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REPORT BY THE U.S.

General Accounting Office

DOE's Physics Accelerators: Their Costs And Benefits

This report provides an inventory of the Department of Energy's existing and planned high-energy physics and nuclear physics accelerator facilities, identifies their associated costs, and presents information on the benefits being derived from their construction and operation. These facilities are the primary tools used by high-energy and nuclear physicists to learn more about what energy and matter consist of and how their component parts or particles are influenced by the most basic natural forces.

Of DOE's $728 million budget for high-energy physics and nuclear physics during fiscal year 1985, about $372.1 million is earmarked for operating 14 DOE-supported accelerator facilities coast-to-coast. DOE's investment in these facilities amounts to about $1.2 billion. If DOE's current plans for adding new facilities are carried out, this investment could grow by about $4.3 billion through fiscal year 1994. Annual facility operating costs will also grow by about $230 million, or an increase of about 60 percent over current costs. The primary benefits gained from DOE's investment in these facilities are new scientific knowledge and the education and training of future physicists. According to DOE and accelerator facility officials, accelerator particle beams are also used in other scientific applications and have some medical and industrial applications.

GAO/RCED-85-96
APRIL 1, 1985

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UNITED STATES GENERAL ACCOUNTING OFFICE
WASHINGTON, D.C. 20548

RESOURCES, COMMUNITY,
AND ECONOMIC DEVELOPMENT
DIVISION

B-217863

The Honorable J. Bennett Johnston
Ranking Minority Member
Subcommittee on Energy and
Water Development
Committee on Appropriations
United States Senate

Dear Senator Johnston:

This report responds to your request dated November 25, 1984. It includes information on the Department of Energy's high-energy physics and nuclear physics accelerator facilities, how much they cost, and what benefits are resulting from their construction and operation.

Unless you publicly announce its contents earlier, we do not plan to distribute this report further until 7 days after its publication date. At that time, we will send copies to other interested committees, members of Congress, and the Department of Energy. Copies will be made available to others upon request.

Sincerely yours,

Ralph Carlone for
J. Dexter Peach
Director

REPORT BY THE U.S. GENERAL
ACCOUNTING OFFICE TO THE
HONORABLE J. BENNETT JOHNSTON,
RANKING MINORITY MEMBER,
SUBCOMMITTEE ON ENERGY AND WATER
DEVELOPMENT, SENATE COMMITTEE ON
APPROPRIATIONS

DOE'S PHYSICS ACCELERATORS: THEIR COSTS AND BENEFITS

DIGEST

During fiscal year 1985, the federal government is providing about $820 million in support of high-energy physics and nuclear physics research. About $728 million, or nearly 90 percent of this amount, is being provided by the Department of Energy (DOE), and the remaining support is being provided by the National Science Foundation. (See pp. 7 to 9.)

Both high-energy physics and nuclear physics are exploratory fields of basic science in which experimental and theoretical studies are conducted. Generally, high-energy physics is aimed at determining what energy and matter ultimately consist of, ascertaining how the component parts (or particles) of matter interact with each other, and understanding the interrelationships between the most basic forces of nature[1] and the effects of these forces on matter. Nuclear physics concentrates on acquiring a better understanding of the atom's nucleus.

Most experiments in both high-energy physics and nuclear physics depend on machines called accelerators (also known as "atom smashers") that produce and accelerate beams of particles such as protons and electrons. These particle beams are made to collide with particles contained in various target materials or in other accelerated beams.

By analyzing these collisions, physicists are able to "see" the inner structure of the atom and its component parts. In this sense, the accelerator is analogous to a super microscope that enables physicists to study the

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[1] The electromagnetic, weak nuclear, strong nuclear, and gravitational forces. (See pp. 2 and 3.)

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substructure of submicroscopic nuclear particles. As the particles become smaller, or more elementary, they are bound together more tightly thereby requiring larger, more powerful, and complex accelerators. Because of their complexity, these accelerators also can be very costly. (See pp. 1 to 6.)

WHY THE REVIEW WAS MADE

In his letter to GAO dated November 25, 1984, Senator J. Bennett Johnston, Ranking Minority Member, Subcommittee on Energy and Water Development, Senate Committee on Appropriations, stated that DOE's plans to build two new accelerators have increased the subcommittee's concern about the need for larger, more costly nuclear physics and high-energy physics facilities.

The first is a nuclear physics accelerator known as the Continuous Electron Beam Accelerator Facility, which DOE plans to locate at Newport News, Virginia. While not firm, DOE's current estimate for this accelerator--if approved by the Congress--is about $220 million to construct and about $30 million to $35 million a year to operate. The second accelerator is known as the Superconducting Super Collider. DOE has preliminary plans to build this high-energy physics machine at a cost of more than $4 billion.

Accordingly, Senator Johnston asked GAO to compile an inventory of DOE's existing and planned accelerator facilities, identify their costs, and provide information on their benefits. (See app. I and pp. 25, 26, 33 to 35, and 39 to 41.)

DOE'S PHYSICS ACCELERATORS: WHAT ARE THEY AND WHERE ARE THEY LOCATED?

Physics accelerators generally consist of four principal types: electrostatic, linear, cyclotron, and synchrotron. They differ primarily in configuration and how they accelerate a beam of particles toward a given target. Synchrotrons are generally the largest and most powerful. These doughnut-shaped machines are currently capable of accelerating protons to energies of a trillion electron volts[2] and to speeds nearly equal to the speed of light. (See pp. 11 to 19.)

DOE supports 14 physics accelerator facilities located at national laboratories and universities from coast-to-coast. Three of these are for high-energy physics and 11 are for nuclear physics. High-energy physics accelerators are located at the Brookhaven National Laboratory in New York, the Fermi National Accelerator Laboratory in Illinois, and the Stanford Linear Accelerator Center in California. The 11 nuclear physics accelerator facilities are located throughout the country at six national laboratories and four universities. (See pp. 19 to 24.)

Each facility may have several accelerators that are linked together, some of which may operate alone or in conjunction with the others. The original accelerator facility at Fermi, for example, actually consists of four accelerators. The first three serve to produce a beam of protons which are accelerated, in stages, to successively higher energy levels. This beam is ultimately injected into the main accelerator, which is an underground ring having a circumference of 4 miles. Although the typical operating mode is to use the beam from the main accelerator ring, the beam can be extracted from either of the other three accelerators for experimental use.

The primary distinction between accelerators at national laboratories and those that are university-based relates to facility ownership and access. At national laboratories, the facilities are usually federally owned, and accelerator beam time is provided free to all researchers (scientists both within the laboratory and from outside research groups) who have experiments that are judged to be scientifically meritorious. At each laboratory, these judgments are usually made by a

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[2] An electron volt is a unit of measure that describes the amount of energy acquired by a particle (such as an electron or proton) as it moves across an electric potential of 1 volt.

committee consisting of members from several laboratories and universities. University-based accelerators were built with federal funds but ownership, in most cases, has been transferred to the universities. Although beam time is also free, the experiments that are carried out are normally those which conform with each university's science curriculum. External researchers, however, may work with university research staff on collaborative experiments. (See pp. 19, 20, and 22 to 24.)

Aside from the facilities that are currently in place, GAO noted that each facility has ongoing and/or planned projects to upgrade and expand their respective accelerator capabilities. These projects are in addition to DOE's plans for constructing the Superconducting Super Collider and the Continuous Electron Beam Accelerator Facility. Beyond these two entirely new accelerator facilities, GAO also noted that efforts underway at DOE and its laboratories could lead to still other new facilities. Within high-energy physics, one laboratory has begun long-range research which could lead to constructing a device referred to as a large linear electron/positron collider. Within nuclear physics, DOE has recently received proposals for two new facilities: one of these, proposed by Brookhaven National Laboratory, is known as the Relativistic Heavy Ion Collider and the other, proposed by Los Alamos National Laboratory, is a project referred to as LAMPF II, which would be a major addition to that laboratory's existing accelerator. (See pp. 24 to 27.)

HOW MUCH DOES IT COST TO BUILD AND OPERATE DOE'S PHYSICS ACCELERATORS?

DOE's costs of building its existing accelerator facilities amount to more than $1.2 billion (then-year dollars). The bulk of this amount--about $991 million--is for the high-energy physics facilities; Fermilab accounts for more than half. DOE's costs for the 11 accelerator facilities used for nuclear physics amount to about $255 million. Individually, these costs range from about $1.4 million for the facilities located at the University of Washington to nearly $90 million for those at the Los Alamos National Laboratory. DOE estimates that it would cost from $2.5 billion to $3 billion (fiscal year 1985 dollars) to replace all of its current facilities. (See pp. 30, 31, 36 and 37.)

DOE's annual costs for operating these facilities over the past 3 years have averaged more than $365 million, as shown below:

Cost of Operating DOE's Physics Accelerators

Accelerator facilities	1983	1984	1985[a]	3-year average
	(in millions of then-year dollars)			
High-energy physics	$244.4	$257.4	$246.9	$249.6
Nuclear physics	104.8	118.5	125.2	116.2
Total	$349.2	$375.9	$372.1	$365.7

[a] Estimated.

Fermilab (at about $112.1 million for 1985) and Los Alamos National Laboratory (at about $49.1 million for 1985) account for the bulk of costs for operating accelerators in their respective scientific fields. (See pp. 31 to 33 and 37 to 39.)

As part of its review, GAO identified the costs associated with ongoing and planned projects aimed at upgrading or improving the various accelerator facilities. Such projects, as well as entirely new accelerator facilities, are considered necessary by DOE to ensure the United States has facilities for carrying out forefront research. If all of these projects are funded, DOE's investment in high-energy and nuclear physics accelerators could grow significantly. For the two new planned accelerator facilities alone, this growth could total more than $4.3 billion (in fiscal year 1985 dollars) through fiscal year 1994 or from 43 to 72 percent more than DOE's estimated replacement cost for its existing facilities. DOE's annual operating costs for these facilities could similarly grow. DOE estimates that such costs could amount to $230 million or about 60 percent more than current facility operating costs. If increased appropriations are not forthcoming for these increased costs, DOE will be faced with finding other sources to fund these facilities. Three basic options available to DOE, separately or in combination, include:

--Eliminating construction upgrades and improvements in existing facilities to provide funds for operating new facilities.

--Closing one or more of the existing facilities to free operating funds for new facilities.

--Obtaining nonfederal funding to help support the programs. (See pp. 33 to 35 and 39 to 43.)

WHAT IS THE UNITED STATES GETTING FOR ITS INVESTMENT IN ACCELERATOR CONSTRUCTION AND USE?

Aside from the education and training of new scientists in experimental techniques, the benefits derived by the United States from its investment in accelerator construction and use are (1) new knowledge about the size, shape, and other attributes of the atomic nucleus and its component elementary particles, (2) how these particles behave and interact, and (3) the fundamental forces that bind them together. Other benefits are of a more incidental nature. According to DOE and accelerator laboratory officials, accelerator particle beams are now used in other scientific fields and have some medical and industrial applications. (See pp. 43 to 48.)

AGENCY COMMENTS

GAO did not obtain official agency comments on this report. However, GAO did discuss the material presented with DOE officials responsible for the high-energy physics and nuclear physics programs and made changes where appropriate to ensure the report's accuracy.

Contents

ABBREVIATIONS

AGS	Alternating Gradient Synchrotron
CEBAF	Continuous Electron Beam Accelerator Facility
d.c.	direct current
DOE	Department of Energy
eV	electron volt
Fermilab	Fermi National Accelerator Laboratory
FY	fiscal year
GAO	General Accounting Office
GeV	billion electron volts
LAMPF	Los Alamos Meson Physics Facility
MeV	million electron volts
NSF	National Science Foundation
RHIC	Relativistic Heavy Ion Collider
SSC	Superconducting Super Collider
TeV	trillion electron volts

GLOSSARY

Accelerator	A device that increases the energy of motion of charged particles such as electrons and protons.
Alpha particle	A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together (hence, the nucleus of a helium atom is an alpha particle).
Antiparticle	Each particle has a partner, called an antiparticle, which is identical except that all charge-like properties are opposite to those of the particles. When a particle and its antiparticle meet, these properties cancel out in an explosive process called annihilation.
Anti-proton	The antiparticle of a proton.
Atom	A particle of matter indivisible by chemical means. The smallest unit of a chemical element, approximately 1/100,000,000 inch in size, consisting of a nucleus surrounded by electrons.
Atomic mass unit (AMU)	A unit of measure used to compare the mass of atomic particles where AMU 1 is approximately equal to the mass of one proton.
Atomic nucleus	The central core of an atom, made up of neutrons and protons held together by the strong nuclear force.
Beam	A stream of particles or electromagnetic radiation going in a single direction.
Charged particle	An elementary particle of matter that carries a positive or negative charge.
Collider	An accelerator that produces two beams of particles that collide head-on.
Colliding beams	A means of attaining very high energy reactions by accelerating two beams of particles and colliding them head-on.
Continuous electron beam	A continuous stream of electrons produced by an accelerator. In many other accelerators, the beam is delivered to the target in short bursts or pulses rather than continuously.
Cryogenic refrigeration	Refrigeration system used to obtain temperatures near absolute zero--about -273° Centigrade. (See Kelvin, below.)

