



Nuclear physics is a quest to understand the origin, evolution and structure of the matter of the universe that leads to stars, the Earth and us.

Introduction

Through research, nuclear physicists are leading us on a journey of discovery into the nucleus of the atom — the very heart of matter. The goal is a roadmap of matter that will help unlock the secrets of how the universe is put together.

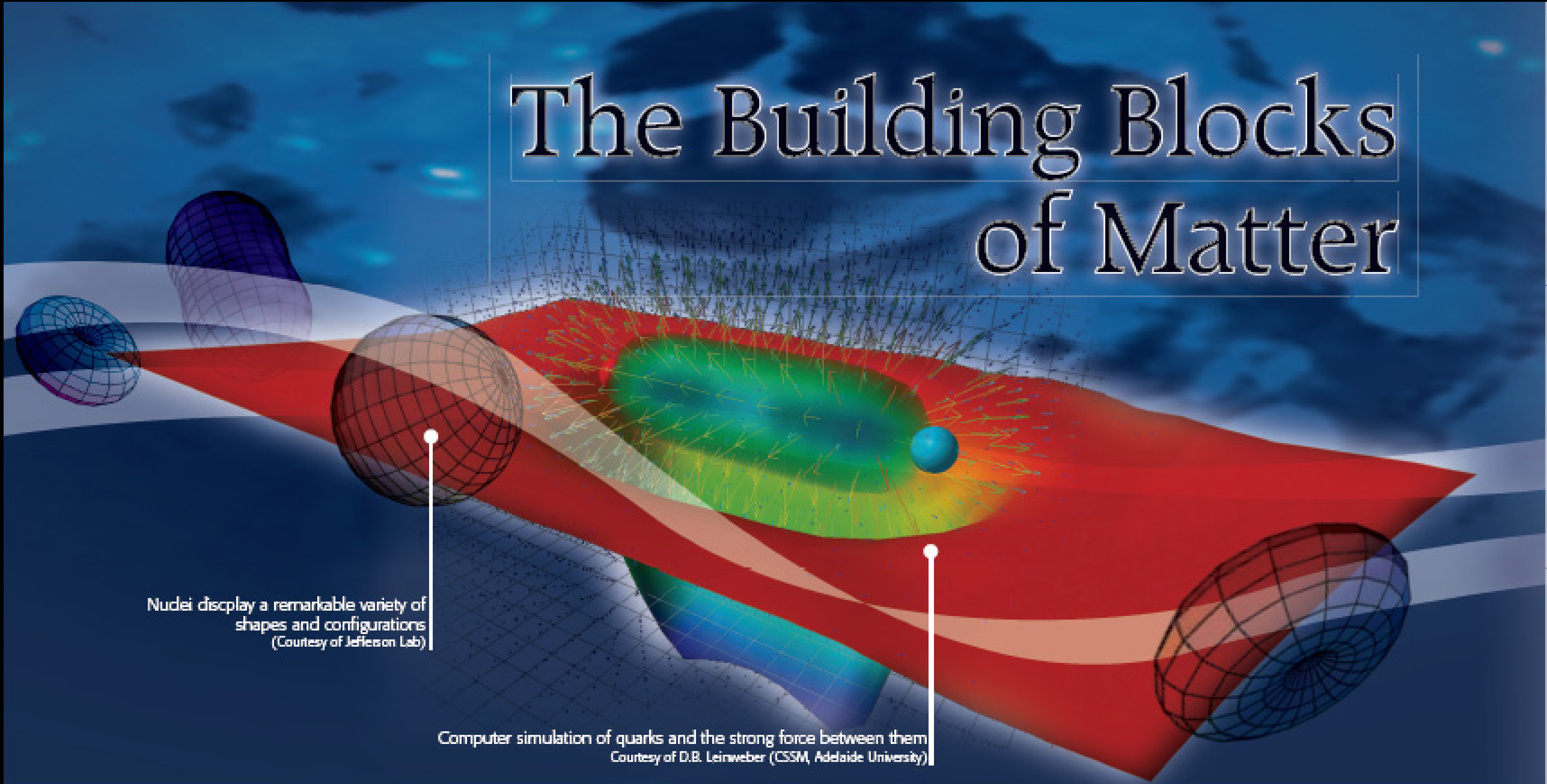
The Office of Nuclear Physics in the Department of Energy's (DOE's) Office of Science supports the experimental and theoretical research needed to create this roadmap. This quest requires a broad approach to different, but related, scientific frontiers: improving our understanding of the building blocks of matter; discovering the origins of nuclei; and identifying the forces that transform matter. Stewardship of the field is shared with the National Science Foundation's (NSF's) Nuclear Physics Program. DOE and NSF fund almost all basic research in nuclear physics.

