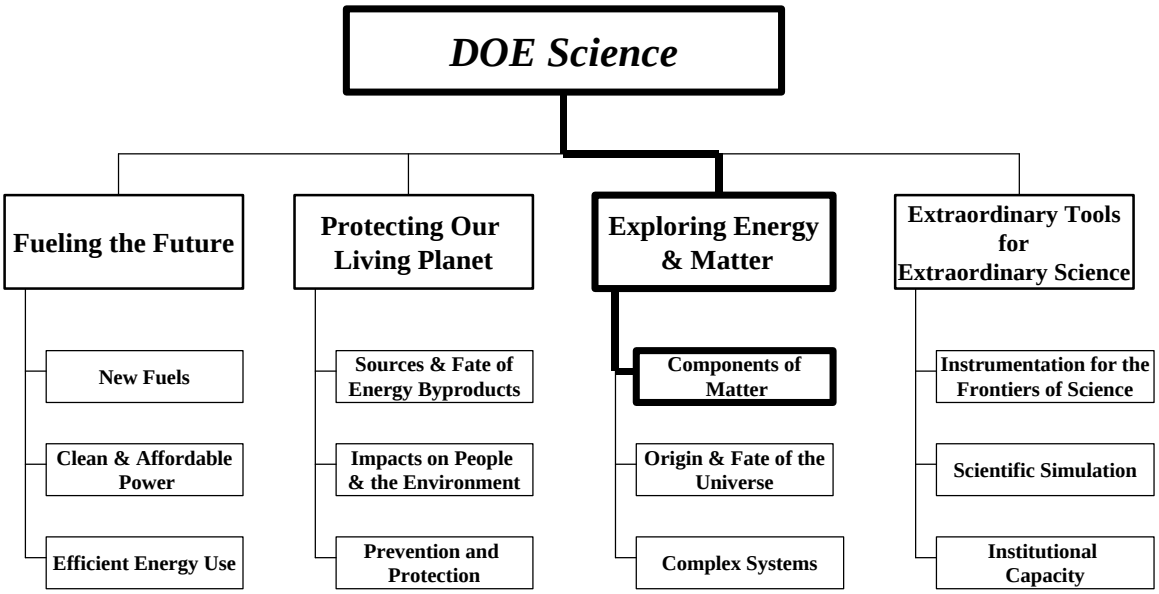
Chapter 8
Components of Matter

Scientific Challenge: ***To understand matter at the most fundamental level.***



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For more than a century, physical science has been imbued with the "atomistic paradigm," which holds that, at all scales of complexity, from the smallest subnuclear quark to the largest living cell, physical processes can be treated as reactions between the relevant basic units. These units, or "atoms," interact with one another, or combine with one another to form more complex objects, or even occasionally annihilate one another to form pure energy. Each atom, when viewed on its own natural scale, is simple and fundamental, but quickly becomes complex when viewed on a finer scale. Such is the case when we pass from biological molecules, which form the basis of life, down through atoms and nuclei to leptons and quarks, which are the smallest building blocks we have observed up to this time, and which we presently believe to be the fundamental building blocks of all matter. The science portfolio of the DOE Office of Science spans the entire range of scales in the effort to understand the basic properties of matter.

Elementary Particles and Their Interactions

Description, Objectives, and Research Performers

Research into elementary particles and their interactions reflects the quest to uncover the nature of matter at its most fundamental level. With this knowledge, scientists strive to understand why the universe is the way it is. Starting a hundred years ago, the first of the basic particles, the electron, was discovered. So began a remarkable journey inward to smaller and smaller scales, from the atom to the nucleus to the quarks. Much of modern technology is based on the deep understanding of matter that has developed over the last century.

Along with this discovery of the fundamental constituents came a growing understanding of the interactions between them. One of the great achievements of the last quarter century is the understanding that apparently different interactions are unified as different manifestations of a single force. This remarkably simple and beautiful synthesis of ideas regarding the fundamental constituents of matter and their interactions has profoundly changed scientists' thinking about the natural world. Despite this period of great revelation, every turn continues to provide major surprises, forces adjustments in thinking, and spurs scientists' efforts to discover whether all interactions, including gravity, can ultimately be understood in terms of a single theory.