Cyclotron	An accelerator in which the charged particles are accelerated and spiral outward from the center of the machine.
Detector	A device that can "observe" the presence of a particle or nuclear fragment and measure one or more of its physical properties.
Electromagnetic force	A force associated with the electric and magnetic properties of particles.
Electron	A particle (thought to be an elementary particle) with a unit of negative electrical charge and whose mass is 1/1840 of a proton's mass. Electrons surround an atom's positively charged nucleus and determine the atom's chemical properties. Electrons are members of the lepton family.
Electron-neutrino	One of three distinct types of neutrinos associated with electrons.
Electron volt	A unit of measure that describes the amount of energy acquired by a particle (such as an electron or proton) as it moves across an electric potential of 1 volt. MeV is a million electron volts; GeV is a billion electron volts; and TeV is a trillion electron volts.
Electrostatic accelerator	An accelerator that uses a pulley-driven belt to deposit an electrostatic charge on a metal shell. The charge on the shell provides the force to propel or accelerate charged particles.
Electrostatic charge	The amount of positive or negative electric charge in a body. An uncharged, or neutral, body has equal amounts of positive and negative charge.
Elementary particle	An elementary particle is a particle that cannot be divided. It is a fundamental constituent of matter. Quarks and leptons now appear to be the elementary particles, but the term is often used in referring to any of the subnuclear particles.
Energy Saver	Term used to describe the Fermilab superconducting synchrotron. The use of superconductivity means that little electrical power is necessary to power the magnets and that a higher magnetic field can be created more efficiently.
Fixed target	Where the matter being struck by the accelerator beam particles is at rest.
Fundamental forces	The four basic forces of nature classified as the strong force; the electromagnetic force; the weak force; and the gravitational force.

GeV	(Giga electron volt)--A unit of energy equal to 1 billion (10^9) electron volts.
Gluon	A particle that is hypothesized to mediate or carry the strong nuclear force between quarks.
Gravitational force	A long-range force that affects all particles. It is so weak that it is observable only in massive objects.
Graviton	The hypothetical, perhaps massless particle that is the carrier of gravitational force.
Heavy-ion	All ions with three or more protons. (See Ion.)
Injector	An accelerator whose beam is injected into another accelerator.
Ion	Ions are charged particles which are the result of atoms gaining or losing one or more electrons. Negative ions have more electrons than protons; positive ions have fewer electrons than protons.
Isotope	An isotope is one of two or more atoms having the same number of protons (which makes them the same chemical element) but having a different number of neutrons (which gives them different atomic weights).
Kelvin temperature scale	A scale of temperature based on thermodynamic principles in which zero degrees Kelvin is equivalent to -459°F or -273°C. This temperature is called "absolute zero," where no molecular motion is thought to exist.
Lepton	A member of the family of weakly interacting particles, which includes the electron, muon, tau, and their associated neutrinos and antiparticles.
Linear accelerator, or LINAC	In this type of accelerator, particles travel in a straight line and gain energy by passing once through a series of electromagnetic fields.
Matter	Made up of massive particles: molecules, atoms, and elementary particles. (See elementary particles.)
Meson	A class of strongly interacting particles. Mesons are composed of quark-antiquark combinations.

Quark	One of a family of particles that may be truly elementary. Each quark is characterized by a number of properties including familiar ones like mass and electrical charge and less familiar ones that are given names like "charm," "strangeness," "top," "bottom," "up," and "down."
Radioactive	The spontaneous transformation of one atomic nucleus into a different nucleus or into different energy states of the same nucleus.
Radio frequency	Refers to the oscillation frequency of electromagnetic field typically associated with radio or television communications.
Radium	A radioactive metallic element that undergoes spontaneous disintegration and transformation.
Strong Force	A short range force, the strongest one known, that affects quarks and all the particles thought to be composed of quarks.
Superconductivity	The ability of some materials to maintain perpetual electric currents without loss, owing to the complete absence of electrical resistance. It is thought to occur only at very low temperatures.
Synchrotron	An accelerator in which the charged particles are constrained to a nearly circular orbit.
Tandem electrostatic accelerator	A d.c. high voltage machine in which negative ions are accelerated toward a positive terminal. Before the ions can reach the terminal they are "stripped" of one or more electrons and become positive ions. These ions are repelled by the positive terminal and then accelerated a second time.
Target	Material subjected to particle bombardment (as in an accelerator) or to irradiation in order to induce a nuclear or subnuclear reaction.
Tau	An elementary particle in the lepton family with a mass that is 3,500 times that of the electron but with similar properties. There are positive and negative tau particles.
TeV	A unit of energy equal to one trillion (10^{12}) electron volts.
Tevatron	A synchrotron accelerator facility located at Fermilab using superconducting accelerator magnets to produce 1-TeV beams.

W and Z bosons	The massive particles that are thought to be the carriers of the weak force.
Weak force	A short-range force that affects all quarks and leptons. It is responsible for the radioactive decay of many particles and nuclei.
X-rays	Photons of electromagnetic radiation produced when high energy atoms decay to states of lower energy.

CHAPTER 1

INTRODUCTION

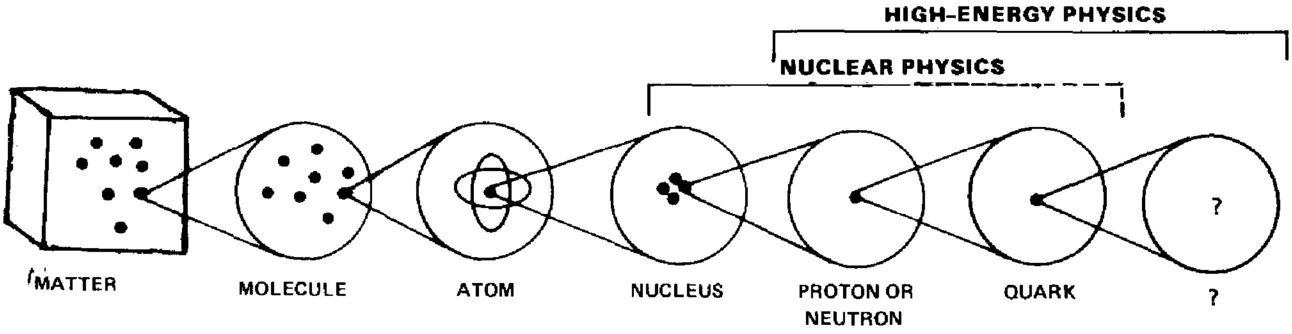
Physics is a science that deals with matter and energy and how they interact in such diverse areas as mechanics, acoustics, astronomy, optics, heat, electricity, magnetism, radiation, atoms, and the atom's nucleus. The physics discussed in this report generally concerns the "atom's nucleus" portion of physics, and the report examines the use of machines called accelerators (sometimes referred to as "atom smashers") to conduct physics experiments. More specifically, the report describes the Department of Energy's (DOE's) programs to fund the construction, operation, and improvement of high-energy physics and nuclear physics accelerator facilities and provides information on the costs and benefits of these efforts.

HIGH-ENERGY PHYSICS AND NUCLEAR PHYSICS

High-energy physics (sometimes called elementary particle physics) and nuclear physics have a common heritage: both are basic sciences (that is, their primary goal is to increase knowledge and understanding of our natural environment); both speak the abstract language developed and nurtured by the mathematics theorist and the research experimentalist; and both use large, complex machines at national laboratories and universities to explore, among other things, the structure and fundamental characteristics of matter and energy.

Matter, as shown in the diagram below, is thought to have several layers of component parts. The quest for high-energy physics involves the search, discovery, and understanding of the most fundamental components and structure of matter. The high-energy physicist is concerned with the interactions, structure, and other characteristics of these fundamental components and the most basic forces of nature (see p. 3) that affect them. Nuclear physics, on the other hand, is primarily concerned with

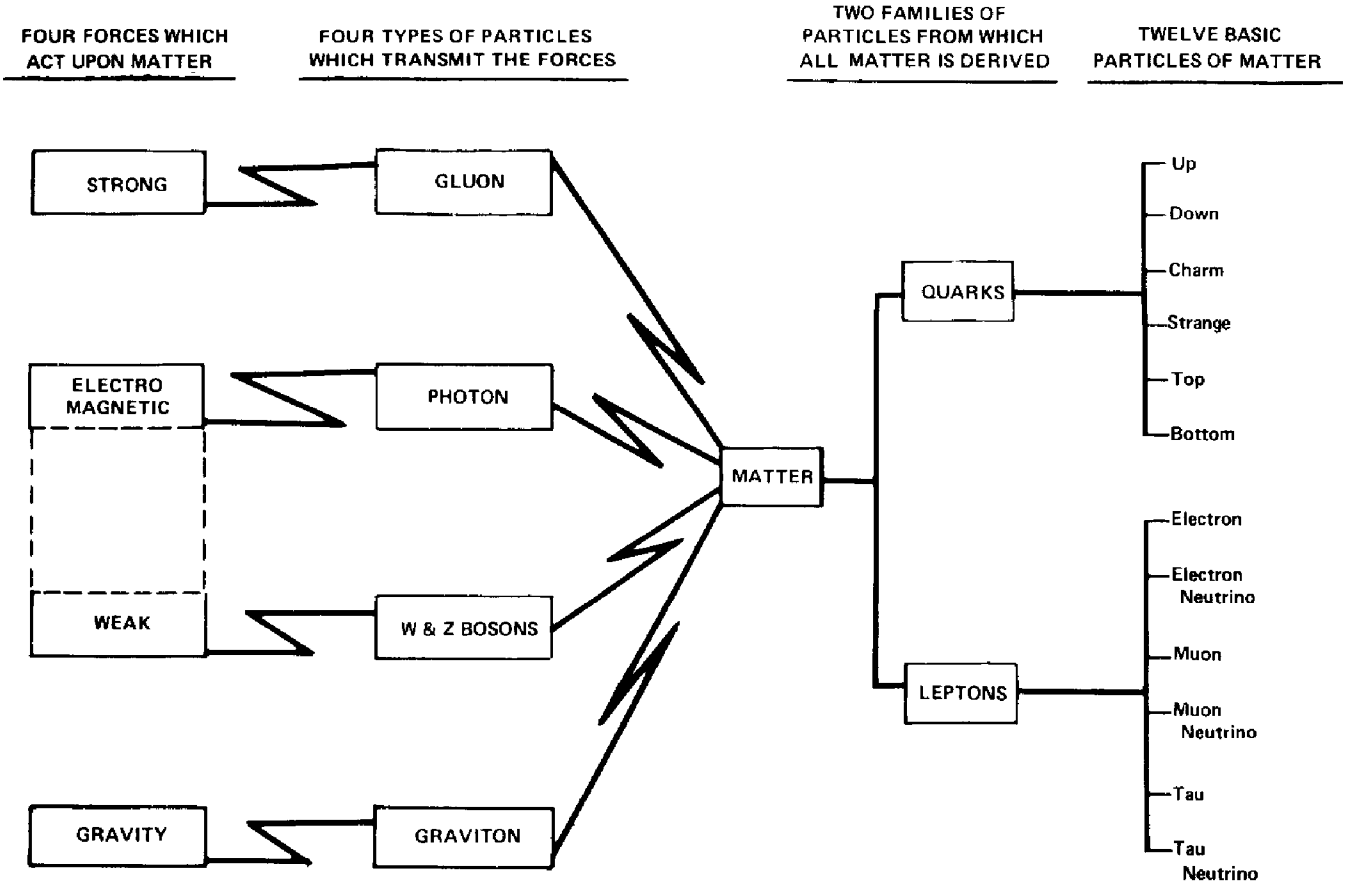
COMPONENTS OF MATTER



the interactions, structure, and other fundamental characteristics of the atom's nucleus. This distinction between high-energy physics and nuclear physics could not have been made 60 years ago, when the proton and electron were recognized as the "indivisible" fundamental components of matter. However, in 1932, the neutron was identified as the atom's second nuclear component and since then--and especially within the last 30 years--numerous subnuclear particles have been discovered. (The dashed line in the diagram for nuclear physics is used to indicate a growing interest by nuclear physicists in understanding the nucleus through the study of the characteristics and behavior of quarks.)

As more and more particles were discovered, it was felt that there were too many for them all to be considered the fundamental components of matter. So, experiments were devised to probe deeper to see if these particles were themselves divisible and if they were comprised of a few common elementary bits of matter. The "standard model" depicted below reflects the physics community's current thinking about the universe of fundamental particles and forces of nature: 12 basic particles of matter (split into 2 "families"), 4 forces which affect matter, and 4 types of particles to transmit those forces among particles of matter.

THE PHYSICS STANDARD MODEL OF NATURE'S FUNDAMENTAL PARTICLES AND FORCES



The standard model is dynamic and is not meant to necessarily represent the "final solution." The dashed lines that connect the electromagnetic and the weak forces in the above diagram highlight the fact that these two forces have recently been shown to be two manifestations of the same phenomenon: the electroweak force. The electromagnetic force itself was recognized in the 19th century as a single force that linked the properties of electricity and magnetism. Scientists see the next possible simplification of the model to be a linking of the strong and electroweak forces. The final step would then link the strong-electroweak force to gravity.

Matter in the standard model

All matter in our everyday world is thought to be composed of only two of the six types of quarks (up and down) shown in the diagram on page 2, and two of the six types of leptons (electron and electron neutrino). The protons and neutrons in all nuclei are made up of these two quarks; electrons orbit nuclei to make atoms; and electron neutrinos are ejected from the atom's nucleus during the natural radiation process of some radioactive materials. Three of the remaining four quarks and the remaining four leptons shown in the diagram on page 2 can be created under experimental conditions but are elusive, unstable, and/or short-lived. There is a strong theoretical basis for the existence of the last quark (the top quark) and it may have been observed experimentally but this has yet to be confirmed.

The four forces in the standard model

The strong force binds the protons and neutrons within the nucleus and the quarks within the protons and neutrons. While it is the strongest of the forces, it is effective only over a short range (approximately the width of one proton). The electromagnetic force holds the electrons in their orbits around the nucleus and binds atom to atom and molecule to molecule; it is weaker than the strong force but is effective over a greater distance. The weak force governs the radioactive decay of many particles and nuclei and is weaker than the electromagnetic and strong forces. Gravity is the weakest force but has the greatest effective range and seems to affect all matter.