Funding for nuclear physics provides leading-edge instrumentation, world-class facilities, and training and support for the people involved in these pursuits. The result is a vast array of information that is helping us understand the universe at ever-deeper levels.

Forefront nuclear physics research provides solid foundations for other fields: the accumulation of new results and the intellectual training of new generations of scientists foster important advances in medicine, chemistry and other sciences.

Join us on our journey into the heart of matter and learn how nuclear physicists are creating a roadmap of the evolution and structure matter that will benefit our nation for generations.

The Building Blocks of Matter



Nuclei discplay a remarkable variety of shapes and configurations
(Courtesy of Jefferson Lab)

Computer simulation of quarks and the strong force between them
Courtesy of D.B. Leinweber (CSSM, Adelaide University)

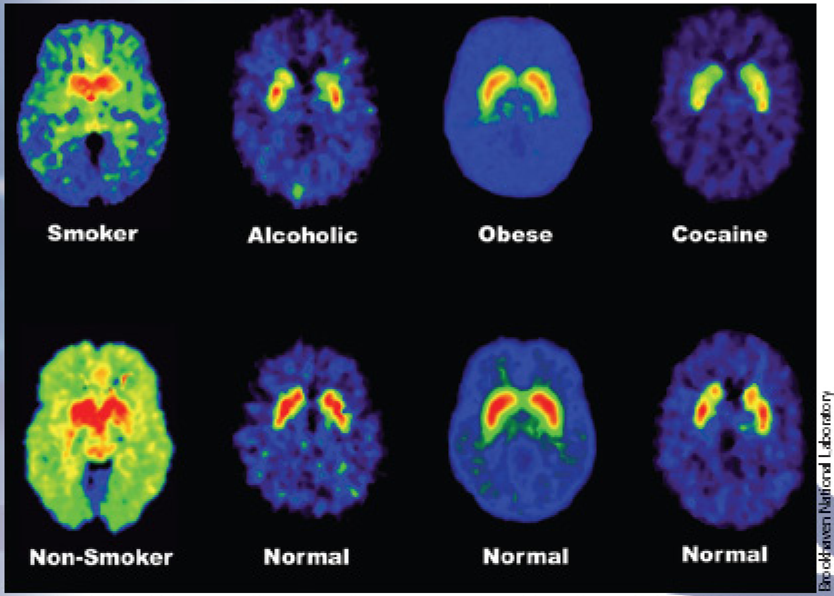
A Journey in Space

Nearly all of what we see in the universe, from people to stars, gets its mass from nuclei. As we zoom into smaller and smaller dimensions, from human hearts to cells, from molecules to atoms, we reach the nucleus at the center of an atom surrounded by a cloud of electrons. If an atom were the size of a football stadium, its nucleus would be about the size of a marble. Despite its tiny dimensions, the nucleus accounts for 99.9% of an atom's mass.

The microscopes that scientists use for peering into a nucleus are accelerators that bounce energetic particles or other nuclei from the nucleus, breaking pieces off of it or adding energy to it. The detectors used to look at these collisions reveal that nuclei are turbulent, active environments. Protons and neutrons swirl around each other at up to half the speed of light in a cosmic dance that gives rise to a remarkable range and diversity of shapes and configurations.

For example, nuclei containing up to some 100 protons and 150 neutrons have been found, but one extraordinary puzzle is that a nucleus with 250 constituents is about the same size as one special case containing just 11. To study such diverse behavior, nuclear physicists are using accelerators to create "designer nuclei." Finding simple, reproducible patterns among the many complex behaviors of both designer and ordinary nuclei will allow us to better understand how and why certain chemical elements are found on Earth and in stars.

