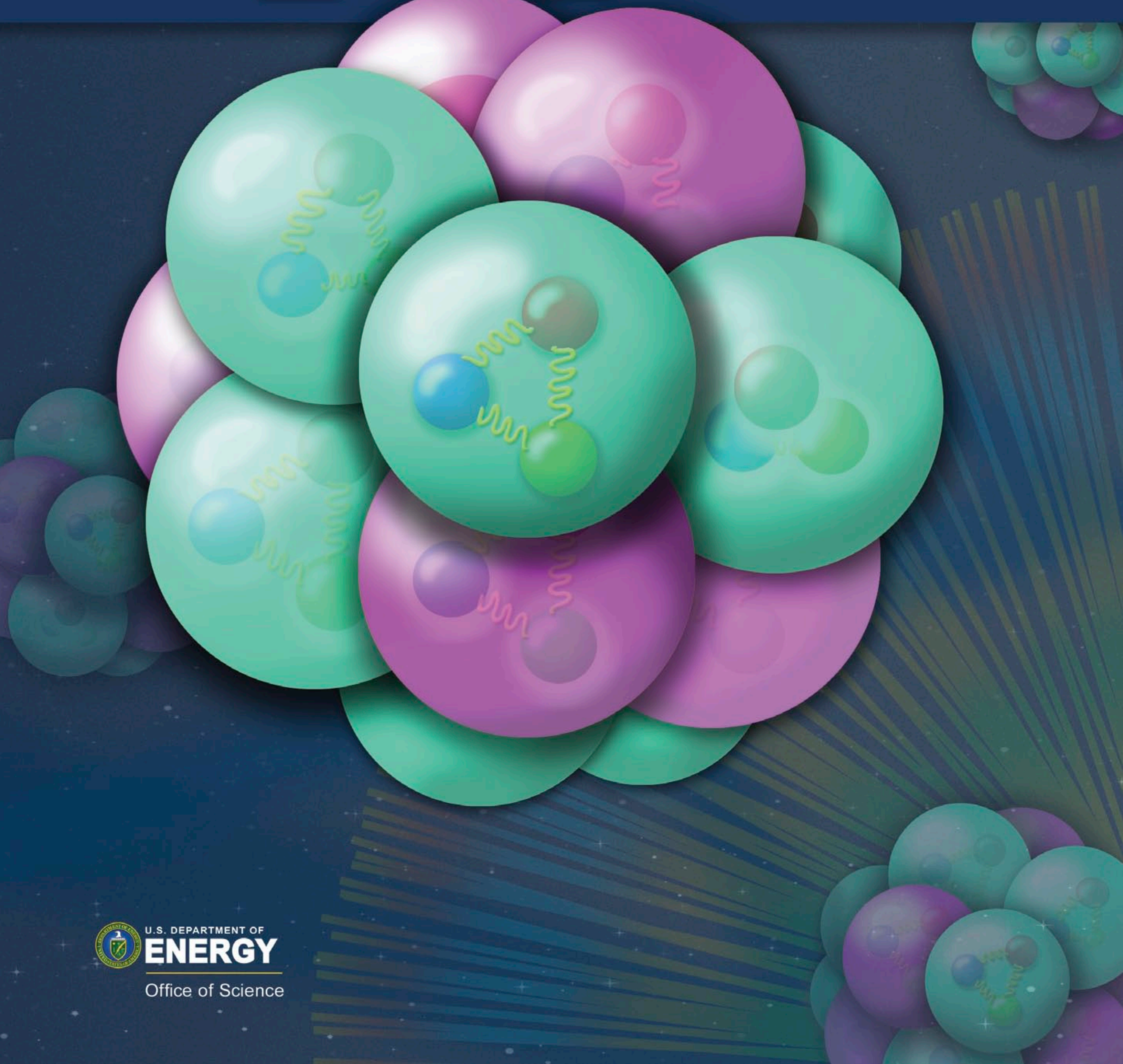
Nuclear Physics
Highlights



U.S. DEPARTMENT OF ENERGY

Office of Science

Nuclear Physics Highlights Committee 2008–2009

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Introduction

The visible matter in the universe—the material that makes up stars, planets, and every living thing—has existed for billions of years. But only recently have we had the knowledge and the tools necessary to begin to understand its origin, evolution, and structure. Nuclear scientists around the world have made tremendous strides toward this goal over the past few decades. And through that effort, we have developed applications that make our world safer and healthier.

For more than 60 years, the U.S. Department of Energy (DOE), and its predecessors, has played a leading role in the quest to understand the core of matter. Nuclear science today is focused on three broad but highly related research frontiers: (1) quantum chromodynamics, which ultimately will tell us how nuclei are held together; (2) the structure of atomic nuclei and nuclear astrophysics, which addresses the origin of the elements; and (3) a new model of fundamental particles, which will explain why our universe is made of matter and not antimatter. Through these research frontiers, nuclear scientists are addressing the basic questions that drive our field. Some of these are highlighted here. Others are discussed in the recently published Nuclear Science Advisory Committee long range plan, *The Frontiers of Nuclear Science* (www.sc.doe.gov/np/nsac/nsac.html).