ACCELERATORS: THEIR ORIGIN AND PURPOSE

Accelerators are complex machines that enable the physicist to "see" inside the atom and its nucleus and study the substructure of nuclear particles having dimensions billions of times smaller than the smallest object that can be seen with an optical microscope. Generally, as the particles of matter to be studied become smaller, or more elementary, their component parts are bound together more tightly thereby requiring larger, more powerful and complex accelerators and other supplementary equipment such as particle detectors (see p. 6) to study them. The following excerpt from a DOE publication[1] presents an analogy that provides insight into the use of the accelerator, the logic that led to its development, and the scientists' rationale for needing more powerful machines.

> "In order to understand the need for larger and larger accelerators, it may be instructive to consider an outrageous analogy. Suppose that we were obliged to study the structure of a peach simply by shooting small projectiles, such as BB's at it. [The peach is shrouded in a fog and cannot be seen by the marksman.]
>
> "A beam of very slow BB's would simply bounce off the peach. By measuring the pattern of scattered BB's, we could learn the size of the peach and that it is round. Faster BB's would lodge within the peach, perhaps causing the production of a secondary product: we could learn that the peach is soft and juicy. With a more powerful BB gun, most of the projectiles would pass straight through the peach. Some, however, would change their direction to emerge from the peach at large angles. How would we understand this? We might conjecture the existence of a small hard 'pit' within the peach. A detailed study of the large-angle scattering of high-energy BB-peach collisions would reveal the size, shape, and weight of the pit. Of course, the pit itself has structure too. A still more powerful BB gun is needed to shatter the pit and reveal the kernel within . . . .
>
> "Let us emerge from the analogy to the real world of atoms and atomic constituents. To study the structure of matter, the projectiles should be chosen to be as simple as possible: hydrogen nuclei (protons), electrons, particles of light (photons), etc. Furthermore, there is a fundamental law of physics that says: the smaller an entity, the higher are the energies involved which hold its component parts together. Therefore, we need higher energies to find out the structure of smaller entities."

The accelerator is the physicist's "BB gun" for exploring the atom and its components. Its roots are found in a series of

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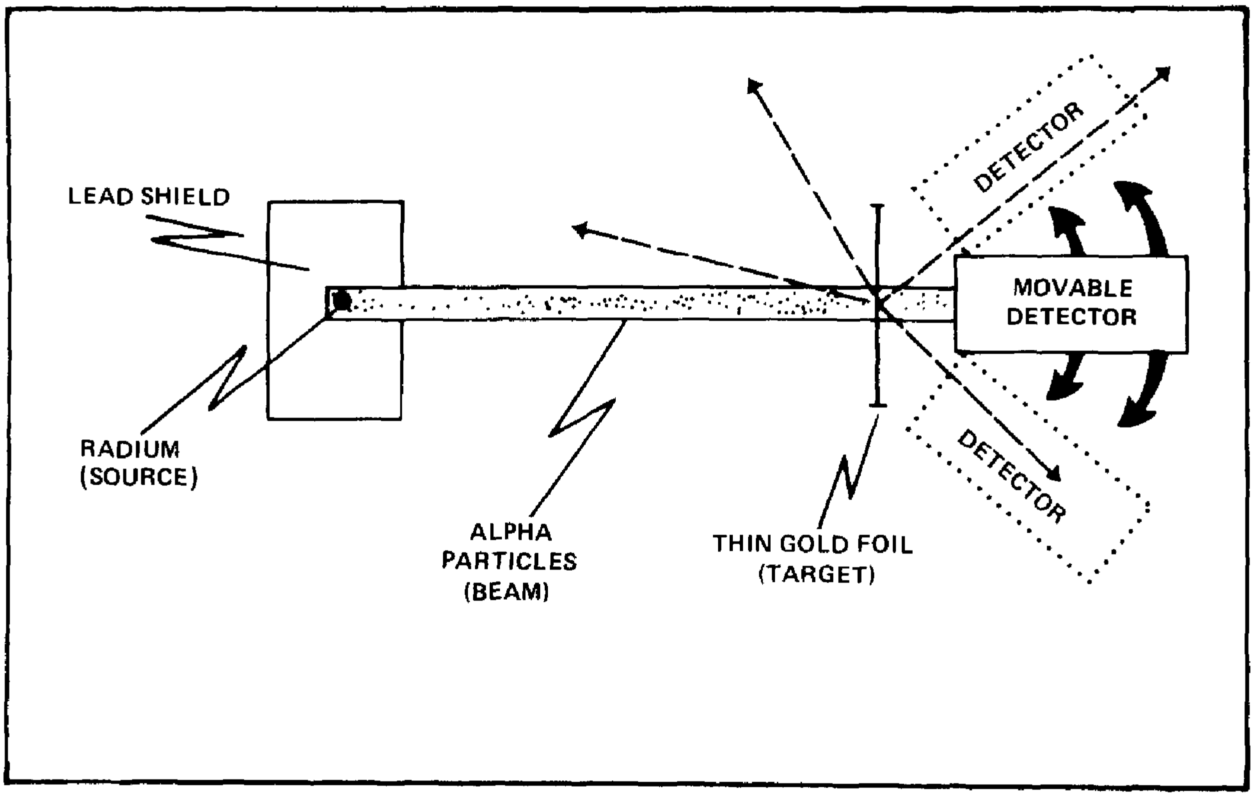
[1] High Energy Physics, the Ultimate Structure of Matter and Energy (DOE/ER-0027, Apr. 1979).

experiments performed by British physicist Ernest Rutherford, between 1908 and 1913. In his experiments, Rutherford used the alpha particles (natural radiation) from radium as his "BBs" to bombard gold atoms (his "peach"). He then rotated a detection device around the gold foil target to determine the effect of this bombardment. Through these experiments, Rutherford discovered the basic structure of the nuclear atom--an atom where relatively light-weight, negatively charged electrons orbit a very small and dense nucleus that is positively charged.

THE RUTHERFORD EXPERIMENTS



Physicists discovered rather quickly that if they were going to be successful in studying the atom in greater detail, they would need "BB guns" that were more powerful and more accurate and over which they could exercise more control. This need began to be met with the development of the first accelerators in the early 1930's. These original accelerators, and those developed since have followed the methodology used by Rutherford:

--There is a <u>source</u> of charged particles.

- --The charged particles are set in motion by various means and directed in a beam to a target.

- --The beam strikes a target and the results of the collisions are recorded by a detector.

Beam/target collision

Once the beam of particles is accelerated to the desired energy level, the next phase of the high-energy physics or nuclear physics experiment is common to all accelerators--the beam/target collision. Increased energy levels for beam/target collisions can be obtained by using two or more accelerators in combination--that is, particles can be accelerated in one machine, directed to and injected into another, and accelerated a second time before being directed to a target. One accelerator at Oak Ridge, Tennessee, for example, is used to inject another accelerator for nuclear physics experiments. At a high-energy physics facility near Chicago five accelerators are used in sequence. (See pages 19 to 24 for a description of all DOE-supported high-energy physics and nuclear physics facilities.)

Besides building more powerful machines or connecting them in series, a third way to obtain more powerful particle collisions is to collide two beams together, instead of colliding a single beam into a fixed target. For example, if a beam of protons with an energy level of 16 billion electron volts[2] (GeV) collides with a fixed target, the effective energy of the collision is reduced to about 4-GeV (approximately the square-root of the beam's energy). However, if an 8-GeV proton beam collides head-on with another 8-GeV proton beam, the energies are added for a combined effective collision of 16 GeV.

Detectors

Devices built to observe the particle collisions and record the results are called detectors. A variety of detectors have been developed to detect, identify, or measure both the beam particles and the secondary particles that result from the collisions. The detectors can be relatively small and uncomplicated devices or large, complex devices which use extremely fast, large-memory computers to record millions of bits of information associated with a single particle collision. According to a DOE official, much of physics research progress and the successes of accelerator programs can be attributed to the development of detector technology.

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[2] An electron volt (eV) is a unit of measure that describes the amount of energy acquired by a particle (such as an electron or proton) as it moves across an electric potential of 1 volt. MeV is a million electron volts; GeV is a billion electron volts; and TeV is a trillion electron volts.

THE FEDERAL GOVERNMENT'S SUPPORT OF HIGH-ENERGY PHYSICS AND NUCLEAR PHYSICS RESEARCH

DOE and the National Science Foundation (NSF) are the two federal agencies primarily responsible for funding high-energy physics and nuclear physics research. DOE provides about 90 percent and 80 percent, respectively, of the federal dollars for high-energy physics and nuclear physics. The NSF provides the rest.

DOE'S high-energy physics and nuclear physics programs

DOE has no specific mandate to support high-energy physics or nuclear physics research programs other than that which is contained in DOE's annual appropriations acts. However, DOE's policy is to support scientific and technical research that advances the frontiers of scientific and engineering knowledge. While DOE's fiscal year 1986 budget document states that high-energy physics and nuclear physics programs have no direct application to energy, DOE feels this research will provide the underlying basis for future technological innovation. Also, DOE feels it is specifically responsible for supporting basic research "where the incentive for and the availability of private investment are severely limited or nonexistent."

The DOE budget for its high-energy physics program in fiscal year 1985 is $545.6 million. Specific program objectives include:

--the search for and discovery of new physical phenomena using high-energy subnuclear particle interactions,

--the pursuit of advanced concepts and technology development, and

--the maintenance of the U.S. program in a world leadership position.

A DOE High Energy Physics Advisory Panel was established in 1967 to review the program and provide advice on overall program balance, scientific priorities and special problems. A subpanel for long range planning was formed in 1981 to review the status and prospects of the DOE and NSF high-energy physics programs. The subpanel issued its report[3] in 1982. Advisory panel members are appointed by the Secretary of Energy and are affiliated with universities that have DOE-sponsored high-energy physics programs

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[3] Report of the Subpanel on Long Range Planning for the U.S. High Energy Physics Program of the High Energy Physics Advisory Panel (DOE/ER-0128, Jan. 1982).

and/or with high-energy physics programs at DOE's national laboratories. These laboratories are government-owned facilities that are operated for DOE by contractors. While DOE and NSF employees participate in the advisory panel's activities, they do not officially represent those agencies.

The DOE budget for its nuclear physics program in fiscal year 1985 was $182.9 million. The program has several major objectives including the following:

--Describing quantitatively the behavior and structure of complex nuclei in terms of fundamental interactions.

--Using nuclei as a laboratory for the study of fundamental forces of nature.

--Advancing research capability by developing new facilities and improving particle beams and ancillary equipment at existing facilities.

--Maintaining a position of leadership in nuclear research for the United States.

DOE and NSF established a joint committee in 1977 called the Nuclear Science Advisory Committee to provide both agencies with advice on a continuing basis regarding the scientific priorities within the field of nuclear physics research. To this end, the advisory committee published its first long-range plan for nuclear science in 1979 and updated that document with another plan in 1983.[4] The advisory committee has members from national laboratories and universities which have DOE or NSF sponsored programs. These members are selected by the Secretary of Energy and the Director of NSF. As with the High Energy Physics Advisory Panel, DOE and NSF employees affiliated with the advisory committee do not participate as official representatives of their agencies.

NSF's high-energy physics and nuclear physics programs

NSF is the principal federal agency for the support of basic research across all fields of science and science education. It supports one high-energy physics accelerator facility (a national laboratory at Cornell University) and 12 nuclear physics accelerator facilities (two national laboratories at Indiana and Michigan State Universities and 10 other university-based facilities). In fiscal year 1985, NSF provided--through grants and contracts--about $47.3 million for high-energy physics and about $44.2 million for nuclear physics activities and facilities. These amounts

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[4] A Long Range Plan for Nuclear Science (DOE/NSF Nuclear Science Advisory Committee, Dec. 1983).

include money to support accelerator facilities operations as well as accelerator and detector research and development, theoretical physics studies, and efforts at various laboratories by outside user groups. As mentioned above, NSF participates in activities of the High Energy Physics Advisory Panel and Nuclear Science Advisory Committee.

OBJECTIVES, SCOPE, AND METHODOLOGY

In his November 25, 1984, letter (see appendix I) to us, Senator J. Bennett Johnston, Ranking Minority Member, Subcommittee on Energy and Water Development, Senate Committee on Appropriations, stated that DOE's plans to build two new accelerators have increased the subcommittee's concerns about the need for larger, more costly high-energy physics and nuclear physics facilities. Senator Johnston requested that we develop information related to DOE's high-energy physics and nuclear physics programs and facilities. Specifically, he requested that we

--compile an inventory of accelerators that have been built or are planned for construction in the United States;

--identify the construction, operation, and maintenance costs associated with those accelerators; and

--identify the benefits being derived from the construction and operation of the accelerators.

To obtain general background information on accelerator physics, how accelerators function, and the federal government's role in high-energy physics and nuclear physics, we conducted a literature search, reviewed pertinent articles and studies, and held discussions with officials representing DOE, NSF, the National Academy of Sciences, the Office of Science and Technology Policy, the Office of Management and Budget, the High Energy Physics Advisory Panel, and the Nuclear Science Advisory Committee.

To help compile an inventory of the existing accelerators, we visited all accelerator facilities funded by DOE's high-energy physics and nuclear physics programs. At each location we ascertained--through discussions with accelerator management personnel and review of pertinent documents--the type(s) and power range(s) of the accelerator(s), the type of beam(s) produced, the costs of the accelerators and related equipment, the nature of experiments normally conducted, the number of experiments conducted, facility historical data, and the major accomplishments that could be attributed to research conducted at the accelerator facility.

To develop information on accelerators that are planned for future operation or construction, we reviewed current physics and accelerator periodicals, held discussions with DOE and accelerator facility officials, and reviewed budgetary documents. We also obtained information on facility improvements planned for existing accelerators by reviewing related proposals submitted to DOE and by holding discussions with accelerator facility and DOE officials.