Going one level deeper, nuclear physicists are looking at the building blocks of protons and neutrons: quarks and gluons. The theory of Quantum Chromodynamics, or QCD, describes how quarks exchange gluons, much the way children toss a ball back and forth. According to QCD, this exchange of gluons binds quarks together via the strong force. This force is so strong that when pried even a little



As a by-product of building and using accelerators, pioneering nuclear physicists have also developed new tools to peer inside the human body. Using radiotracers and positron emission tomography (PET) scanners developed by nuclear physicists, biochemical clues have been identified for a range of addictive behaviors including smoking, alcoholism, overeating, and drug abuse. The PET scans reveal that people with addictions have fewer receptors for one of the brain's "pleasure" chemicals and may be attempting to compensate for a blunted pleasure response by taking drugs.

Nuclear Physics Applications

The precise knowledge of nuclear materials and nuclear reactions gained through basic research in nuclear physics has yielded many benefits for society, including:

- radiation therapy for eradicating cancer while shielding healthy tissues from harm
- medical imaging technologies such as X-ray, MRI and PET
- the potential for abundant nuclear power and safer ways to dispose of nuclear waste
- radiation detectors for screening cargo and protecting our national security

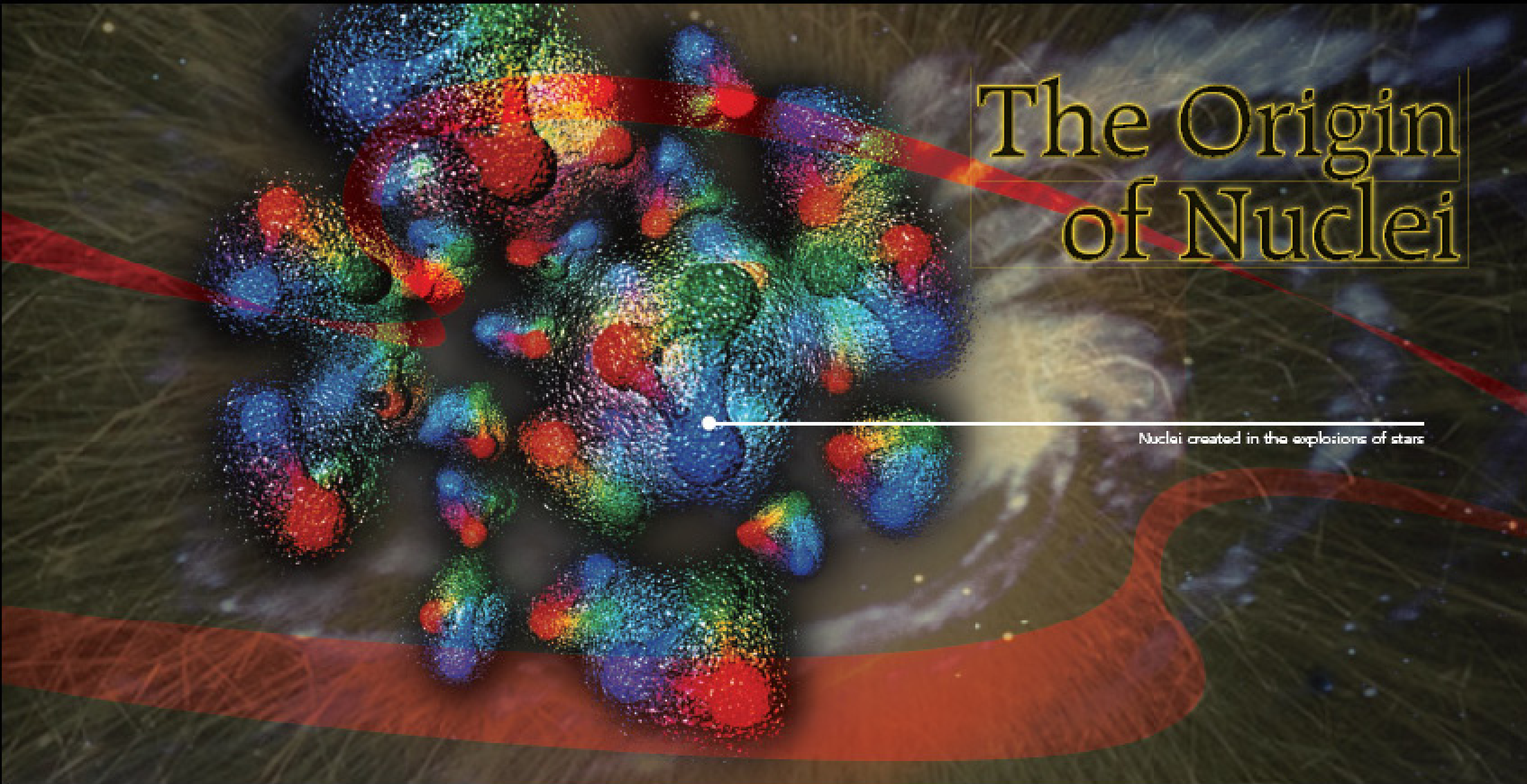
apart, quarks experience many tons of force pulling them together again.