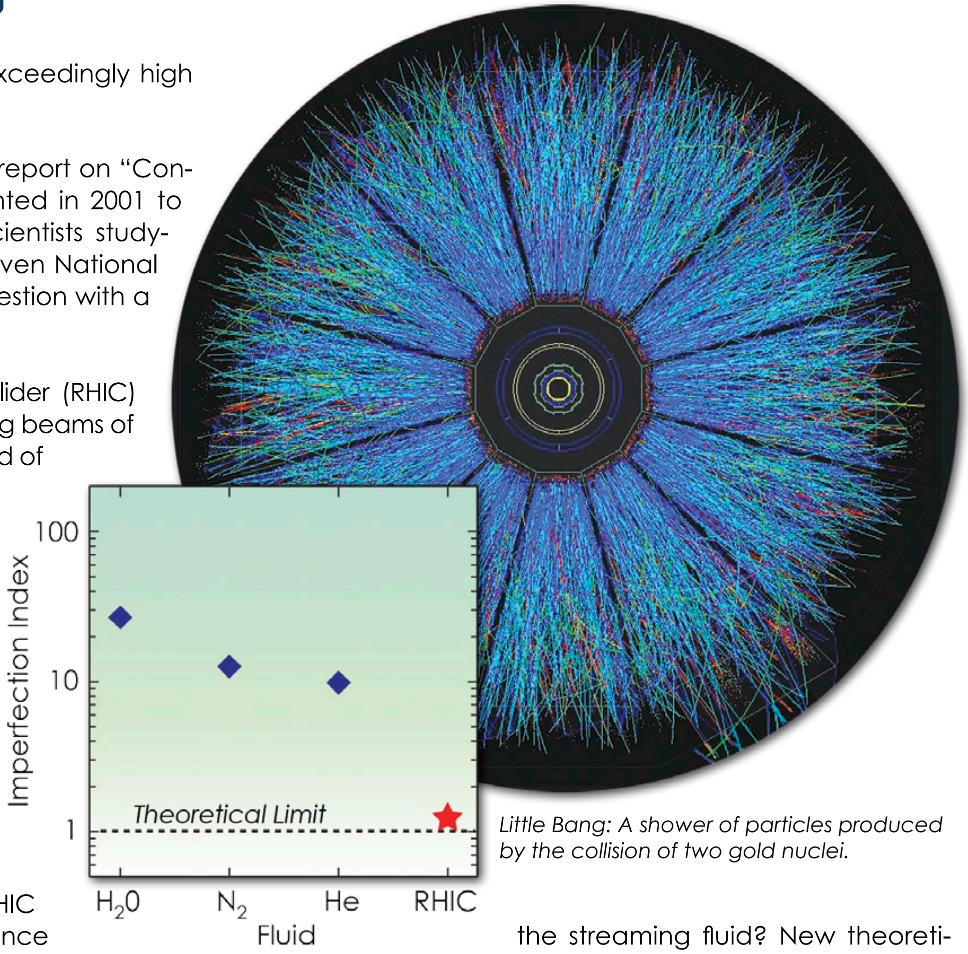
Driven by our quest to understand the world around us, basic research in science has led to innumerable applications that impact our daily lives. Indeed the world we live in today is a reflection of the enormous advances in technology over the past century. Nuclear science has contributed directly to key areas of this technological revolution, including energy production and medicine, and indirectly through training of the scientific workforce. New applications derived from basic research in nuclear science continue to be developed.

A New State of Matter Formed in "Little Bangs"

Are there new states of matter at exceedingly high density and temperature?

This question was one of 11 posed in a report on "Connecting Quarks to the Cosmos" presented in 2001 to the National Academy of Science. Scientists studying results from experiments at Brookhaven National Laboratory have now answered this question with a resounding "Yes!"

Brookhaven's Relativistic Heavy Ion Collider (RHIC) provides researchers with counter-rotating beams of heavy nuclei traveling at nearly the speed of light. When these beams intersect, each tiny nuclear collision produces a "little bang," with temperatures and densities similar to those found in the early universe a few millionths of a second after the Big Bang (**figure at right**).



Little Bang: A shower of particles produced by the collision of two gold nuclei.

These experiments have yielded dramatic evidence that the unimaginably hot and dense state of matter produced in nuclear collisions is a new state of matter, called a "perfect liquid." "Perfect" in this context refers to the absence of friction—the RHIC fluid's motion showed little or no evidence for the effects of friction, which would cause additional heating and damping of the fluid's flow. An example of an imperfect fluid is honey, thick and viscous, resistant to any motion through it.

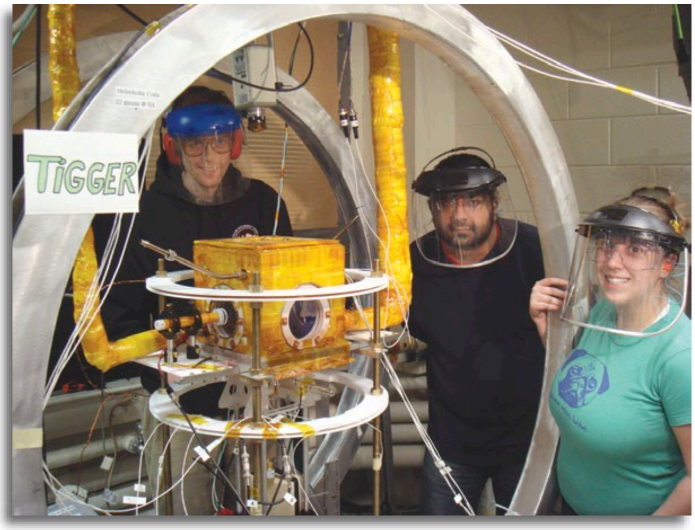
These observations present a conundrum: Friction in a fluid is described by its viscosity, and general quantum mechanical arguments suggest that the viscosity cannot be zero. These qualitative arguments were given a sharp quantitative focus in 2003, when it was conjectured that the ratio of viscosity to the thermal density, or entropy, must always be greater than a specific number, which corresponds to the value 1 in the **inset above**. Support for this conjecture came from all known fluids (e.g., water, liquid nitrogen, and helium), which exceeded this hypothetical boundary by factors ranging from eight to the thousands. Yet rough estimates indicate that the RHIC fluid has a value very near the boundary.