Operating cost data were obtained from DOE's Financial Information System and were compared with data obtained at the accelerator facilities visited. Acquisition cost data were obtained from accelerator facility officials and were compared with pertinent cost records. Conversion of cost data to current-year dollars was accomplished by using the annual inflation rate reported in the Economic Report of the President, February 1985. (This report is submitted to the Congress with the Annual Report of the Council of Economic Advisors). Cost information presented in the tables in chapter 3 was compiled by GAO based on data supplied by DOE and accelerator facility officials. Information on the cost of future accelerator construction and improvements was obtained from review of proposals and information submitted to DOE from the accelerator facilities and from discussions with DOE and accelerator facility officials.

To obtain information on the benefits derived from constructing and operating high-energy physics or nuclear physics accelerators, we reviewed pertinent literature and documents and discussed the subject with accelerator facility officials. We then compiled a narrative discussion summarizing the benefits identified and obtained from DOE a more technically-oriented listing of derived benefits. In addition, we asked DOE program officials to compile a listing of program accomplishments. The resulting documents are included as appendixes III through VI to this report.

While Senator Johnston has stated his preference for obtaining official agency comments on draft reports prepared by GAO, as agreed with his office, we did not obtain such comments on this report to ensure its issuance in time for use during the current budget cycle. Nevertheless, we did discuss the report with DOE program officials, and changes were made where necessary to ensure the report's accuracy. Except for not obtaining official DOE comments, our review was performed in accordance with generally accepted government auditing standards between November 1984 and March 1985.

CHAPTER 2

DOE'S PHYSICS ACCELERATORS: WHAT ARE THEY AND WHERE ARE THEY LOCATED?

Accelerators and their ancillary equipment and the facilities to house them can cost hundreds of millions of dollars to construct and operate. They can take the shape of a grain silo, a 2-mile long tube, or a circle 4 miles in circumference. A circular accelerator currently being considered for construction in the United States could have a circumference of between 60 and 120 miles.

DOE provides funds to build, improve, and operate high-energy physics and nuclear physics accelerator facilities at national laboratories and universities across the nation. Different types of accelerators at these facilities generate a wide variety of particle beams for research. In addition to the current facilities, DOE is developing plans for one new high-energy accelerator facility and one new nuclear physics facility and is evaluating a proposal for another nuclear physics facility. Scientists in the high-energy physics and nuclear physics communities are also developing other proposals for new accelerator facilities designed to continue scientific research in the next decade.

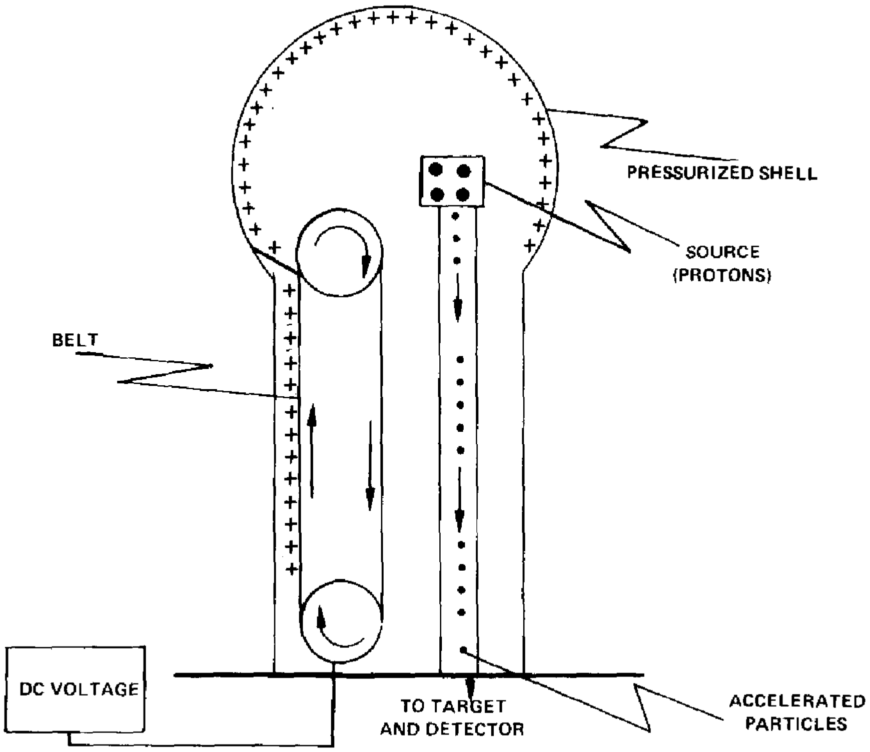
TYPES OF ACCELERATORS

There are four basic types of accelerators and they all use the same four principal components outlined in chapter 1: a source of particles to be accelerated, a beam of accelerated particles directed toward a target, and a detector that records the results of the beam-target collision. These four types of accelerators also share a common principle of operation: they use basic laws of electromagnetism to accelerate particles (one principle is that objects with opposite electric charge attract each other, and those with similar electric charges repel each other). The main distinction between the four accelerators is in configuration and the manner in which the beam is speeded up and directed to the target. The four types of accelerators and a simplistic explanation of how each accelerates a beam of particles follows.

Electrostatic accelerators

Electrostatic charge is responsible for the shock one sometimes gets when touching something metallic after walking across a carpet or for the crackling-popping noises one may hear when pulling fuzzy sweaters or socks out of a clothes dryer. Electrostatic accelerators are relatively simple machines that create and harness electrostatic charge.

The principles of how an electrostatic accelerator works are illustrated in the diagram below. A direct current (d.c.) voltage provides a positive charge to a belt, the belt rotates around two pulleys, and the belt deposits its positive charge to the top of the dome. When the dome becomes fully charged, the positively charged particles from the source are accelerated down the acceleration tube--repelled by the positively charged dome and attracted toward the end of the tube that is negatively grounded.



A modification to this process is the tandem electrostatic accelerator, where negative ions[1] are introduced near the negative ground and accelerated toward the positively charged dome. Before the negative ions reach the dome, they collide with a target that strips them of their extra electrons plus one or more of their original electrons so that they are now positively charged ions (atoms with more protons than electrons).

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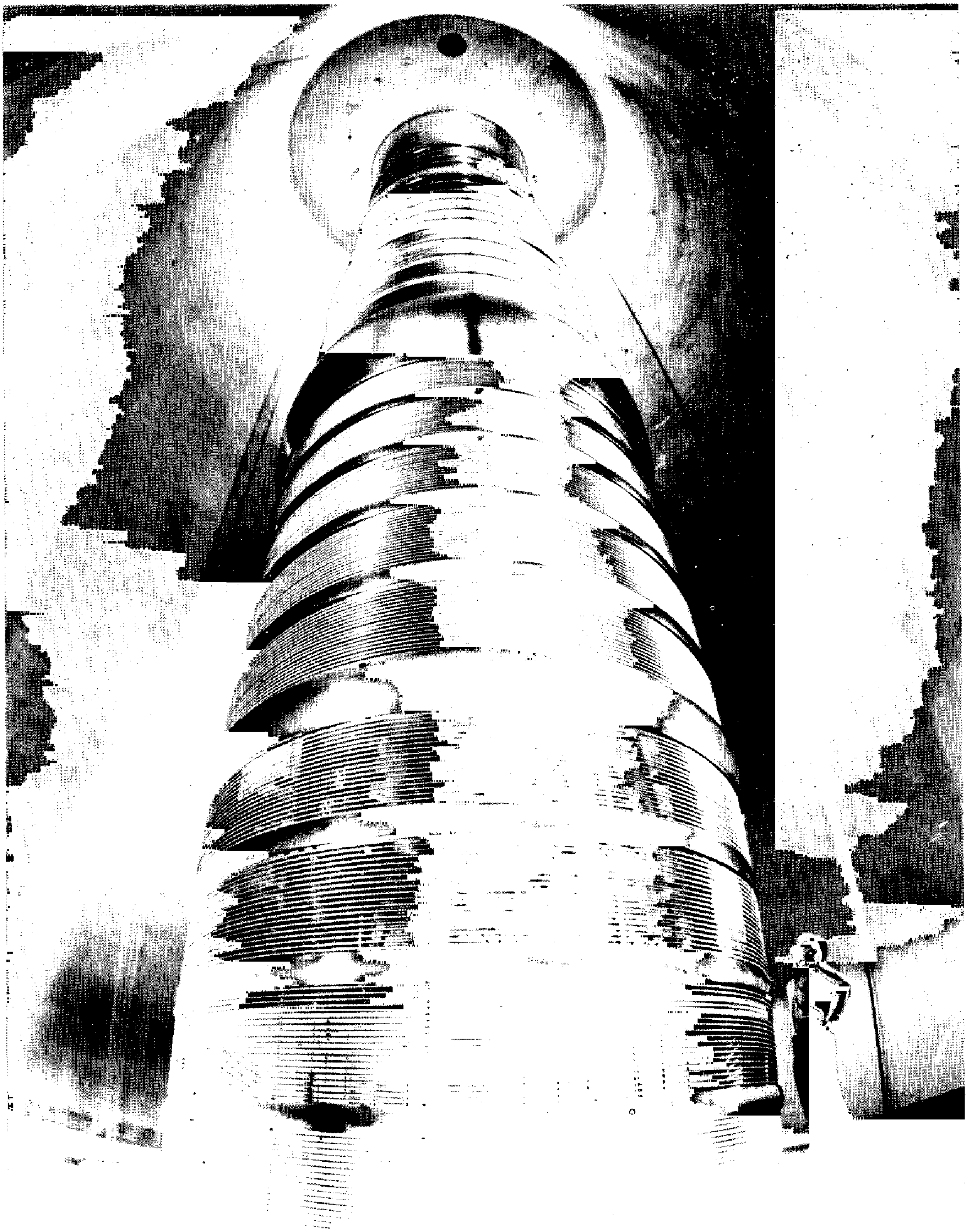
[1] Ions are charged particles which are the result of atoms gaining or losing one or more electrons. Negative ions have more electrons than protons; positive ions have fewer electrons than protons.



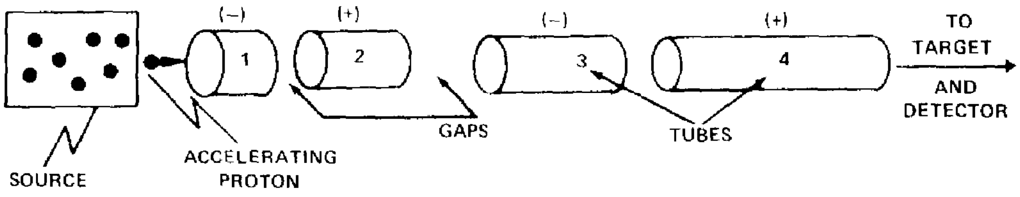
THE ELECTROSTATIC ACCELERATOR AT OAK RIDGE, TENNESSEE.

The positive ions are then accelerated for the second time--away from the positively charged dome and toward the negative ground. The tandem version of the electrostatic accelerator can double the accelerator energies of the single version. The picture on the preceeding page shows the tandem electrostatic accelerator at the Holifield Heavy Ion Research Facility in Oak Ridge, Tennessee. (See pp. 19 to 24 for a description of all high-energy and nuclear physics facilities supported by DOE.)

Linear accelerators

In a linear accelerator, charged particles (electrons, protons, or heavy ions[2]) travel in a straight line and gain energy by passing through a series of electrically charged tubes. The tubes alternate at regular cycles with either a positive or a negative charge. In the diagram below, protons, which have a positive charge, are being accelerated from the source to the target (from left to right).

PHASE I: PROTON IS ACCELERATED FIRST TIME



In phase I (depicted above), protons are produced at the source and are attracted (accelerated) toward tube number 1 because the tube's surface is negatively charged. (At this point, all odd numbered tubes are negatively charged and all even numbered are positively charged.) Once inside the tube, the protons are unaffected by the charge on the tube's surface and they continue their movement toward the number 2 tube and the target.

As shown in the diagram below, when the protons exit tube number 1, the electrical charge on all tubes has been reversed (all even numbered tubes are now negatively charged). The protons are now accelerated a second time because they are repelled by the positive charge behind them in tube number 1 and they are attracted to the negative charge of tube number 2 in front of them. This process is repeated for the length of the electric field and the protons are speeded up at each gap.

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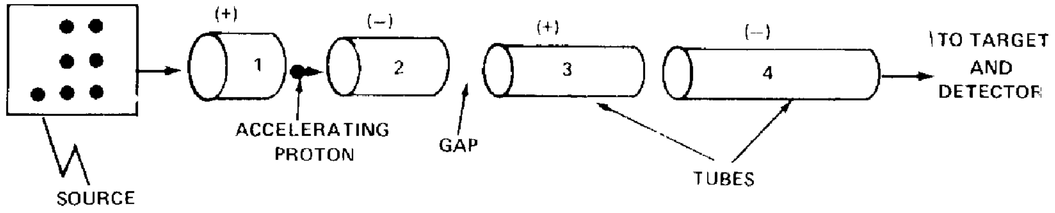
[2] Helium and hydrogen, which consist of one and two protons, respectively, are considered "light" ions; all ions with three protons (lithium) or more are considered "heavy" ions.

PHASE II: PROTON IS ACCELERATED SECOND TIME



This method of proton acceleration requires that the electrically charged tubes get progressively longer and longer. The reason for this is that the tubes switch their positive and negative charges at a constant rate but the protons are going faster and faster, and therefore, take less time to go the same

THE STANFORD LINEAR ACCELERATOR CENTER, PALO ALTO CALIFORNIA.