To peer into the microcosm has required great imagination in the design of large, high-energy particle accelerators, the fundamental probe for the journey inward. The seeming paradox exists that to observe the smallest objects requires the most energy—energy almost beyond comprehension—to explore a realm governed by both relativity and quantum mechanics. Yet the technology developed in pursuit of this fundamental knowledge has led to many other remarkable applications, including radiation therapy, neutron sources used for materials science, and synchrotron light sources used for research in many fields, including materials science, environmental chemistry, and structural biology.

Research into elementary particles and their interactions is carried out primarily at universities and, to a lesser extent, at national laboratories. Industry participation is limited to modest funding for research supporting advanced particle accelerator concepts.

Research Challenges and Opportunities

All of the forces discussed in the previous section are characterized by interaction strengths that increase very slowly, but steadily, with the energy of a particular interaction process. Unification of the forces means that at some very high energy, much higher than has been obtained in present-day laboratories, they attain exactly the same strength. There are indications from our present knowledge that the strengths might well extrapolate to a common value when we use a unifying theory known as supersymmetry. Supersymmetry requires that for every known particle there exists a super partner with different intrinsic spin and higher mass. A principal goal of the High Energy Program is to search for such partners, especially at the Large Hadron Collider (LHC). Supersymmetry also offers the hope of unifying gravity with the three other fundamental forces of nature. This ultimate goal, to develop and confirm the theory that unifies all four forces of nature, is the underlying grand science quest motivating much if not all of the research into elementary particles and their interactions.

Other important questions remain to be answered. Why are there six types of quarks? Does the difference in the behavior of matter and antimatter predicted by the theory actually describe the world? Why is the top quark more than ten thousand times heavier than the light quarks found in the proton and neutron? Finally, what contribution can string theory make to interpreting particle behavior and bringing alternative perspectives to the Standard Model? In all of this research, advanced computational and technology research plays a vital role in experimentation and theoretical efforts and future activities will be increasingly demanding of computational ability.

Research Activities

Research activities include experiments designed to explore and understand the nature and origin of the differences in behavior between matter and anti-matter, e.g., violation of symmetry in charge conjugation parity (CP) that is inconsistent with the Standard Model; experiments to determine whether neutrinos have mass and to determine their nature; search for the Higgs Boson particle predicted by the Standard Model which, if found, could help to confirm the existence of supersymmetry and possibly double the elementary particle spectrum; search for other rare particles in collisions of protons and antiprotons, or of electrons and protons, that reveal symmetries at ever smaller distances, supporting the theory of supersymmetry; experiments into electroweak interactions to further understand and refine the Standard Model; precision experiments designed to understand the spectrum of hadron masses and properties and supporting quark structures; research exploring how the spin structure of nucleons is affected by the spin of its internal constituents, quarks and gluons; theoretical research employing advanced computation and simulation as a framework for understanding phenomena involving fundamental particles, the Standard Model, and unification of forces; research into more sensitive, accurate, and radiation hardened particle detectors and electronics leading to technologies with spinoff applications; research into conventional and advanced particle accelerator concepts that break the constraints of current limits posed by present physical structures and materials—superconductivity, very high powered radio frequency sources, and so forth.

Accomplishments

- Researchers developed Quantum Chromodynamics and the Standard Model, which form the basis of all modern theories of the fundamental constituents of matter and the forces that bind them into the materials of the world around us.

- A Nobel Prize was awarded to an SC-sponsored researcher for initial observation of CP violation, the asymmetry between matter and anti-matter, which is essential for the evolution of a matter-dominated universe.

- Experiments have ruled out a Higgs Boson and similar particles below 90 GeV in mass, thus helping to eliminate a significant range of theories of grand unification.

- The top quark was discovered. The top quark is the final member of the third family of elementary particles. Its high mass, almost 200 times that of the proton, is a major theoretical puzzle.

- A Nobel Prize was awarded to an SC-sponsored researcher for the discovery of the tau lepton, the first indication that there are more than two families of elementary particles.

- Highly precise measurements for electroweak interactions and precision measurements of W and Z bosons' masses gave the first indications that the top quark would be very much heavier than other quarks. They also indicated a range for the Higgs Boson mass.