As a result, nuclear scientists now seek to answer a new question: "Is the RHIC liquid the most perfect of all imperfect fluids?"

Experiments are being upgraded to better study the flow of heavy particles—are they too carried along by the streaming fluid? New theoretical tools are being sharpened and deployed. Enhancements to RHIC are being planned and implemented. And because the equations of fluid dynamics routinely used to improve the energy efficiency of automobiles and aircraft break down when applied to velocities approaching the speed of light, the data from RHIC have compelled nuclear theorists to completely reexamine these equations, solving along the way puzzles that have impeded progress in fluid dynamics for three decades. Guidance and inspiration has been drawn from many sources, especially the mysterious connection between quantum theory and a theory of gravity with extra spatial dimensions which motivated the original viscosity bound conjecture.

The experimental data are now being compared with computer calculations to precisely determine the viscosity of the RHIC fluid. The best efforts to date support the original supposition that the RHIC fluid is within a factor of 2–3 of the conjectured boundary. DOE-funded researchers at RHIC and at the Large Hadron Collider in Geneva, Switzerland, will study both lower and higher energy collisions, seeking to map out the domain of perfect liquids and continuing the quest for new states of matter at exceedingly high temperatures and densities.

Peeking Inside the Neutron: Where Did All the Charge Go?



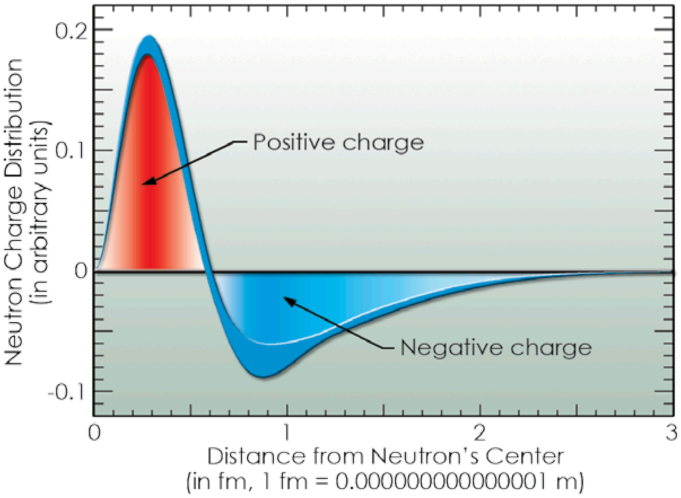
More than 99% of the mass of the visible universe is made up of protons and neutrons, and for a long time these subatomic particles were thought to be the elementary building blocks of our world. Today we know, however, that the interior of each proton and neutron is filled with action: lurking inside are more fundamental particles, the quarks, and a seething "sea" of quark-antiquark pairs. Quarks are held together by a strong force, which is a hundred times stronger than the more familiar electromagnetic force.

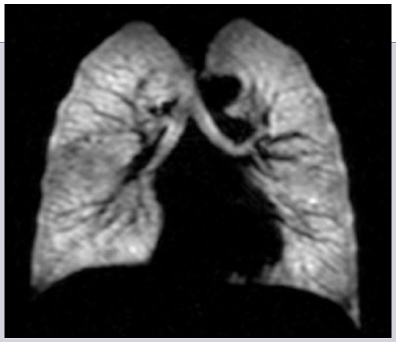
Because the neutron has no net charge, it is much more difficult to identify and study. The charged proton was discovered in the early days of nuclear physics (1918), but because of its lack of charge, the neutron wasn't added to the atlas of subatomic particles until 1932. The neutron's name originates from the Latin root for "neutral." But we know the quarks inside are charged, so how does that net neutrality come about?

To answer this fundamental question, incredible microscopic resolution is required. To this end, nuclear scientists use high-energy electrons, one of our most effective tools for understanding the neutron's interior below the distance scale of 1 fm (10^{-15} m). By measuring electrons scattered off its quarks at higher and higher energies, we can construct images of the neutron's charge distribution at smaller and smaller spatial resolutions.

Such experiments were made possible by the development of a new generation of extremely high-density polarized ^{3}He targets. From a "spin" point of view, a gas of polarized ^{3}He looks very nearly like a gas of polarized neutrons, which in turn provides an ideal target for measuring electron scattering from the neutron. The **photo at left** shows the test stand for the ^{3}He target and the students from the University of Virginia who helped to develop it.

Measurements at the Thomas Jefferson National Accelerator Facility (JLab) and the Massachusetts Institute of Technology Bates Linear Accelerator Center used this new target technology to dramatically extend both the precision and the range of the distance scale over which electron scattering has been measured. The remarkable image of the neutron that has emerged from an analysis of all available data is illustrated by the **graph below**, where the charge distribution of the neutron is plotted as a function of the distance, r, from its center. Amazingly, the neutron is not neutral when viewed at high resolution: it has a positive charge deep in its interior surrounded by a negatively charged halo. Only when it is viewed from a distance that is significantly larger than the radius of the neutron do the positive and negative contributions cancel each other out, . . . and the neutron's given name fits.