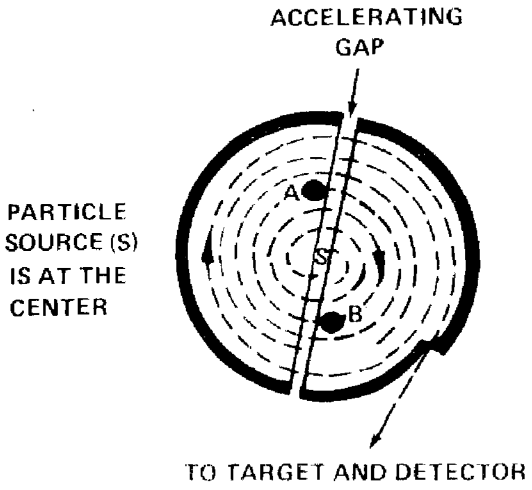
distance. If the tubes' size remained the same, the protons would progressively take less and less time to traverse the length of each tube and would soon be exiting a tube before the electrical charge is switched. If the protons enter a gap where the positively charged tube is in front of them instead of behind them they will be decelerated. Since electrons are so much lighter than protons, they achieve maximum velocity (nearly the speed of light) very quickly so most of the tubes in an electron accelerator do not progressively increase in length.

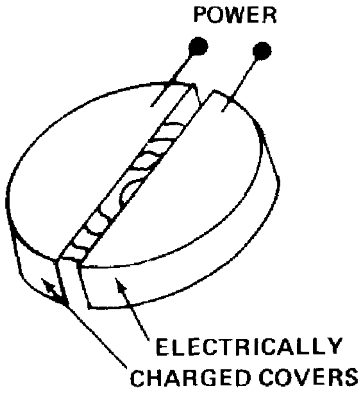
The picture on page 15 shows the Stanford Linear Accelerator Center. The accelerator crosses under a major highway and is approximately 2 miles long. The large buildings at the bottom of the picture house some of the experimental areas.

Cyclotrons

The cyclotron uses the same principle as the linear accelerator--the particles get accelerated as they cross a gap between two areas which have an opposite electric charge. However, instead of a long straight tube, the cyclotron is circular and the accelerating gaps form a straight line in the center between two electrically charged "D"-shaped covers as shown in the sketch below. (The sketch on the left is a top view). The particles are injected into the center of the machine and magnets then cause the particles to move in a circular fashion, spiraling outward as they pick up speed.

The "D"-shaped covers--like the tubes in the linear accelerator--switch back and forth between positive and negative electrical charges at regular intervals so that when a particle approaches the gap, the D-cover on the far side will have an opposite charge. For example, when a proton (which has a positive electrical charge) is in position "A" (under the left D-cover),





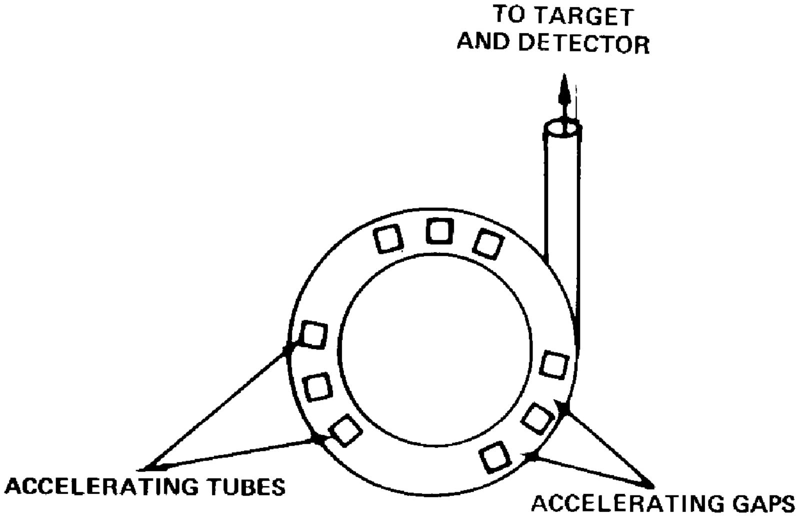
the right D-cover will be negative to pull the proton across the gap as the left D-cover (which is positive) repels or pushes the proton across the gap. By the time the proton gets to point "B," the D-covers have switched their electrical charges again and are ready to repeat the acceleration cycle.

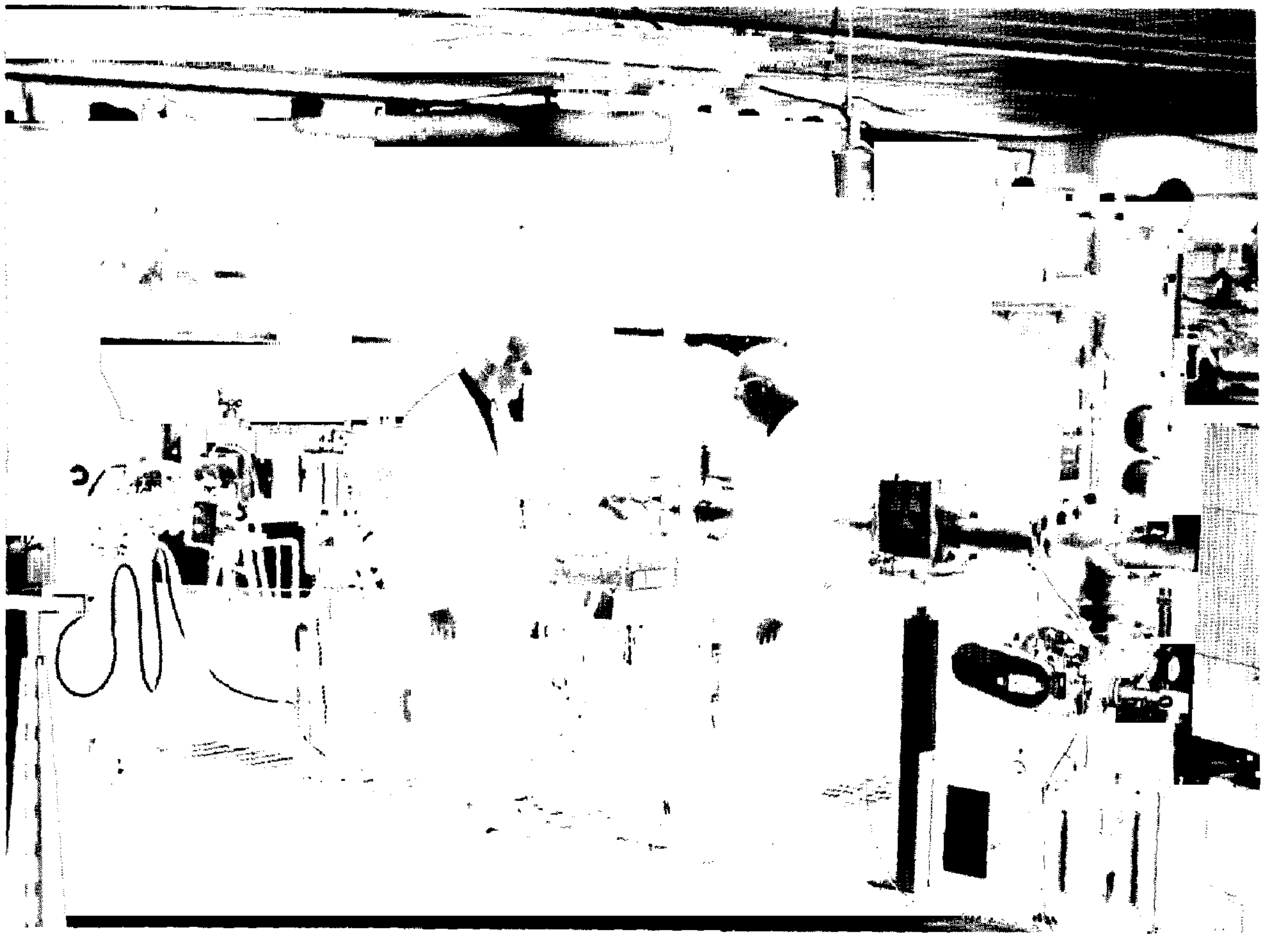
Like the tubes for the linear accelerator, it is essential that the cyclotron's D-covers have the correct electrical charge when the accelerated particle reaches the gap. Since the D-covers alternate electrical charge at a constant rate and the accelerated particles move faster every time they are accelerated across the gap, an adjustment must be incorporated to ensure that the particles do not reach succeeding gaps too soon. The time required for the particles to make a single orbit must remain the same throughout the acceleration process. This is achieved through the spiraling path the particles are forced to take--with each succeeding revolution, a particle is moving at faster speeds, but because of its spiral path, the particle also has farther to travel before it reaches the gap.

The picture on the following page shows the Texas A&M University cyclotron. The long white object to the left of the two men is a side view of the cyclotron. The dark areas above and below the cyclotron are the magnets that impart the spiraling motion to the accelerated particles.

Synchrotrons

The largest and most powerful accelerators today are synchrotrons. Just like the linear accelerator, the synchrotron has a series of tubes and accelerating gaps, but the similarity ends there. As shown in the sketch below, a synchrotron is doughnut-shaped and, unlike the linear accelerator, the synchrotron's tubes do not have to progressively increase in length because the frequency of change in each tube's electrical charge is synchronized to match the accelerated particle's speed. This means that as the

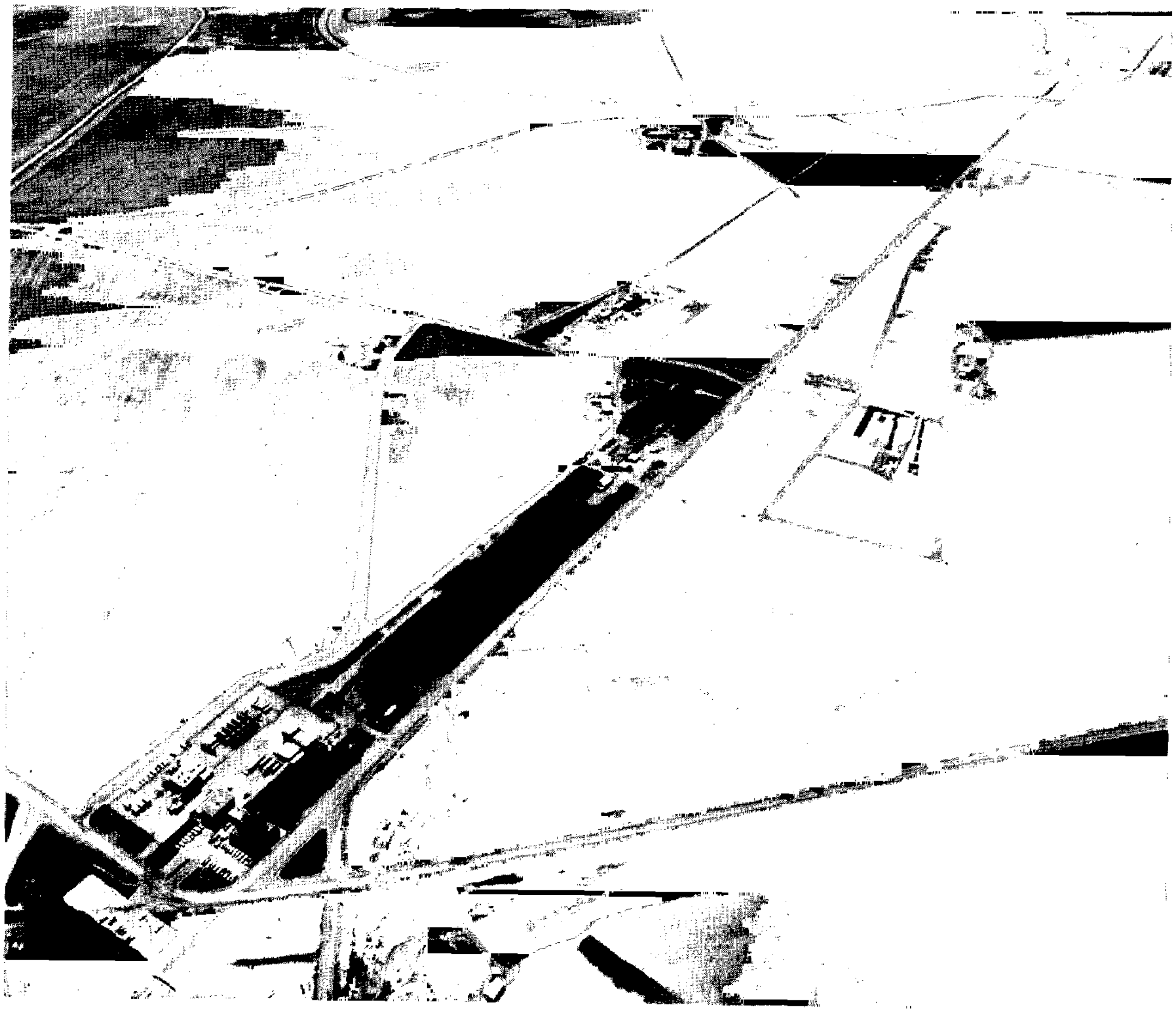




THE 88" CYCLOTRON AT TEXAS A&M UNIVERSITY, COLLEGE STATION, TEXAS.

speed of the particle increases, the electrical charge of the tubes remains correctly phased--the tube immediately in front of the accelerated particle will always have an opposite charge. A magnetic field, used to bend the beam of particles and keep it in the "doughnut" (ring), also varies in strength with the momentum of the particles. When the correct energy levels are achieved, the accelerated beam of particles is diverted (by magnets) out of the ring and toward the target area.

An aerial view of the Fermilab synchrotron facility is pictured on the next page. The accelerator is about 4 miles in circumference, and it can accelerate protons around the ring at a rate of nearly 50,000 times a second (nearly the speed of light) with energy levels up to 800 GeV.



FERMI NATIONAL ACCELERATOR LABORATORY, BATAVIA ILLINOIS.