- The properties of hundreds of hadrons have been characterized by their mass, their intrinsic spin (or angular momentum, like a spinning top), and discrete quantum mechanical properties called parity (P) and change conjugation parity (CP). The regularities of hadrons provided the first clues for the existence of the u, d, and s quarks.

- A Nobel Prize was awarded for the discovery of the charm quark.

- A Nobel Prize was awarded for the discovery of quark substructures in the neutron and proton through deep inelastic electron scattering.

- A Nobel Prize was awarded for the discovery of the existence of two distinct neutrino types. This was a critical discovery in the determination of families and led to the formation of the standard model.

- The discovery of bottom quark-antiquark states, and baryons containing charmed and bottom quarks established the reality of the third family of quarks and provided a lower bound on the mass of the top quark.

- Researchers discovered that most of the spin of the proton and neutron is not found in the three main quarks that make up the nucleon. The three quarks contribute about ½ of the total spin of neutrons and protons; the remainder must come from other, presently not understood, mechanisms.

- Researchers developed super-string theory, including gravity, which had been a major goal of high-energy theory—the development of a "Theory of Everything."

- The modern million-turn simulation of storage rings for new machines is a significant computational tool for the design of future accelerator facilities.

- Laser wakefield and laser beat wave plasma accelerator concepts have been invented; these could be the key to future accelerators of much higher energies than existing machines.

- Proof-of-principle demonstration was accomplished for the Inverse Free Electron Laser that, by providing unique high precision sources of photons, will bring the benefits of high energy physics technology to other fields of science.

- The development of Lattice Gauge theories allowed the calculation of fundamental physics parameters from first principles.

- The invention of the strong focusing principle made the construction of high energy accelerators possible.

Nuclear Matter and Interactions

Description, Objectives, and Research Performers

Nuclear science has as its objective the understanding of nucleons and nuclei, which are the hearts of atoms and the place where almost all of the mass of ordinary matter resides. Despite the ubiquity of nuclear matter in the universe, understanding its behavior remains a major challenge. Nuclei are assembled in stars from individual protons and neutrons, and nuclear properties are governed by their motions and interactions within the nucleus. But, at a deeper level, protons and neutrons themselves are found to have a complex structure, being composed of quarks and gluons that seem forever trapped inside. And yet, we believe quarks and gluons roamed independently during the first microsecond of the universe's existence. Quantum Chromodynamics (QCD) is considered to be an exact description of the interaction of the quarks, but the complexities of the theory make the way in which nuclear matter is constructed from quarks still mysterious. Solving this problem is essential to understanding matter under both normal and far-from-normal conditions. Extreme conditions existed in the early universe, exist in the cores of stars, and can be created in the laboratory during collisions between nuclei.

Research into nuclear matter and interactions is accomplished primarily by researchers from DOE's national laboratories and the nation's universities, with the larger emphasis in research funding at the national laboratories. This research, too, is conducted on particle accelerators designed/tailored for these applications, funded by the Department, employing highly specialized detectors and ultra-precision electronics.

Research Challenges and Opportunities

Research in nuclear matter and interactions is mainly directed toward the challenges of understanding the strong force binding nuclei together, effects of smaller constituent particles and their resulting structure in the behavior of nucleons, characteristics of nuclei under extreme conditions of temperature and pressure that may give rise to possible quark-gluon plasmas and new states of matter, and the range of small to exceptionally large nuclei that form through fusion and nuclear reactions in stars. This information will help to refine the Standard Model. Advanced computational and technology research plays a vital role in experimentation and theoretical efforts and future activities will be increasingly demanding of computational ability.

Research Activities

Research activities are aimed at improving the fundamental understanding of the structure of atomic nuclei in terms of their contributing elemental particles, quarks and gluons, spin structure, and the overall impact on the strong forces binding the nuclei of atoms; the properties, behavior, and stability of atomic nuclei and nuclear matter over a wide range of nucleus-nucleus collisions; the effects of extreme conditions on nuclear matter with the goal of observing deconfinement of normal matter into a new form of matter; effects on the nucleons at the surface of a nucleus, as well as other nuclear reaction mechanisms and tests of fundamental symmetries; polarized ion nuclear reactions for unique high resolution spectroscopic information; and theoretical nuclear physics and the resulting phenomenological models required to interpret experimental results and explain the structure, forces, and interactions of atomic nuclei.