*The use of polarized ^{3}He has also led to a new magnetic resonance imaging (MRI) technique for imaging the gas space of the lungs—"noble gas imaging." This is a good illustration of the spin-off applications of fundamental research; it provides unprecedented resolution for the gas space of the lungs without exposing the patient to undesirable ionizing radiation. The **image at left**, created using this technique, shows the lungs of a firefighter who was at "ground zero" following the 9/11/01 terrorist attacks that destroyed the World Trade Center in New York City.*

Rare Isotopes, Weak Force, and the 2008 Nobel Prize in Physics

Outside of physics journals discoveries about the "weak force" don't grab many headlines since it only acts among subatomic particles. Nevertheless, the weak force is one of the fundamental forces of nature (the others being gravity, electromagnetism, and the strong force). While the strong force, which is responsible for nuclear binding, is 10^5 times more powerful, it is the weak force that determines and governs the very existence of most nuclei. Indeed, only about 300 nuclei are stable enough to exist in nature: the majority of the 3,000 others known to science decay via a type of radioactivity known as beta decay, which only occurs because of the weak force.

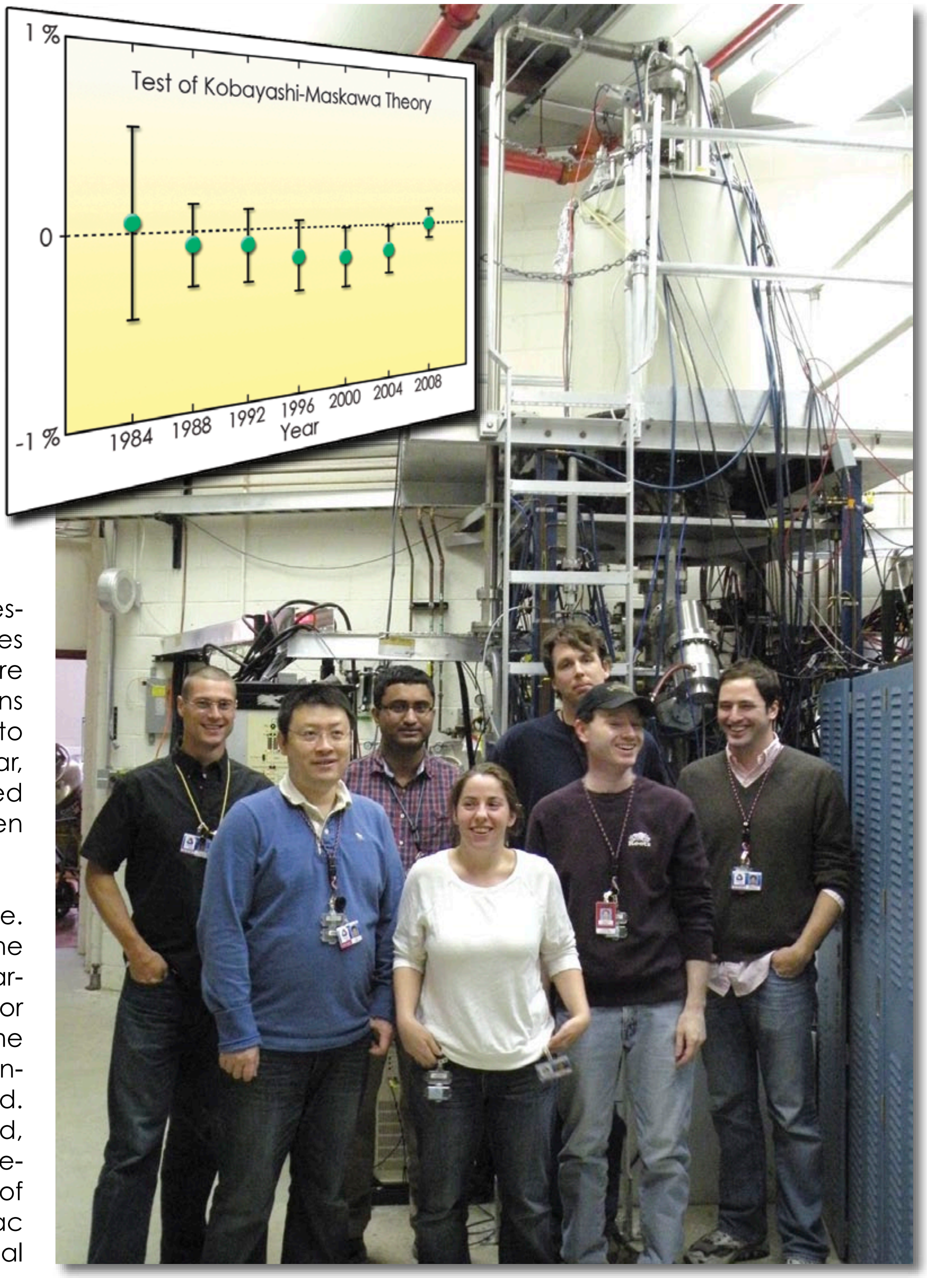
In 2008, the Nobel Prize for Physics was awarded to Makoto Kobayashi and Toshihide Maskawa, whose theory, proposed in 1973, has become an important ingredient of physicists' understanding of the weak force and its influence on the subatomic world.

We now accept that the force of gravity is universal: It is the same on earth as it is throughout the universe. Until recently, though, we had no proof that the weak force is equivalently universal for the complete panoply of subatomic particles, even though Kobayashi and Maskawa's theory assumed that it was.