DOE HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS ACCELERATOR FACILITIES

DOE supports high-energy physics and nuclear physics experiments at several national laboratories and university-based laboratories. High-energy physics and nuclear physics accelerators located at national laboratories are usually government-owned and contractor-operated. They provide free "beam time" to all scientists conducting experiments at the facility, and experiments are approved at each location on the basis of their scientific merit by a committee whose members represent several laboratories and universities. Scientists in outside research groups can also conduct experiments at the national facilities. However, they must plan experiments and fabricate detectors and other instruments at their home institutions, execute and partially analyze experiments at the national facility, complete analyses at their home institutions, and ultimately, publish their research results.

University-based facilities, on the other hand, may be available for collaborative efforts with scientists from other laboratories and universities but are usually dedicated to a research program that is established as part of the university science curriculum. The accelerators at university-based laboratories are usually owned by the university and beam-time is provided without charge for scientifically meritorious research.

High-energy physics accelerator facilities

The three DOE high-energy physics accelerator facilities are located at Brookhaven National Laboratory, Fermi National Accelerator Laboratory, and Stanford Linear Accelerator Center. All three laboratories have the common goal of seeking the fundamental components and structure of energy and matter. They differ in the type of accelerator beams produced and the energy levels of the machines.

Brookhaven National Laboratory

Brookhaven National Laboratory in Upton, New York, is government-owned and operated by Associated Universities Incorporated, a nonprofit consortium of nine universities. Brookhaven uses a 750,000 eV electrostatic accelerator and a 200 MeV linear accelerator to inject the main accelerator--a 33-GeV synchrotron. The three machines (known collectively as the Alternating Gradient Synchrotron, or AGS) accelerate protons, and during normal operations, up to 7 experiments can be conducted concurrently. Full beam energy was obtained from Brookhaven's original main accelerator in 1960. Since 1965, the accelerator facility has been upgraded several times, including the addition of a new magnet power supply and a new experimental hall.

Work began in 1984 to connect the AGS with an existing nuclear physics electrostatic accelerator. This will allow heavy-ions to be injected into the AGS and accelerated to higher energy for nuclear physics experiments. According to DOE, this upgrade would be beneficial if another accelerator, a heavy-ion collider, were to be built at Brookhaven since the Brookhaven accelerators could then be used collectively as an injector for the new accelerator. (See page 26.). Fiscal year 1986 funds were requested by Brookhaven for a second project--a new synchrotron booster--but funds for this project were not included in the President's fiscal year 1986 budget request.

Fermi National Accelerator Laboratory

Fermi National Accelerator Laboratory (Fermilab), located near Chicago, Illinois, achieved full beam energy on its original accelerator in 1971. Fermilab is a government-owned facility that is operated for DOE by a consortium of 54 universities--University Research Associates, Incorporated. The Fermilab accelerator facility consists of a series of five accelerators that successively boost proton beams to higher energies. The beam originates in a 750,000 eV electrostatic accelerator and is then injected into a 500-foot-long linear accelerator. The beam emerges from the linear accelerator with energies of about 200 MeV. The third accelerator is a booster synchrotron--about 500 feet in diameter--that boosts the protons to about 8 GeV and injects the beam into the main synchrotron ring that is about 4 miles in circumference. Protons can be accelerated by this fourth accelerator to about 500 GeV but is limited to about 150 GeV when the fourth accelerator is used as an injector to the fifth accelerator.

In December 1983 Fermilab began operating with a fifth accelerator, called the "Energy Saver," which uses a ring of superconducting magnets[3] to boost the energy of the particles being examined to about 800 GeV. This accelerator will be capable of accelerating protons to about 1 TeV when an upgrade of the facility (called Tevatron I) is completed.

The Tevatron I project will also enable the facility to operate in a second mode--colliding beams. Fermilab is modifying its facilities so that a proton beam circling within the superconducting ring of magnets, can be collided with an antiproton[4] beam that is circling in the opposite direction within the same magnet ring, at energies up to 1 TeV for each beam. Project completion is scheduled for 1986.

Stanford Linear Accelerator Center

Stanford Linear Accelerator Center, located near Palo Alto, California, is operated for DOE by Stanford University. The Center's original 2-mile-long linear accelerator achieved full beam energy of 21-Gev in 1966. With subsequent upgrades and improvements, the accelerator now produces electron and positron[5] beams at energies up to 32-Gev and injects those beams into two circular electron-positron colliding-beam facilities--one almost 270 feet in diameter, producing collision energies of 8 GeV (called SPEAR), and the other almost 2,700 feet in diameter, producing collision energies of 30 GeV (called PEP). The linear accelerator can be operated independently or as an injector to the colliding-beam facilities. Up to ten experiments can be run concurrently at the Stanford Center.

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[3] Superconductivity refers to the ability of some materials to maintain perpetual electric currents without loss, owing to the complete absence of electrical resistance. It occurs at very low temperatures.

[4] An antiproton is the antiparticle of a proton. When a particle and its antiparticle meet, the result is annihilation of the two particles.

[5] A positron is the antiparticle of an electron.

A linear collider accelerator is currently under construction at the Stanford Center. The primary goals of this new accelerator are to test the feasibility of the linear-collider concept and to explore electron-positron colliding-beam physics at energy levels of 100 GeV. Construction began in October 1983 and includes upgrading the energy level of the existing linear accelerator from 32 to 50 GeV so it can serve as an injector to the linear collider. Project completion is scheduled for late 1986.

Nuclear physics accelerator facilities

DOE provides support for 11 accelerator facilities; 7 are at national laboratories and 4 are at university-based laboratories. The accelerators at the national laboratories are owned by the government. One of the accelerators at the university-based facilities (Yale) is also owned by the government; the others are owned by the universities.

At DOE's nuclear physics accelerator facilities, scientists have access to each of the four types of accelerators described on pages 11 through 19: electrostatic, linear, cyclotron, and synchrotron (and at some facilities, combinations of these accelerators). While the types of beams are duplicated at several of these facilities--many provide light-to-heavy ion beams--the energy range and program emphasis often varies. Listed in the table on the following page is each of DOE's nuclear physics facilities, their location, and the type of accelerator used. All of the accelerators in the table accelerate protons except the Bates machine which accelerates electrons. Additionally, while the Los Alamos machine accelerates protons as its primary beam, this beam is merely a catalyst used to produce muon, neutrino, and pion beams.[6] These three secondary accelerator beams are the primary experimentation beams. A table is provided in appendix II to show selected capabilities of the DOE-supported nuclear physics accelerators. (See p. 51.)

DOE-Supported Nuclear Physics Accelerators

Facility	Location	Accelerator name	Accelerator type
A. W. Wright Nuclear Structure Laboratory	Yale University New Haven, Connecticut	Tandem Van de Graff Accelerator	Electrostatic
Argonne National Laboratory	Argonne, Illinois	Atlas	Electrostatic injecting a linear
Brookhaven National Laboratory	Upton, New York	Tandem Heavy Ion Facility	Two electrostatics
Cyclotron Institute	Texas A&M University College Station, Texas	Texas A&M Cyclotron	Cyclotron
Lawrence Berkeley Laboratory	Berkeley, California	88-Inch Cyclotron	Cyclotron
Lawrence Berkeley Laboratory	Berkeley, California	Superhilac/Bevalac	Linear injecting a synchrotron
Los Alamos National Laboratory	Los Alamos, New Mexico	Clinton P. Anderson National Meson Physics Facility (LAMPF)	Linear
Massachusetts Institute of Technology	Massachusetts Institute of Technology Middleton, Massachusetts	Bates Linear Accelerator Center	Linear
Nuclear Physics Laboratory	University of Washington Seattle, Washington	Tandem Accelerator	Electrostatic
Oak Ridge National Laboratory	Oak Ridge, Tennessee	Holifield Heavy Ion Research Facility	Cyclotron injecting an electrostatic
Triangle Universities Nuclear Laboratory	Duke University Durham, North Carolina	Cyclograaff Accelerator	Cyclotron injecting an electrostatic

According to DOE and accelerator facility officials, existing accelerator facilities must be upgraded and augmented with new, more powerful machines to aid the quest for deeper probings into matter and the atomic nuclei and/or to prevent or delay facility obsolescence. Major improvements are being made or have been proposed for all of the DOE-supported nuclear physics accelerator facilities. These improvements vary from installation of new radio frequency transmitters for the Bates Center accelerator to the installation of a new linear accelerator at the University of

Washington. Some of the accelerator improvement projects are completed in phases and spread out over several fiscal years. The improvements include upgrades to existing accelerators, purchase of new instruments and equipment, or the addition of new accelerators to connect to those already in operation. The following examples are given to illustrate some of the improvements being made to the nuclear physics facilities.

In fiscal year 1984, Lawrence Berkeley Laboratory completed a project to upgrade the beam transport line connecting the linear accelerator (Superhilac) with a synchrotron (Bevalac). This project included upgrading the beam line and incorporating improved data analysis instrumentation into the beam line. Another upgrade project is scheduled for fiscal year 1986 and involves installation of a new ion source for the linear accelerator and improvements in the hardware associated with the beam transport system.

In fiscal year 1982, Argonne National Laboratory began a project to enlarge its linear accelerator and add a new experimental area. This project--to be completed in fiscal year 1985--was undertaken to improve beam quality and experimental flexibility.

The Yale University accelerator is being upgraded to increase the maximum power from 13.5 MeV to almost 22.5 MeV. The Yale accelerator improvement project started in fiscal year 1984 and is expected to be completed by the end of fiscal year 1986.

FUTURE PHYSICS ACCELERATOR FACILITIES

The High Energy Physics Advisory Panel and the Nuclear Science Advisory Committee have recommended, respectively (and DOE has endorsed), the development of one new high-energy physics accelerator facility and one new nuclear physics accelerator facility to pursue the scientific opportunities beyond the reach of existing facilities or facilities under construction. In addition, the Nuclear Science Advisory Committee advised DOE in December 1983, that the United States should proceed with the planning for construction of a heavy-ion colliding-beam accelerator facility.

DOE has provided research and design funding for the high-energy physics program's facility--the Superconducting Super Collider (SSC)--and the nuclear physics program's facility--the Continuous Electron Beam Accelerator Facility (CEBAF). To date DOE has not approved funding specifically for the heavy-ion colliding-beam accelerator. The three facilities are further discussed below. In addition to these three facilities, at least two other accelerators are being contemplated by DOE laboratories--a high-energy machine for which some preliminary research is being performed and a nuclear physics accelerator for which a formal proposal has been presented to the Nuclear Science Advisory Committee.

Superconducting Super Collider

The need to explore physics phenomena at energies higher than achievable on existing high-energy physics accelerators was addressed in 1983 by the High Energy Physics Advisory Panel. That panel concluded, based on the long development of superconducting accelerator technology, that an SSC was technically feasible. According to DOE officials, if it is completed, the SSC would be in the forefront of world high-energy physics accelerator facilities. In addition, the advisory panel stated that the facility is essential for a strong U.S. program into the 21st Century.

Sometimes called the "ultimate answer machine," the SSC is expected to have a circumference of 60 to 120 miles and generate energies 20 times greater than Fermilab's accelerator. (See pp. 20 and 21.) According to the advisory panel report, the project's concept is to collide protons traveling in opposite directions at combined energy levels up to 40 TeV. The advisory panel report indicated the project would provide a capability not provided by existing or planned high-energy physics facilities.

According to DOE officials, preconstruction research and development for SSC began in fiscal year 1984 and is expected to last 3 years. It is then expected that construction of the project would take 6 additional years and experimental use of the collider facility would begin in 1994. In March 1984 DOE assigned responsibility for the project's preconstruction research and development effort to Universities Research Association, Incorporated. There are four research and development groups involved in various aspects of the accelerator's technology development: Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley Laboratory, and the Houston Area Research Center.

A central design group has been established by the Association to coordinate preliminary SSC technology development and identification of technical site requirements. The group is expected to issue a report to DOE by April 15, 1985. While no specific protocol has been established, DOE has contacted the National Academy of Sciences and the National Academy of Engineering about the possibility of those organizations assisting in the site selection process.

Continuous Electron Beam Accelerator Facility

Interest in a continuous-electron-beam nuclear physics accelerator surfaced in a National Research Council report entitled *Future of Nuclear Science*. The 1979 Long Range Plan for Nuclear Science prepared by the Nuclear Science Advisory Committee reported a need for a national electron accelerator laboratory. Subsequently, five proposals for a new facility were submitted to and reviewed by a Nuclear Science Advisory Committee Panel on Electron Accelerator Facilities. In 1983 the panel recommended the construction of a 4-GeV continuous-electron-beam accelerator facility (CEBAF) proposed by the Southeastern Universities Research Association. The panel indicated a need for an accelerator with higher energies and higher beam intensities than those currently available in order to better investigate the influence of quarks and gluons on the characteristics and interactions of nuclei.

For fiscal year 1985, DOE provided research and development funding to the Association for a CEBAF facility to be built in Newport News, Virginia. In its fiscal year 1986 budget submission, DOE indicates that CEBAF meets the highest priority need for new accelerator construction in the nation's nuclear physics program. DOE plans to obtain funding to start construction in fiscal year 1987 and, after 6 years of construction, to have CEBAF operational in the 1993-94 time frame.

Relativistic Heavy Ion Collider

The 1983 Long Range Plan for Nuclear Science prepared by the Nuclear Science Advisory Committee recommended a relativistic heavy-ion collider as the highest priority--after CEBAF--for the next major nuclear physics facility to be constructed. This recommendation was made on the basis of "a new scientific opportunity of fundamental importance--the chance to find and to explore an entirely new phase of nuclear matter." The committee recommended an accelerator be built that can provide colliding beams of very heavy ions with energies of about 30 GeV per nucleon in each beam.