Accomplishments

- Using the Liquid Scintillation Neutrino Detector, scientists have found evidence for the existence of neutrino oscillations. Such oscillations can only occur if the neutrinos have mass. Thus, confirmation of this evidence will require significant modifications of the so-called Standard Model.

- Reactions induced by proton and heavy ions have identified a low density phase transition in nuclei, similar to the transition between liquid and gas phases in condensed matter physics.

- Established in this decade, the National Institute for Nuclear Theory at the University of Washington has become the premier international center for the development of new initiatives and collaborations in nuclear theory research.

- The first completed experiments at the Continuous Electron Beam Accelerator Facility (CEBAF) have confirmed the facility's capability to illuminate the transition between the older nucleon-meson and the newer quark-gluon description of nuclei.

- From early experiments that used the new Gammasphere detector, scientists have found a new and unexpected mode of collective nuclear motion. One is a so-called magnetic rotation, involving only a few nucleons on the surface of the nucleus. The other is a

previously unobserved mode of nuclear fission, where no neutrons are emitted during the fission process.

- Radioactive beams of ^{18}F have been used on the ATLAS facility to measure proton capture and reaction cross sections, which provide very stringent constraints to nuclear astrophysicists trying to understand the production of nuclei heavier than oxygen.

- Precision measurements of giant resonance excitations in nuclei using the Texas A&M cyclotron have led to an accurate determination of the compressibility of nuclear matter at the density of ground state nuclei.

- Conditions that occurred at the Big Bang and the nuclear reactions occurring in the core of the Sun have been probed by examination of neutron capture in ^{7}Li. Results obtained at the Oak Ridge Electron Accelerator (ORELA) have resolved a discrepancy in the absolute reactions rate and are consistent with models that predict the formation of heavy elements like carbon, nitrogen, and oxygen in the Big Bang.

Atoms and Molecules

Description, Objectives, and Research Performers

One of the greatest scientific accomplishments in the early twentieth century was the proof that the world around us is composed of atoms and molecules. On the scale of atoms and molecules, it is important to understand the physical properties that define their individual behavior, collective behavior, response to various external forces, and to enhance the ability to modify and alter their forms and properties for new applications. In particular, the electronic structure of materials has major consequences for the bulk properties of the materials. Two major questions pertain to the understanding of high-temperature superconductivity and giant magnetoresistance.

Theoretical and computer applications of quantum mechanics can be used to analyze the structure of materials. Tools include unique instruments such as 100 tesla, pulsed magnetic fields.

Electrons and photons are the basic probes, and the detailed knowledge thus acquired, especially in its impressive degree of precision, has wide applications in many fields of science. Magnetic optical traps have been used to create a new form of matter, the Bose-Einstein Condensate, predicted many years ago independently by Einstein and Bose on the basis of quantum mechanics. Lasers, the existence of which depends on the detailed properties of atomic systems, play an important role in this field. Research is conducted predominantly by researchers at the national laboratories and, to a lesser extent, at universities.

Research Challenges and Opportunities

Understanding the properties of solids, liquids, glasses, surfaces, thin films, and artificially structured and multicomponent materials at the atomic and molecular levels can significantly improve our ability to control and harness matter and to envision and create new materials for different applications. Challenges exist in condensed matter physics, condensed matter theory,

the behavior behind particle-solid interactions, and atomic, molecular and optical science. Breakthoughs in understanding can lead to better superconductors, better semiconductors and photovoltaics, improved lasers, stronger magnets, and other material breakthroughs. Particular challenges and opportunities exist in high temperature superconductivity, including the electronic structure and properties of complex, multicomponent materials, and improved understanding of the phenomenon of giant or colossal magnetoresistance.

Research Activities

Key activities include experiments in condensed matter physics addressing magnetic materials, superconductors, semiconductors and photovoltaics, liquid metals and alloys, and complex fluids; experiments with optical and laser spectroscopy, photoemission spectroscopy, electrical and thermal transport, thermodynamic and phase transition, nuclear magnetic resonance, and scanning-tunneling and atomic-force miscroscopies; studies of the fabrication of structures using x-rays, design and operation of new and unique research instruments, such as the 100 Tesla Pulsed Field Magnet and the actinide photoelectron spectrometer at Los Alamos National Laboratory. New electron miscroscopy techniques are also in progress, such as development of the Z-contrast electron microscope; theory development and experiments to understand the interactions among atoms, molecules, ions, electrons, photons, and electromagnetic fields, building on capabilities at the synchrotron radiation light sources, the electron beam microcharacterization centers and the neutron scattering facilities.