This is where atomic nuclei came to the rescue. Of the thousands of different isotopes undergoing beta decay, a handful of rare isotopes with similar numbers of protons and neutrons provide the best laboratory to study the strength of the weak force. So far, 13 such handpicked cases of the so-called "superallowed" beta decays have been carefully studied.

The measurements were far from simple. The radioactive isotopes necessary for the decay studies had to be produced by a particle accelerator, and most of them lived for at most a few seconds, during which time measurements with a precision of a few hundredths of a percent had to be completed. Many laboratories worldwide contributed, but particularly important were measurements from two DOE facilities: the studies of vanadium-46 at the Argonne Tandem Linac Accelerator System at Argonne National Laboratory (ANL) and the studies of chlorine-34 and argon-34 at the Cyclotron Institute at Texas A&M University.

The first important advance came when the results of combined nuclear measurements showed that a key part of the weak force is the same within 1 part in 10 thousand for the 13 different nuclear decays studied. This precise result made it possible to enlarge the scope to test Kobayashi and Maskawa's prediction that the universality of the weak force extends beyond nuclei to all subatomic particles. The outcome confirms their 35-year-old prediction to unprecedented accuracy, a stunning success for both experiment and theory!

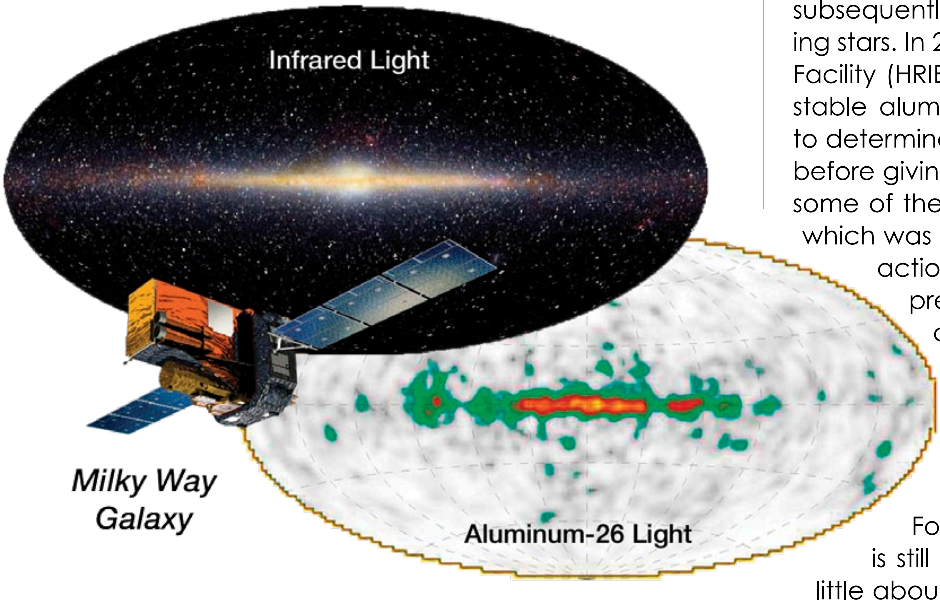


ANL team involved in precise tests of the weak force. Inset: Results plotted on a graph showing the experimental results versus measurement year converging on the theoretical limit proposed by Kobayashi and Maskawa.

Exploring the Cosmic Origin of the Elements

Where do all the elements that make up our bodies and our world come from?

For most of recorded history, the answer to this question has been the stuff of speculation, if not myth. Today DOE scientists, in concert with their colleagues around the world, synergistically combine cutting edge measurements in nuclear accelerator labs with computer simulations and satellite observations to probe the mysteries of our Galaxy and the Universe.

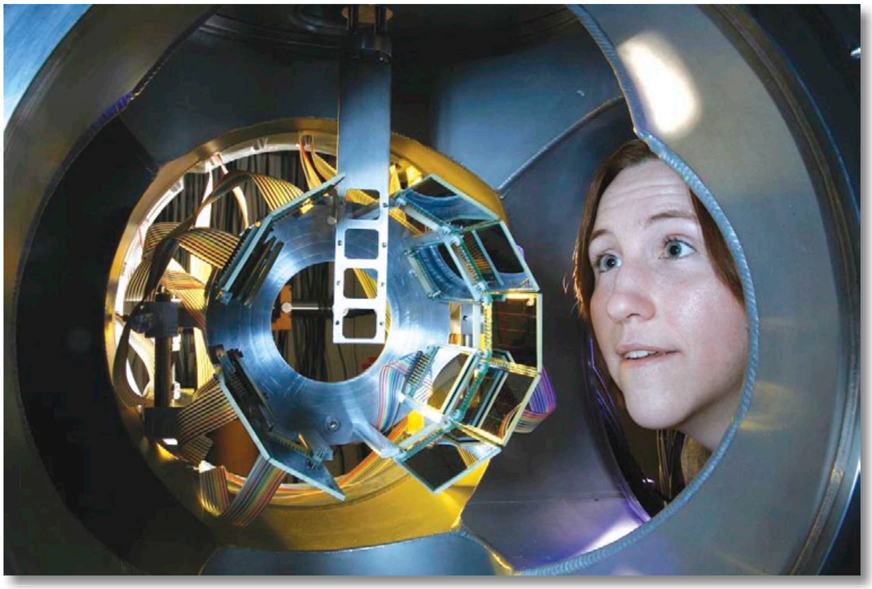


As a consequence of their work, we now know some answers to the "elements puzzle." Some of the elements, for example, were formed in the Big Bang, when the universe was created. Others were cooked up in the seething maelstrom of stars. Still others, we think, are created in cataclysmic stellar explosions, such as supernovae or novae. But just how much material is synthesized in exploding stars is still a mystery.