In August 1984 Brookhaven National Laboratory submitted a proposal to DOE for construction of a Relativistic Heavy Ion Collider (RHIC). The RHIC would provide head-on colliding beams of heavy ions at about 100 GeV per nucleon in each beam. According to DOE, this collision will allow the study of quarks and gluons. According to the proposal, the construction of the facility represents the natural continuation of the laboratory's role as a center for high-energy physics and nuclear physics research and extends the uses of existing laboratory facilities. Although DOE has not formally approved Brookhaven's RHIC proposal, it has authorized funding for major upgrades to the existing Brookhaven facilities (see p. 20) that would enable the facility's accelerator to be used as an injection source for RHIC.

Other accelerators

Two other accelerators are receiving attention in the science community. The first is a very large linear collider and the second is LAMPF II (see below) proposed by the Los Alamos National Laboratory.

DOE is funding long-range research at the Stanford Linear Accelerator Center to develop the technologies that would be necessary for a very large linear collider. This machine would expand the capabilities of the Stanford Linear Collider now under construction. The goal of this new accelerator would be to provide the capability to collide beams of electrons and positrons with an energy range up to several TeV. Before this accelerator can become a reality, however, numerous components must be designed and developed. No formal proposal has been submitted to the High Energy Physics Advisory Panel or to DOE by Stanford to build such an accelerator.

In December 1984 the Los Alamos National Laboratory submitted a proposal to DOE to construct and operate LAMPF II. This facility would consist of the current linear accelerator (injector), a 6-GeV booster accelerator, and a 45-GeV synchrotron. The Los Alamos proposal indicated LAMPF II would provide facilities for basic research and education to a generation of scientists in the 1990's and well into the next century. If approved, Los Alamos officials believe that LAMPF II construction could begin in fiscal year 1988. LAMPF II has not been endorsed by DOE or the Nuclear Science Advisory Committee.

CHAPTER 3

HOW MUCH DOES IT COST TO BUILD AND OPERATE DOE'S PHYSICS ACCELERATORS?

DOE's support of physics research amounts to hundreds of millions of dollars annually. A major portion of these costs is to operate accelerator facilities and to upgrade these facilities to allow scientists to study the frontiers of physics. DOE's total support for the high-energy physics and nuclear physics programs has increased from $558 million in fiscal year 1983 to an estimated $728 million in fiscal year 1985, including construction costs, capital equipment purchases, and annual operating expenses. Also DOE's two, new planned facilities, if approved, are estimated to cost $4.3 billion to build and about $230 million a year to operate when completed. If substantial increases in federal funding to support these new facilities are not forthcoming, DOE's options appear to be quite limited. The options include closing existing facilities, obtaining greater foreign financial participation, and reducing upgrades to existing facilities.

BUILDING AND OPERATING ACCELERATOR FACILITIES

Conducting high-energy physics and nuclear physics experiments is based on using complex accelerator facilities. For the large facilities, like Fermilab, an extensive amount of research is necessary to develop the concept and the technology upon which the new accelerators are based. The technology must then be engineered and designed to assure reliability and operational efficiency. Because of the complexity and sophistication of modern accelerators, they are designed by developing separate subsystems (i.e., magnets, detection devices, computer systems, etc.) and then combining the various subsystems into a integrated unit. Depending on the complexity of the machines, prototypes or models of the accelerator subsystems may be constructed to demonstrate the workability of the various subsystems in the overall unit. The cost associated with this effort represents a significant portion of the program's cost. For example, in the high-energy physics program, about $90 million in fiscal year 1985 is for conducting research and development on accelerators under construction, developing new accelerator concepts, and improving existing accelerators.

Constructing the high-energy physics accelerators is a major undertaking because of the size and complexity of the facilities involved. To illustrate the magnitude of the effort, DOE constructed the main Fermilab accelerator by digging a 4-mile circular tunnel 30 feet below ground. The 9-foot-wide tunnel was then encased in precast concrete. Inside the tunnel about 1,000 magnets were installed. Subsequently, DOE installed an additional 1,000 specially designed superconducting magnets, which are cooled to a temperature of 4.6 degrees Kelvin.[1] The facilities also use an extensive amount of computer equipment. At Fermilab, DOE's operating contractor uses more than 500 microprocessors throughout the complex. In addition, 34 computers are in operation in a central control system and in experimental areas. Sixty more computers are used to collect data from experiments and equipment. Besides constructing the accelerator, experimental areas and administrative facilities must also be built.

Building nuclear physics accelerator facilities can also be a major undertaking. For example, at the Los Alamos Meson Physics Facility, accelerator construction involved building a machine about one-half mile in length to strict specification. In addition, DOE funded construction for support facilities such as an administrative building, utility extensions, and experimental areas with expensive detection devices. Further, the facility's electronics equipment pool consists of more than 3,000 items costing millions of dollars.

In addition to the construction and capital equipment costs, operating an accelerator facility can be costly. For example, in the high-energy physics program, providing the beams and facility maintenance are expected to account for about $168 million of the $247 million in operating expenses incurred by the accelerator facilities in fiscal year 1985. In this regard, DOE's expenses to operate facilities ranges from $81 million in fiscal year 1985 for Fermilab to less than $1 million for the cyclotron at Texas A&M University. Electricity, labor, and overhead represent the major expense components in providing beams and maintaining the accelerator facilities for both the high-energy physics and nuclear physics programs. At Fermilab, for example, these expense components are estimated to be more than $63 million in fiscal year 1985, or about 80 percent of the facility's operating and maintenance cost. At the Los Alamos Meson Physics Facility, these same cost components are estimated at $31 million, or three-fourths of the facility's total operating cost (excluding experimental research and theoretical studies) for the same year.

DOE'S FUNDING OF HIGH-ENERGY PHYSICS

Since fiscal year 1983, DOE's support of the high-energy physics program has increased 29 percent[2] from $421.9 million to an estimated $545.6 million in fiscal year 1985. In particular, construction and capital equipment costs associated with upgrading

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[1] Kelvin is a scale of temperature based on thermodynamic principles in which zero degrees Kelvin is equivalent to -273° Centigrade.

[2] Adjusted for inflation, this increase amounts to about 22 percent.

and improving existing facilities are expected to increase from $99.7 million in fiscal year 1983 to an estimated $172.7 million in fiscal year 1985. Program operating costs, including research performed at non-accelerator facilities, are also expected to increase from $322.2 million to an estimated $372.9 million in the same period.[3] DOE's investment in accelerator facilities and their associated operating costs are expected to increase in the years ahead as present upgrades are completed and new facilities are built. The following section discusses DOE's total investment in accelerator facilities, its cost to operate them, and what can be expected in the future for new facilities and their operating costs.

Cost to build high-energy physics accelerator facilities

As of January 1985, DOE's investment in these high-energy physics accelerator facilities was nearly $1 billion. The original cost to construct the three facilities totaled nearly $390 million. Since constructing the original facilities DOE has completed various additions and/or upgrades to these facilities at a cost of $603 million. A summary of the cost of the original accelerators and improvements to those accelerators is shown on the next page.

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[3] Adjusted for inflation, this increase amounts to about 9 percent.

DOE Investment In High-Energy Physics Accelerator Facilities

Facility	Original construction cost[a]	Upgrades and additions[b]	Total
	------(in thousands of then-year dollars)-----		
Brookhaven National Laboratory--Alternating Gradient Synchrotron	$ 30,605	$ 82,290[c]	$112,895
Fermi National Accelerator Laboratory	243,498	294,599	538,097
Stanford Linear Accelerator Center	114,000	226,058	340,058
Total	$388,103	$602,947	$991,050

[a] Includes the cost of accelerators and buildings.

[b] Excludes additions and upgrades currently in progress. These are discussed on pp. 33 to 35. Includes the cost of accelerators, buildings, related equipment, and associated research and development costs.

[c] Excludes research and development costs for which records are not available.

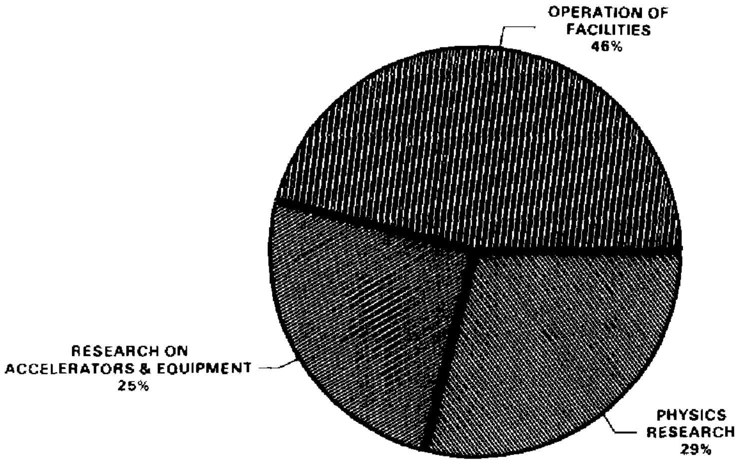
DOE's estimated cost of replacing these facilities in fiscal year 1985 is about $1.8 billion, excluding accelerator-related equipment. DOE estimates the current replacement cost of the equipment to be less than $500 million.

Cost to operate high-energy physics accelerator facilities

DOE's support for operating accelerator facilities, developing new accelerators and related equipment, and carrying out physics research amounted to $373 million in fiscal year 1985. As shown in the chart on the next page, about 71 percent of the program's operating cost in fiscal year 1985, (or $265 million) was for operating facilities and conducting research and development on accelerators and related equipment. The remaining 29 percent (or $108 million) was for physics research.

OPERATING COST OF DOE HIGH-ENERGY PHYSICS PROGRAM

FOR FISCAL YEAR 1985



Source: Prepared by GAO from DOE Financial Information System data

Fermilab, Stanford, and Brookhaven costs accounted for about $247 million, or about two-thirds, of the total program operating cost in fiscal year 1985. The remaining operating cost of about $126 million was for about 90 universities and various other organizations for physics research and accelerator and equipment development. A summary of DOE's operating costs at the three high-energy physics facilities is shown on the next page.

DOE Operating Cost Incurred by High-Energy Physics Accelerator Facilities[a]

Facility	FY 1983	FY 1984	Estimated FY 1985
	(in thousands of then-year dollars)		
Brookhaven National Laboratory--Alternating Gradient Synchrotron:			
Physics research	$ 6,467	$ 6,931	$ 7,218
Facility operations	33,120	35,758	36,265
Accelerator and equipment development	20,537	22,833	14,000
Total	60,124	65,522	57,483
Fermi National Accelerator Laboratory:			
Physics research	7,750	10,144	9,967
Facility operations	75,564	75,524	80,920
Accelerator and equipment development	23,744	31,983	21,200
Total	107,058	117,651	112,087
Stanford Linear Accelerator Center:			
Physics research	10,807	10,735	11,348
Facility operations	43,625	48,330	50,550
Accelerator and equipment development	22,788	15,133	15,450
Total	77,220	74,198	77,348
Total	$244,402	$257,371	$246,918

[a] Includes experimental research and theoretical studies funded by DOE through the facility and performed at other locations. Excludes the cost of separately funded capital equipment purchases and facility maintenance and improvement projects.

High-energy physics upgrades and new facilities

Two of the high-energy physics accelerator facilities have ongoing projects to improve their existing capabilities. The third, Brookhaven's AGS, is being modified to improve the facility's overall research capability. The cost of the Brookhaven AGS modification is shown in the nuclear physics section of this chapter. The following table shows the current improvement projects and DOE's associated costs.

Estimated Cost of DOE Upgrades to High-Energy Physics Accelerator Facilities[a]

Facility	Accelerator and buildings	Equipment	Research and development[b]	Total
	(thousands)			
FERMILAB:				
Tevatron I	$84,000	$94,118	$80,054[c]	$258,172
Tevatron II	49,800	6,000	12,300[c]	68,100
Total	133,800	100,118	92,354	326,272
STANFORD:				
Stanford Linear Collider	115,272	56,467	65,655[d]	237,394
Total	$249,072	$156,585	$158,009	$563,666

[a] Includes DOE funding to other organizations for upgrades to these facilities.

[b] Includes research on detector facilities.

[c] Excludes research prior to construction that cannot be separately identified.

[d] Includes research prior to construction.

In addition to these upgrades, DOE is doing research and development at Fermilab and at other locations on the new SSC facility. DOE estimates the construction and the initial equipment cost of SSC will be about $3.5 billion. DOE anticipates spending another $398 million to $450 million for research and development prior to and during construction and $225 million in pre-operating cost for such functions as testing the various subsystems and staff training. Thus, in total, the cost to build the SSC would be more than $4 billion in fiscal year 1985 dollars.

Beyond the SSC, there are indications DOE's support of long-range research at the Stanford Linear Accelerator Center could lead to a proposal to build a large linear electron/positron collider mentioned by a subpanel of the High Energy Physics Advisory Panel in a July 1983 report.[4] According to a budget official at the Center, about $2.4 million will be spent on this research in fiscal year 1985. DOE has not estimated the cost for such a collider because research is just beginning; it also has not yet received a proposal to build such a machine. Nonetheless, the above

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[4] Report of the 1983 HEPAP Subpanel on New Facilities for the U.S. High Energy Physics Program (DOE/ER-0169, July 1983).

mentioned 1983 subpanel report provides some insight into the possible costs involved. The subpanel estimated that a facility of this type could cost from $2.4 billion to $3 billion, if the necessary technology and hardware developments can be accomplished.

Upgrades and new facilities oftentimes involve additional operating costs. For example, according to DOE budget records, the operating cost of Fermilab is expected to increase from $59 million in fiscal year 1982 (when a fixed target program was in operation at 400 GeV) to more than $80 million in fiscal year 1985, partly as a result of Tevatron I and II and other improvements to the facility.[5] Similarly, construction data sheets for Stanford show the total cost of the facility could increase by $17 million annually as a result of the Stanford Linear Collider. In addition, DOE estimates the operating cost for SSC in its operating phase will be about $202 million annually in 1985 dollars.[6] Thus, assuming full program funding, SSC costs would substantially increase the total operating cost of existing facilities from $247 million in fiscal year 1985 to about $449 million.