As a result, protons and neutrons are hot, bubbling cauldrons of activity. Quarks and gluons jiggle around inside at nearly light-speed, and extra gluons and quark/anti-quark pairs may even pop into existence one moment only to disappear the next. It is this flurry of activity, fueled by the energy of the gluons, that generates nearly all the mass of protons and neutrons and thus ultimately of all the matter we see. One of the most bewildering questions nuclear physicists are trying to answer is how the basic properties of protons and neutrons like mass, shape and spin come about from this flood of gluons, quark/anti-quark pairs and a few ever-present quarks.

Scientists are also investigating how the strong force that glues quarks and gluons together influences nuclear properties. A small fraction of that force leaks out beyond the edges of protons and neutrons and binds them together to form nuclei. Thus, the very same force that makes a proton or a neutron also generates nuclei. We are only beginning to understand how this "leakage" occurs and how it results in the impressive variety of nuclei found in nature.

Nuclear physicists study the building blocks of nuclei that make up 99.9% of the mass of our everyday world.

The Origin of Nuclei



A Journey Through Time

When you examine the matter surrounding us, you are seeing material distilled in the hearts of stars. Tracing the origin of the carbon in your blood or the calcium in your bones is a journey through time.

More than 15 billion years ago, the Big Bang produced a scorching-hot fireball of the most basic particles. A few millionths of a second later, just as hot water vapor condenses to liquid, some of the simplest components of the matter we see today — protons and neutrons — formed as the primordial fireball expanded and cooled. For the first time since this unique event, nuclear physicists are now recreating in the laboratory the matter that existed in that first fraction of a second of the universe's life to learn how it condensed into protons and neutrons.

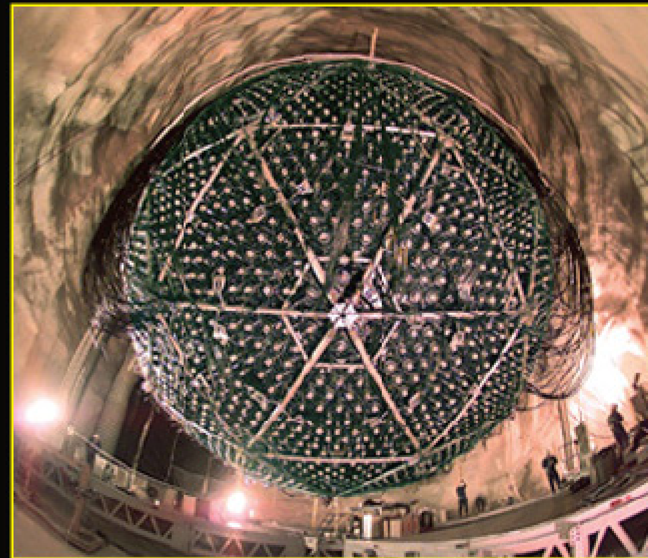
One of the greatest mysteries scientists are exploring is why the pure energy of the Big Bang did not turn into equal amounts of matter and antimatter. Antimatter is extremely rare in nature. Experiments in nuclear physics are helping to reveal secrets of the forces that acted during the universe's earliest moments to find out why.