To address this, we launch satellites with special "eyes" to capture traces of these cosmic detonations and try to devise explosion simulations that match their snapshots. A magnificent example of this took place ninety-five thousand miles above Earth, where NASA's Compton Gamma Ray Observatory spent about 10 years gathering data, not in visible light but in "aluminum-26 light" which, when coalesced into a detailed map of our galaxy (the **figure above**), revealed numerous hot spots. The lumpy distribution, representing about three solar masses of radioactive aluminum-26, is inconsistent with some models of how the elements are created. Whatever created this aluminum-26, it must have happened recently—within the last million years or so—because this exotic aluminum decays into magnesium in that time, emitting energy in the form of gamma rays—the source of the hot spots.

To make sense of these and related discoveries, an international effort has been launched to make laboratory measurements of the nuclear reactions that create, and subsequently destroy, this unusual aluminum in exploding stars. In 2009 at DOE's Holifield Radioactive Ion Beam Facility (HRIBF) in Oak Ridge, Tennessee, a beam of unstable aluminum-26 bombarded a target of hydrogen to determine how fast this exotic aluminum is burned up before giving off its special light. The **photo below** shows some of the sophisticated detectors used for this study, which was a search for "sweet spots" in the nuclear reaction that would destroy more aluminum than previously thought. When the HRIBF results are combined with a complementary measurement at the TRIUMF facility near Vancouver, Canada, and results from other facilities, we will get a better handle on exactly what this map is telling us about exploding stars.

For all that we have discovered so far, there is still much to learn. For example, we know very little about how elements heavier than iron came into being. DOE's Facility for Rare Isotope Beams (aka FRIB), planned for nearly a decade, will give us the ability to study this right here on Earth to find additional pieces in the elements puzzle.

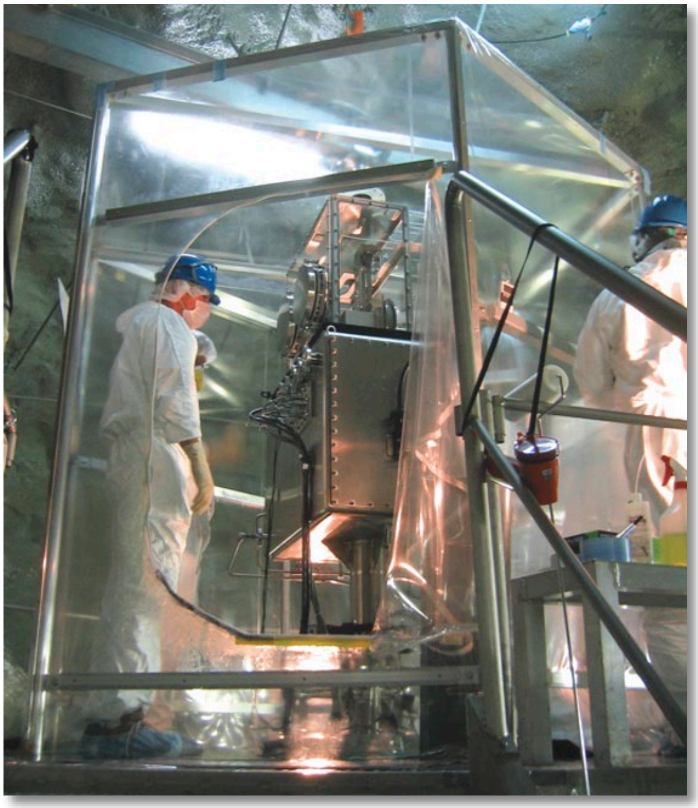


Seeking the Origin of Matter

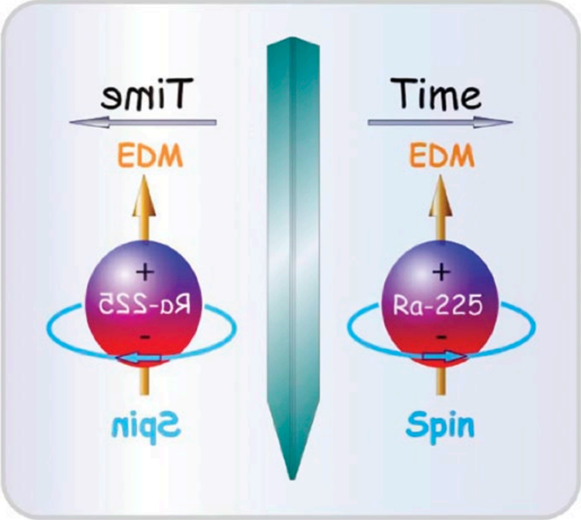
Why does our universe contain more matter than antimatter?

Most people take for granted the existence of the matter that makes up stars, planets, and all living things. However, what we know about the history of the cosmos suggests that visible matter could have been destroyed by an equal amount of antimatter long before the present day. Explaining why this did not occur—and, therefore, why the cosmos as we know it exists—is a fundamental problem. To solve it, DOE scientists are conducting exquisitely precise experiments and carrying out intricate theoretical calculations.