Accomplishments

- A Nobel Prize in Physics was awarded to an SC-sponsored researcher for control of the motion of atoms with lasers, leading scientists to restrict the motion of atoms to that equivalent to a temperature close to absolute zero, producing an atomic cloud known as a Bose-Einstein Condensate.

- Scientists developed a new state of matter called vortex matter using a high temperature superconductor.

- Photovoltaic efficiency of solar cells was improved from 10-20% to 30% efficiencies.

- A new refrigeration/engine concept based on thermoacoustics was developed.

- Pencil-shaped organic molecules called “rodcoils” were developed with half the molecule flexible, and the other half rigid. The films that can be made with rod-coils have one sticky and one slippery surface. Such films have many potential applications, such as an anti-ice coating on an airplane wing or a blood-clot lining for artificial blood vessels.

- The recent discovery of a new polymer has renewed the possibilities for an effective membrane separation of oxygen and nitrogen (O_2 and N_2). The new strategy involves selectively stopping rotational motions of the slightly longer N_2 molecule, while allowing O_2 to continue rotating during its passage through the membrane. The polymeric membrane gives O_2 a greater diffusion coefficient compared to N_2 and allows high

efficiency separation. This major advance in polymer science could enable inexpensive membrane separation technologies with broader applicability.

- Melting has been experimentally observed in an exotic material created from the magnetic vortices in supercomputers. Vortices are the small regions where magnetic fields first penetrate the superconductor, destroying the superconductivity at the vortices. Recent measurements found that these highly structured vortices behave much like particles and closely mimic matter-like states. For example, they exhibit two classic signatures of melting: a jump in density and the latent (transition) heat. Such measurements are being used to create known experimental cases to test theoretical models of superconductivity.

- Only a relatively small fraction of the huge number of possibilities for combining elements in the periodic table is used in real materials. A new strategy using fast computers and concepts from quantum mechanics has been developed to search for "winning combinations" of atoms that produce novel, stable crystal structures with improved, physical properties. This approach—Linear Expansion in Geometric Objects (LEGO)—recognizes that even complex crystal structures can be viewed as a collection of simple geometric objects such as dumbbells and triangles of atoms. The LEGO approach has predicted several unsuspected intermetallic compounds missed through conventional approaches.

- Researchers achieved first principles quantum simulations of atomic structure, electronic conductance and dynamical fluctuations in metalic nanowires, and carbon nanotubes.

- Scientists predicted novel ordered intermetallic compounds and their properties.

- A new generation of x-ray optics was developed.

Biomolecular Building Blocks

Description, Objectives, and Research Performers

At the next larger stage of matter are proteins and DNA molecules that are and contain the information for the building blocks of life. Understanding proteins and other biomolecular building blocks is fundamental to scientific understanding of the human genome, and the genomes of plants and microbes. Understanding genomic structures has broad applications in energy, the environment, medicine, agriculture, and industry.

The ability to understand, predict, and even modify protein structure will be a central thrust of research in biology and medicine for much of the next century. New enzymes will command considerable attention as well for their medical, energy, and industrial potential. DOE has committed to sequencing a substantial fraction of the human genome as part of its contribution to the U.S. and international human genome projects. The information derived from this effort provides fundamental information and technology resources for scientists, biotechnology and pharmaceutical companies, and clinicians. Across these various areas, research is conducted at the national laboratories and at the nation's universities.

Research Challenges and Opportunities

Progress in the biomedical sciences and in biotechnology is increasingly dependent upon understanding the relationship between the structure and function of biological molecules. Application of advanced x-ray and neutron imaging detectors will reveal new, important insights into structural biology.

Genomic-level determinations of protein structure, as a follow-on to genomic DNA sequencing, will be one of the most important challenges for biologists in the coming decades, and high-speed, multiple processing of protein structures will be required to keep pace with development and information needs on all fronts. And the schedule for decoding the human genome has been accelerated by two years, with completion planned by 2003. Ethical, legal, and social challenges resulting from the availability and use of increasing volumes of genetic information will require increased attention. Ever-faster sequencing devices and techniques will be required over time, pressing the limits of technology, computational abilities, and the underlying science that makes this possible.