In the minutes following the Big Bang, the first, simplest nuclei formed. Gravity exerted its sway on the swirling gas of atoms and formed clumps of hydrogen atoms, which compressed, heated and started to fuse and glow. A new light shone in the formerly dark universe, powered by the energy of nuclear reactions. As the stars evolved, these nuclear reactions produced heavier and heavier nuclei.

Relatively small stars like our sun burn steadily for billions of years, creating the conditions needed for life. Nuclear physics experiments can detect not only the light from the surface of our sun but also ghost-

NASA/JPL-Caltech/O. Krause (Steward Observatory)

Using tools like the NSCL at Michigan State University, ATLAS at Argonne National Laboratory and HRIBF at Oak Ridge National Laboratory nuclear physicists are deciphering the processes by which supernova explosions create elements.



Ernest Orlando Lawrence Berkeley National Laboratory

Neutrinos are produced in vast numbers in some nuclear reactions, such as those that occur in the processes that light the stars and in the nuclear power plants that light our cities. But neutrinos rarely interact with other matter. They can pass through the entire Earth without interacting with a single atom. Neutrinos get even stranger: they can morph into one of three different types and back again. These properties make neutrinos notoriously difficult to study — and fascinating. The Sudbury Neutrino Detector, located over one mile underground (pictured above), provided the first direct evidence that neutrinos change as they travel from the core of the sun to the Earth.

like neutrinos that emerge from the fiery nuclear reactions at its core. These experiments are confirming our picture of the sun. They have also revealed that neutrinos change their nature during their 93-million-mile journey to Earth. This "oscillation" from one neutrino type to another demonstrates that neutrinos have mass. While that mass is tiny, there are so many neutrinos in the cosmos that their total mass may outweigh that of the visible stars.

Large stars burn up quickly and can end their lives in catastrophic explosions. Supernovas, which briefly shine brighter than an entire galaxy of stars, may be the source of over half the elements heavier than iron and may create additional short-lived nuclei, such as those containing extra neutrons. Fingerprints of these unusual nuclei can be seen in the chemical distribution of the elements on Earth.

However, this story can only be partly told: simulated supernovas in today's computer models fail to explode at all. What does nature know about the properties of neutrinos and nuclei that we do not? Through nuclear physics research, scientists are aiming to find out.

Massive detectors enable nuclear physicists to study the processes that allowed matter to form after the Big Bang and learn about the origin of nuclei and the ultimate fate of stars.

Changing Matter

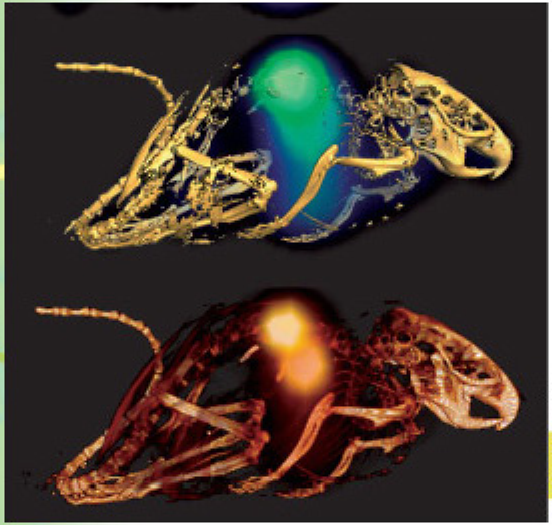
A Journey to the Extremes

What happens when you boil water? Bend metal? Burn wood? Throughout human history, scientific thinkers have asked questions about what happens when you change matter. Even babies act as scientists, pushing and pulling on everything around them to learn how things work. Such experimentation is essential to our survival and often helps us gain control of our world.