The solution may be provided by mysterious and elusive particles called neutrinos. During the past decade scientists have discovered that neutrinos morph from one type into another and back again. These "oscillations" imply that neutrinos have nonzero mass but are also anomalously light, relative to other particles. Results from the SNO and KamLAND experiments, in which U.S. nuclear physicists played a leading role, firmly established the presence of these oscillations in neutrinos. In the KamLAND experiment—carried out by an international collaboration with a substantial DOE-NP–supported U.S. contribution (**figure below**)—neutrinos emitted from the cores of nuclear reactors were detected by the largest liquid scintillator detector (1 kTon) ever built. It is located deep underground in the Kamioka mine in Japan.



The calibration system for KamLAND built by the United States.



This remarkable instrument has allowed us to study oscillations of antineutrinos emitted by the large number of Japanese nuclear power plants from the time they are emitted in nuclear reactions to the time they interact with the KamLAND detector. In the next generation of experiments scientists aim to determine whether the cause of neutrino oscillations leads to the matter-antimatter imbalance. These experiments include deep underground searches for radioactive nuclear decays in which two electrons but no neutrinos are emitted. If observed, this decay would imply that neutrinos are themselves their own antiparticles, a possible key ingredient for explaining the net excess of matter over antimatter.

Another set of clues may be revealed by experiments searching for a property of atoms, nuclei, and their building blocks called an "electric dipole moment" (EDM). This property corresponds to an internal separation of electric charge, and it would exist if fundamental interactions appeared to be different when viewed in reverse (**figure above**). Evidence for violation of this "time reversal" symmetry could reveal another one of the basic ingredients needed in the early Universe to break the matter-antimatter balance.

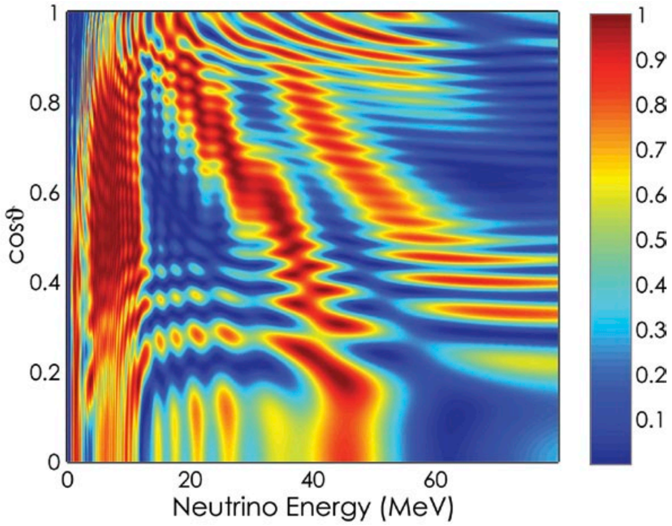
An experiment is being designed at the Fundamental Neutron Physics Beamline at the Spallation Neutron Source in Oak Ridge, Tennessee, to look for the neutron EDM with one hundred times greater sensitivity than ever achieved before. Nuclear scientists are pursuing similar searches with neutral atoms at Argonne National Laboratory (ANL), TRIUMF, and other institutions.

Recently, ANL researchers captured and stored radium atoms in a trap formed by laser beams—a major milestone in the search for a radium EDM. Together with recent substantial theoretical advances, results from these experiments may help us solve the origin of matter puzzle.

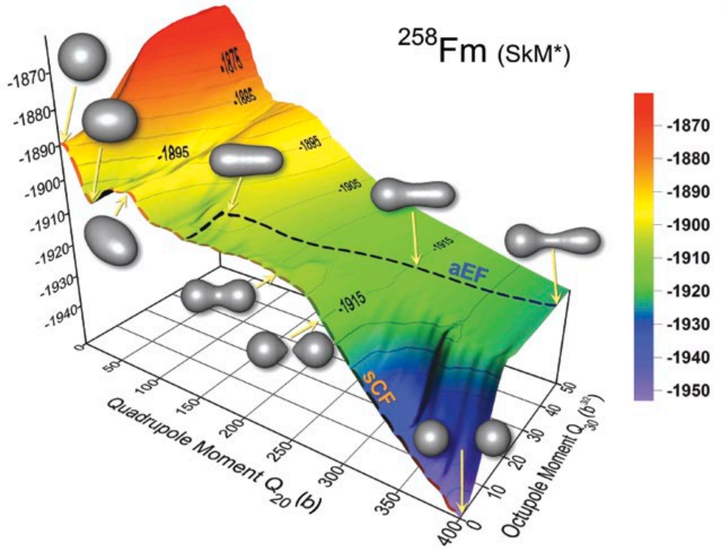
Supercomputing—Helping Crack the Nuclear Puzzle

One of the most striking trends in science today is the increasingly important role played by computational science. Today's terascale computers, capable of a trillion calculations per second, have helped us move closer to solving the nuclear puzzle. They will soon be replaced by petascale computers, which will be a thousand times faster, and scientists are even now working on exascale computers, which will be a thousand times faster again (that's a million trillion calculations per second!). All of this vast computing power will provide an unprecedented opportunity for nuclear science within the next few years. The following are just two examples of what we have been able to do on the terascale.

Core collapse supernovae are violent explosions of massive stars. Explaining these cataclysmic events requires expertise in many areas of science, with nuclear physics playing a major role. During the collapse, most of the energy radiated by the star is in the form of an immense burst of neutrinos, elusive elementary particles which pass through ordinary matter almost undisturbed. Knowledge of neutrino propagation in the hot, dense supernova environment is essential for translating the neutrino signal detected on Earth into information about the innermost regions of the explosions and about the properties of neutrinos themselves.