Research Activities

Research activities in biomolecular building blocks are centered on improvements in structural biology imaging and experimental capabilities; development of computational tools for predicting gene structure from DNA sequence information; new strategies and tools to automate aspects of protein expression, crystallization, and structure determination; investigation of protein structures with important applications in bioremediation, carbon sequestration, and energy production; and development and automation of high-throughput human DNA sequencing.

Accomplishments

- Research has led to charge-coupled device detectors (CCDs) for structural biology that have become the standard detectors for protein crystallograpy.

- DOE scientists were the first to reliably achieve sub-Ångstrom resolution of protein structures.

- Records are being set for speed and resolution of protein structure determination at the new beamlines of the Advanced Photon Source and Advanced Light Source.

- The Joint Genome Institute, a virtual human genome center, was formed.

- Researchers sequenced more than 20 million bases of human DNA in FY 1998, a nearly ten-fold increase over the prior year and second among publicly funded US sequencing centers.

Portfolio Summary

This portfolio area, Components of Matter, encompasses research and supporting activities from many programs. Because of the nature of basic research, these programs and activities often crosscut many of the topics discussed above, within Components of Matter, and in many cases, they crosscut other science portfolio areas as well. The table below summarizes those programs that strongly support or moderately support elementary components of matter, including particles and their interactions, nuclear matter and interactions, atoms and molecules, and biomolecular building blocks. The funding totals for these areas are an analytic tool reflecting the highly crosscutting, leveraged aspects and implications for individual research areas within DOE's science portfolio. **Because research areas may appear in multiple chapters, there will be significant instances of multiple counting, and the chapter totals will not sum to the overall science budget.** Additional details are presented in the Research Summary Matrix and the corresponding Research Summary Profiles.

Strongly Supportive RSPs (Combined Budget: $1,320.79 Million)
Adv. Particle Accelerator Concepts
Advanced Computing and Communications Facility Operations
Advanced Computing Software and Collaboratory Tools
Applied Mathematics
Atomic, Molecular, and Optical Science
Computer Science to Enable Scientific Computing
CP Violation - B-Meson System
CP Violation - K-Meson System
Electroweak Interactions
Experimental Condensed Matter Physics
Facility Operations: AGS
Facility Operations: Fermilab
Facility Operations: SLAC
General Technology: Accelerator R&D
General Technology: Detector R&D
Hadron Spectroscopy
Heavy Ion Facility Ops. & Constr.
High Energy Physics Theory
High Performance Computer Networks
High Throughput DNA Sequencing
Low Energy Facility Ops. & Constr.
Medium Energy Facility Ops. & Constr.
Microbial Genomics
Neutrino Mass and Mixing
Nuclear Structure & Astrophysics - Low Energy Nuclear Physics
Nuclear Structure/Dynamics ... Phase Trans. - Heavy Ion Nuclear Physics
Quark/Gluon Substructure of Nuclei - Medium Energy Nuclear Physics
Resources and Tools for DNA Sequencing and Sequence Analysis

Scientific Computing Application Testbeds Search for Higgs & Supersymmetry Spin Structure of Nucleons Strong Interactions, Supersymmetry & Particles Theoretical Nuclear Physics Theory & Simulations of Matter, Engineering Physics Understanding and Predicting Protein Structure
Moderately Supportive RSPs (Combined Budget: $780.88 Million) Advanced Fusion Materials Research Analytical Chemistry Instrumentation Environmental and Molecular Sciences Laboratory (EMSL) General Plasma Science General Purpose Plant & Equipment (GPP/GPE) Heavy Element Chemistry Materials Chemistry Multiprogram Energy Lab Facilities Support (MELFS) Natural and Accelerated Bioremediation research Program Neutron and Light Sources Facilities Neutron and X-Ray Scattering Particle Astrophysics & Cosmology Photochemistry and Radiation Research Production DNA Sequencing Facility Science Education Support Small Business Technology Transfer (STTR) Program Structural Biology Research Facilities Structure of Materials Understanding Gene Function
NOTE: Please see Appendix A for more information on the budgets, the research performers, and other related information for each Research Summary.