In experiments using powerful particle accelerators, nuclear physicists poke and prod nuclei by colliding atoms or subatomic particles to discover what happens when these packets of particles are heated to extreme temperatures under extreme pressure. These experiments are allowing scientists to change things in a predictable way, so they can see what happens as conditions like temperature and density vary, observe at what point significant changes occur, and determine how to control the transitions. It's much like being able to watch the evolution of the universe on "videotape" — rewinding, fast-forwarding and freeze-framing to better understand what transpired.

Nuclear physicists are also probing matter at larger scales to see nuclei we have never seen before, how nuclei transform themselves from one type to another, how long they live, and how to detect such a change has taken place.

Future facilities will allow scientists to create the neutron-rich exotic nuclei that may be formed in supernovas to understand how elements are produced in the universe. They are also aiming to create nuclei with exotic species of quarks. Most nuclei in nature are primarily made of "up" and "down" quarks. Nuclear physicists are creating nuclei



Oak Ridge National Lab

The knowledge of unstable nuclei is allowing the collaboration of Oak Ridge National Lab, Jefferson Lab and Johns Hopkins University to develop a small-animal imager that collects metabolic and structural images of mice as they move freely within a very small space. Scientists are developing a similar system for medical imaging of children, eliminating the need for sedation.

with a third species of quark, "strange" quarks, to probe how the force that holds the nucleus together changes when different building blocks are used to make nuclei.

Today's experiments are only just beginning to allow nuclear physicists to examine the properties of these exotic nuclei, and tomorrow offers even more exciting possibilities. New advances in accelerator technology pioneered by this scientific community have made it possible to plan new facilities that can cook up fresh batches of star-stuff. This will help us understand, for example, why the sun burns as brightly as it does and how long it's likely to continue. It may also help us discover which nuclei might be used as tiny specialists to journey into our bodies to diagnose disease and vanish once their job is done.

Accelerators allow nuclear physicists to study matter under different conditions to learn how its building blocks interact and combine to form more complex particles and materials, helping scientists search for new ways to benefit society.

Nuclear Science Education

Profiles in Nuclear Physics

Jennifer Thomas, a Naval Officer with HSL-49, the Helicopter Anti-Submarine Squadron Light, served in 2005 aboard the USS Ingraham, deployed with Expeditionary Strike Group One in support of the Global War on Terrorism. She is an Aircraft Commander flying SH-60B Seahawk helicopters. Her leadership, reasoning skills and hands-on technical experience were developed while studying for her master's degree in instrumentation from the State University of New York at Stonybrook. That experience enabled her to build large detector systems for nuclear physics experiments at Brookhaven National Lab and prepared her for a successful career in the Navy.

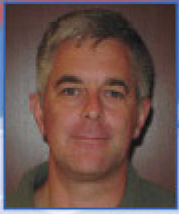
Investing in Our Nation's Future

Nuclear science is a key component of the Nation's research capabilities. In addition to providing fundamental insights into the origin, evolution and structure of matter, nuclear scientists create knowledge and devices that are directly applicable to the nation's energy resources, security safeguards, health needs, environmental protection and economic vitality. Students with nuclear science training become the skilled workforce necessary for the many industries that apply nuclear science and related technologies.

Research and development for homeland security is an important application of nuclear science. Detection systems based on the very same technologies developed in nuclear physics experiments are providing important techniques for efficiently and unobtrusively screening transport containers at our nation's borders. These methods draw heavily on nuclear science expertise in detector development, experimental simulation, source design and analysis.

Declining oil reserves and mounting concerns about greenhouse gases and global warming are making nuclear power more attractive as a reliable source of energy for the future. Nuclear science faculty educate and train nuclear power engineers. Responsible stewardship of the Nation's nuclear power industry relies on a capably trained nuclear science workforce.

The growing field of nuclear medicine has its origin in nuclear science. Applications developed in the last 50 years include beams of ionizing radiation, magnetic resonance imaging, and radionuclides for medical imaging. These techniques, for example, enable the early detection of cancer and detailed studies of how the brain and heart function.