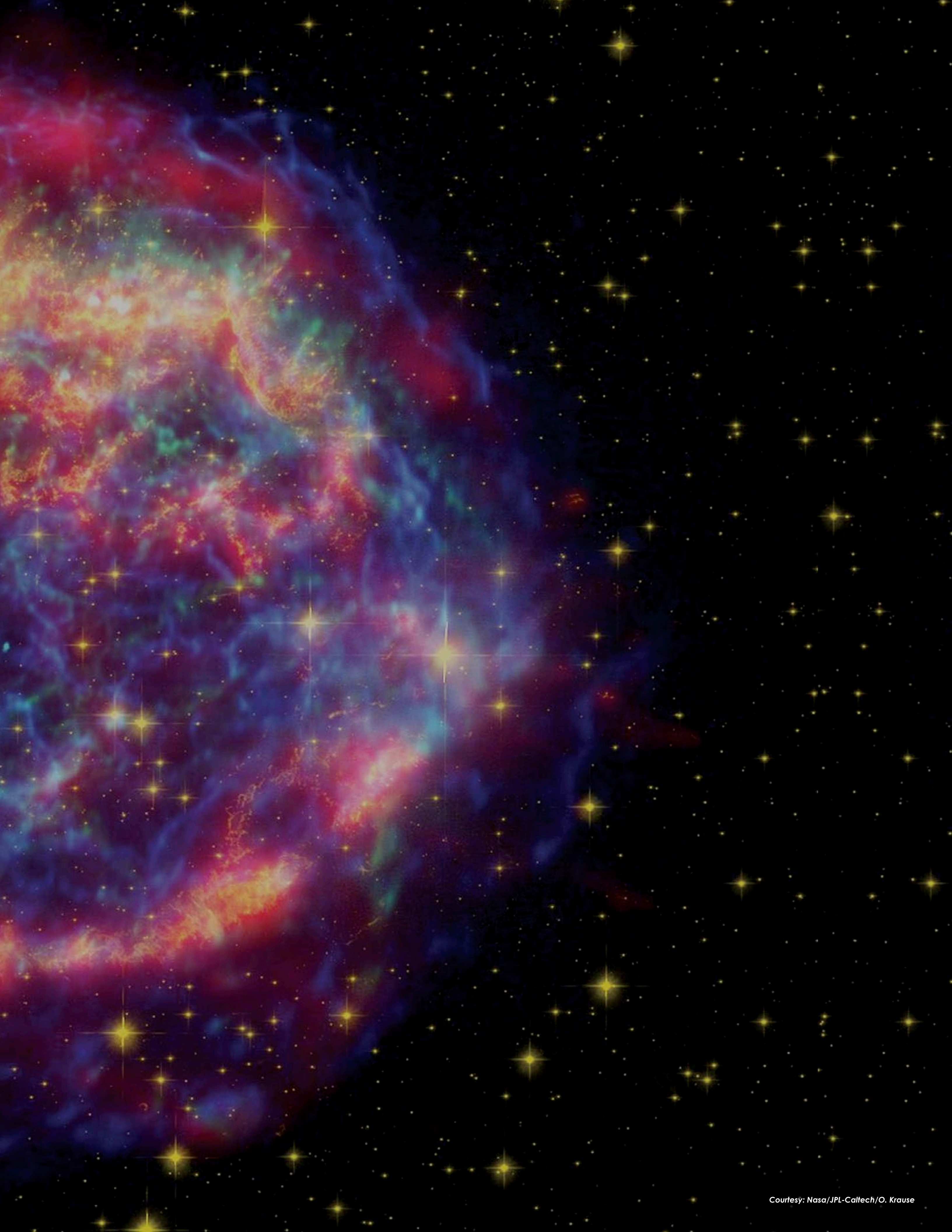


There are three types of neutrinos, and they continuously oscillate (morph) from one kind into another. The **figure above** shows the neutrino oscillation probability as a function of neutrino energy and the direction of emission from the surface of a collapsing star. Such simulations, involving the solution of nearly one million coupled nonlinear differential equations, demonstrate that the mass ordering of neutrinos may be determined via observations of neutrinos from supernovae and that extremely weak interactions between neutrinos may alter explosion mechanisms.



This year marks the 70th anniversary of the experimental discovery of nuclear fission, a fundamental nuclear decay of great relevance to society. In a seminal paper in 1939, Bohr and Wheeler developed a theory of fission based on a schematic model. Today, our understanding of the fission process is still fairly incomplete due to the intricacy of the problem, involving hundreds of protons and neutrons in a splitting nucleus. There are great expectations, however, that with the help of high-performance computers we may finally unlock the secrets of fission, and this will have measurable practical consequences in meeting energy needs and enhancing national defense, for instance.

The **figure above** shows a nice example of progress in this area: calculations explaining the phenomenon of bimodal fission observed in some transactinide nuclei such as the fermium (Fm) isotopes with the atomic number Z=100. In these systems, a sharp transition takes place from an asymmetric division of fission fragments as in ^{256}Fm to a symmetric split as seen in ^{258}Fm. Such calculations are an important step along the road to explaining the various shapes the nucleus assumes on its way to fission, but it takes about 3 CPU-years to carry out the full analysis for 20 isotopes of interest; hence the need for massively parallel computers.



Courtesy: Nasa/JPL-Caltech/O. Krause

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