David Fields began his career in experimental nuclear physics, gaining experience in detection and sensor hardware and analysis of complex data. He has worked at Lawrence Livermore National Laboratory and the Defense Advanced Research Projects Agency (DARPA), managing research programs focusing on weapons, weapons physics, non-lethal systems, land mine detection, sensors, and communications. As an independent government contractor, he now supports defense, intelligence, and homeland security organizations. His undergraduate research in nuclear physics at Tennessee Technological University was supported by the DOE. Fields has a Ph.D. in physics from Michigan State University, and he credits his Ph.D. training with enhancing his ability to grasp complex physical concepts in diverse disciplines and to parse problems and projects.

Roland Henry is pioneering new MRI techniques to study brain structure and function at the Center for Molecular and Functional Imaging in the University of California, San Francisco Radiology Department. These studies include neurological disorders like brain tumors, Multiple Sclerosis, and Amyotrophic Lateral Sclerosis (ALS), as well as normal and abnormal development of the neonatal brain. As an associate professor, he is also teaching and training a new generation of biomedical engineers in the Graduate Program in Bioengineering at UC's Berkeley and San Francisco campuses. His skill at extracting signals from large backgrounds was developed by taking some of the first measurements of highly elongated heavy nuclei using efficient gamma-ray detectors at Argonne National Lab. He is the second person originally from Belize to received a Ph.D. in physics (1992).

Ani Aprahamian is the Chair of the Department of Physics at the University of Notre Dame and the Director of the Institute for Structure and Nuclear Astrophysics. She is investigating how the properties of nuclei can affect the distributions of the "star stuff" that we are all made of. She is presently measuring the half-lives of the most neutron-rich nuclei made in the laboratory. These measurements provide crucial historical information about our universe. At the same time, Aprahamian and her graduate students are investigating the role long-lived states (isomers) in nuclear reactions have on neutron stars. These studies lead to a wide range of potential applications – from medicine to energy storage to basic nuclear science. Aprahamian earned her Ph.D. from Clark University.

Diagnostic techniques with roots in nuclear science become even more important as our society ages.

Students in nuclear science gain a broad range of skills that are invaluable to the workforce, including problem solving, mining of data from large data sets, working in teams, advanced theoretical modeling and mathematical skills, and computer simulation of complex systems. Over two-thirds of nuclear science graduates find employment outside of academia, representing a significant transfer of knowledge to meet society's needs.

Advanced education in nuclear science has contributed to America's prosperity and technological advances for more than half a century. A robust educational system supporting and training the best U.S. scientists and engineers and attracting outstanding students and scientists from other nations is essential for producing a world-class workforce.

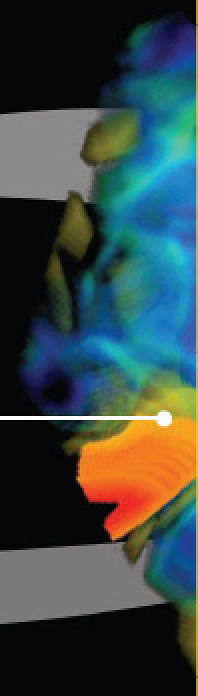
Nuclear scientists fill a variety of roles in government and industry in careers ranging from finance to medical physics.

The Department of Energy's Office of Nuclear Physics is the primary funding agency for the quest to understand the origin, evolution and structure of the matter in the universe leading to the stars, the Earth and us.

The Department of Energy's Office of Nuclear Physics supports national labs and university research groups and provides research tools utilized by the national and international research community. These trailblazers are adding to the knowledge base of humankind, developing new technologies, training the next generation of scientists, and improving the science literacy of the general public.

From the question of how it all began, to what the far future holds, from dissecting things we can observe in the universe, to searching for things unseen, nuclear physicists are testing the boundaries of our knowledge. The only way to find out where these experiments might lead is to keep moving forward with the endeavor to explore and understand the heart of matter.

For more information, visit: www.science.doe.gov/feature/NP.htm



Computer simulation of fluctuations in the strong force
Coutesy: Brookhaven National Lab

This brochure was collaboratively prepared by participants from Argonne National Lab, Brookhaven National Lab, Jefferson Lab, Lawrence Berkeley National Lab, Oak Ridge National Lab, Massachusetts Institute of Technology, Michigan State University, National Science Foundation and the University of Maryland using funds from the Office of Nuclear Physics.