DOE'S FUNDING OF NUCLEAR PHYSICS

Nuclear physics accelerator facilities are generally smaller than those for high-energy physics and are, therefore, less costly to build and operate. DOE's funding for operating the entire program has increased 34 percent[7] from $136.9 million in fiscal year 1983 to an estimated $182.9 million in fiscal year 1985, including construction cost, capital equipment purchases, and operating expenses. Like the high-energy physics program, one of the causes for the increase is the upgrading of existing facilities. In this regard, construction and capital equipment costs have increased from $19 million in fiscal year 1983 to an estimated $36 million in fiscal year 1985. Accompanying this increase, program operating costs have also risen from $117.7 million to an estimated

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[5] Adjusted for inflation, this increase amounts to about 23 percent.

[6] In addition, DOE estimates $42 million annually will be required for capital equipment and about $16 million for annual maintenance and improvements to the facility. Overall, SSC's annual cost during its operating phase will be about $260 million in fiscal year 1985 dollars.

[7] Adjusted for inflation, this increase amounts to about 26 percent.

$146.9 million.[8] DOE also plans to build CEBAF and, if Brookhaven's RHIC proposal is approved by DOE, these new facilities together could be more costly to build and operate than those presently in the program.

Cost of nuclear physics accelerator facilities

As of January 31, 1985, DOE's total investment in the 11 nuclear physics accelerator facilities was about $255 million, excluding the cost of upgrades currently in progress. The initial investment in currently operating nuclear physics accelerators, associated buildings, and instruments and detection devices was about $114 million. Each of the facilities has been upgraded at an aggregate cost of about $141 million. A summary of DOE's investment in the nuclear physics facilities in terms of accelerators, buildings, and related equipment is shown on the next page.

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[8] Adjusted for inflation, this increase amounts to about 18 percent.

DOE Investment In Nuclear Physics Accelerator Facilities

(in thousands of then-year dollars)

Laboratory	Original	Upgrades and Additions	Total
A.W. Wright Nuclear Structure Laboratory/ Yale University	$ 5,334	$ 3,600	$ 8,934
Argonne National Laboratory	4,300	6,700	11,000
Brookhaven National Laboratory	12,410	5,520	17,930
Cyclotron Institute/Texas A&M University	3,000	5,068	8,068
Lawrence Berkeley Laboratory-- 88-Inch Cyclotron	4,567	7,195	11,762
Lawrence Berkeley Laboratory-- Superhilac/Bevalac	15,207	38,074	53,281
Los Alamos National Laboratory	57,000	32,125	89,125
Massachusetts Institute of Technology	5,700	17,011	22,711
Nuclear Physics Laboratory/ University of Washington	380[a]	982	1,362
Oak Ridge National Laboratory	3,573	23,423	26,996
Triangle Universities Nuclear Laboratory/Duke University	2,500	1,143	3,643
Total	$113,971	$140,841	$254,812

[a] Excludes about $2.5 million in funding NSF.

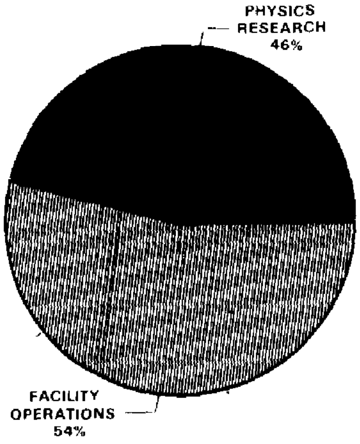
DOE's estimated replacement cost for these facilities is about $725 million in fiscal year 1985 dollars.

Cost to operate nuclear physics accelerator facilities

DOE's cost to operate the nuclear physics program is estimated to be about $147 million in fiscal year 1985, excluding separately funded capital equipment purchases and facility maintenance and improvement projects. As shown in the chart below, about 46 percent (or $68 million) of the program's operating cost was for physics research. The remaining 54 percent (or $79 million) was for operation and maintenance of facilities.

OPERATING COST OF DOE NUCLEAR PHYSICS PROGRAM

FOR FISCAL YEAR 1985



Source: Prepared by GAO from DOE Financial Information System data

About 85 percent (or $125 million) of the program's operating cost (excluding construction and capital equipment purchases) in fiscal year 1985 was incurred by the nuclear physics facilities. The remaining 15 percent (or about $22 million) was provided to about 75 universities and other organizations for physics research at various locations. A cost summary for operating the DOE facilities since fiscal year 1983 is shown on the next page.

DOE Nuclear Physics Operating Cost At Accelerator Facilities[a]

Laboratory	FY 1983	FY 1984	Estimated FY 1985
	(in thousands of then-year dollars)		
A.W. Wright Nuclear Structure Laboratory/ Yale University	$ 2,710	$ 2,968	$ 3,025
Argonne National Laboratory	8,185	9,730	10,700
Brookhaven National Laboratory	7,083	7,138	7,800
Cyclotron Institute/ Texas A&M University	1,022	1,112	1,185
Lawrence Berkeley Laboratory[b]	23,863	28,952	29,555
Los Alamos National Laboratory[c]	41,520	45,725	49,138
Massachusetts Institute of Technology	8,502	9,655	9,795
Nuclear Physics Laboratory/University of Washington	2,018	2,191	2,315
Oak Ridge National Laboratory	8,951	9,644	10,118
Triangle Universities Nuclear Laboratory/ Duke University	951	1,424	1,565
Total	$104,805	$118,539	$125,196

[a] Includes experimental research and theoretical studies funded by DOE through the laboratory and performed at other locations. Excludes separately funded capital equipment purchases and facility maintenance and improvement projects.

[b] Includes cost of operating the 88-inch Cyclotron and the Bevalac accelerator.

[c] Includes DOE defense program funding of $3 million in fiscal years 1983 and 1984, and $3.1 million in fiscal year 1985.

Nuclear physics upgrades and new facilities

At the present time, each of the nuclear physics accelerator facilities is upgrading its experimental capabilities. DOE's estimated cost of these upgrades is $57 million. A summary of the upgrades by facility is shown on the next page.

DOE Cost of Upgrades to Nuclear Physics Accelerators

Laboratory	Total estimated cost[a] -----(in millions)---
A.W. Wright Nuclear Structure Laboratory/Yale University	$ 11.5
Argonne National Laboratory	13.7
Brookhaven National Laboratory	12.3
Cyclotron Institute/Texas A&M University	-0-
Lawrence Berkeley Laboratory	2.8
Los Alamos National Laboratory	3.8
Massachusetts Institute of Technology	1.9
Nuclear Physics Laboratory/University of Washington	9.2
Oak Ridge National Laboratory	1.4
Triangle Universities Nuclear Laboratory/ Duke University	.4
Total	$ 57.0

[a] Includes DOE costs incurred and to be incurred. Other upgrades may be ongoing that are not funded by DOE. For example, although upgrades at Texas A&M University is shown to be zero, a new accelerator is being added at a cost of $7.3 million with funds provided by state and private donors.

In addition to these upgrades, DOE plans to build CEBAF at a cost which is expected to be about $220 million in fiscal year 1985 dollars. To better define construction costs, DOE is spending $3.5 million in fiscal year 1985 operating funds for architect/ engineering work and research and development on components. Though DOE envisioned starting construction in fiscal year 1986, the Office of Management and Budget did not include the project in the President's fiscal year 1986 budget request. With the start of construction now planned for fiscal year 1987 and operations scheduled to begin in the 1993-94 time frame, DOE estimates that CEBAF's annual operating cost would be about $30 million to $35 million in fiscal year 1985 dollars.

If DOE were to support the Brookhaven National Laboratory's proposed RHIC facility, construction would cost about $230 million, including the cost of research and equipment. The Director of the nuclear physics program estimates the annual operating cost of RHIC to be about $50 million in fiscal year 1985 dollars. Assuming construction funds for both CEBAF and RHIC are provided and no existing facilities are shut down, DOE's nuclear physics accelerator operating expenses could increase more than 60 percent from $125 million to about $205 million in 1994 (fiscal year 1985 dollars) after construction of the new facilities.

In addition to these facilities, the Los Alamos National Laboratory's proposed LAMPF II, if approved, would be the most expensive of the new nuclear physics facilities now under consideration. The construction cost of LAMPF II is expected to be about $450 million in fiscal year 1985 dollars. The proposal has not been approved by DOE or the Nuclear Science Advisory Committee, and DOE has not estimated the operating cost of LAMPF II.

FUNDING OF PLANNED PHYSICS FACILITIES

Accelerator facility officials believe that DOE is maximizing the amount of physics research and the training of physicists by building new accelerator facilities and continuing to operate the existing ones. However, DOE believes that to the extent existing facilities become obsolete, they should be shut down. If some existing facilities are not shut down, the large additional cost of operating the new facilities and the federal budget deficit will make it difficult for DOE to obtain full federal funding for new and existing facilities.

The Chief of the Program Operations Branch for the high-energy physics program told us DOE is developing projections on total program cost that include SSC. Because of the tentative status of the projections, this official did not reveal the specifics of the various projections. The Director of the nuclear physics program provided us his views on financing the program, cautioning that his views do not represent a formal commitment by DOE. On the basis of our work, there appear to be three basic options available to DOE, separately or in combination, in the event full funding is not forthcoming.

--Eliminate construction upgrades and improvements in existing facilities to provide funds for operating new facilities.

--Close one or more of the existing facilities to free operating funds for new facilities.

--Obtain nonfederal funding to help support the program.

The first option--eliminating construction upgrades and improvements to existing facilities--appears to be somewhat limited for the high-energy physics program because annual construction and capital equipment funds are currently less than the estimated annual operating cost of SSC. For example, construction and capital equipment funds appropriated by the Congress for the three existing high-energy physics facilities have ranged between $105.2 million in fiscal year 1983 and $172.7 million in fiscal year 1985, far less than the estimated $260 million to operate the SSC (including separately funded capital equipment costs and facility maintenance projects). In addition, if upgrades and improvements were eliminated for the existing facilities, DOE contends these facilities may no longer be capable of exploring the frontiers of physics in areas not covered by the SSC. As such, the quality of experiments conducted at those facilities may be adversely affected. For the nuclear physics program, construction and capital equipment funds for upgrades and improvements of $18 million to $36 million annually have been appropriated by the Congress since fiscal year 1983. While funds of this magnitude may be sufficient to offset CEBAF's $30 to $35 million operating cost, such funds would not offset the combined estimated operating cost of CEBAF and RHIC, which together would total $80 to $85 million annually.

The second option involves closing one or more of the existing physics facilities to provide operating funds for the new ones. Notwithstanding the construction cost, this option has the advantage of allowing DOE to operate the SSC with no overall increase in the program's operating cost. However, by closing all three existing facilities, DOE contends it would be eliminating several areas of scientific investigation that will not be covered by the new facility. The nuclear physics program has more facilities to choose from in deciding which facilities to close. However, this option is still limited. Both of the Lawrence Berkeley Laboratory accelerator facilities and the Los Alamos Meson Physics Facility would have to be closed to offset the combined operating cost of CEBAF and RHIC. If DOE chooses not to close either of these facilities, even closing all of the other facilities, including the university facilities, will be inadequate to offset the additional operating cost of CEBAF and RHIC.

The third option--obtaining nonfederal funding--has the advantage of allowing DOE to operate more facilities without increasing federal support. The cost of upgrading existing facilities and constructing new facilities such as SSC has increased awareness of the need for international cooperation between countries as the cost of high-energy physics machines increase. For example, in January 1982 the High Energy Physics Advisory Panel recommended that the United States ". . . entertain the possibility of major bilateral accelerator construction projects with Europe or Japan, if they are cost effective and have strong physics motivation."[9] To date DOE has not participated in the construction of any foreign accelerators. Nonetheless, in an effort to offset some of SSC's construction and equipment costs, efforts are underway to obtain foreign participation. Canada and Japan are viewed as potential partners in the SSC project. No formal agreements have been reached, however, and DOE believes the federal government must first make a commitment to SSC before participation by other countries can be seriously pursued.

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[9] Report of the Subpanel on Long Range Planning for the U.S. High Energy Physics Program of the High Energy Physics Advisory Panel (DOE/ER-0128, January 1982).

CHAPTER 4

WHAT BENEFITS ARE BEING DERIVED FROM DOE'S HIGH-ENERGY PHYSICS AND NUCLEAR PHYSICS ACCELERATORS?

According to DOE and accelerator facility officials, experiments conducted using DOE's high-energy physics and nuclear physics accelerators have resulted in many important discoveries related to the structure and properties of atomic nuclei and subnuclear particles. DOE's funding of high-energy physics and nuclear physics research and accelerator facilities has also directly contributed to the education of future physicists. Further, DOE's programs, according to DOE and laboratory officials, have contributed to understanding the origin of the universe, have promoted accelerator use in medicine and other sciences and have indirectly led to industrial uses of the equipment and technology developed for the accelerators. DOE officials also recognized the societal value of basic research even though the benefits may be esoteric and difficult to quantify.

PHYSICS ACCOMPLISHMENTS

Experimental results of the 1970's and 1980's have refined and consolidated the standard model of physics (see pp. 2 and 3). According to DOE and accelerator facility officials, the three DOE-funded high-energy physics accelerator facilities contributed in a major way to that advance. These officials described several major high-energy physics accomplishments resulting from experiments conducted at the DOE-funded high-energy physics accelerators.

--Experiments in the late 1960's on the Stanford linear accelerator demonstrated that the heart of the atomic nucleus, the proton, is comprised of smaller particles, known as quarks.

--In 1975, a particle called the tau lepton was discovered during an experiment on the SPEAR accelerator at Stanford. The discovery of this particle suggested the existence of the top and bottom quark. Later, experiments conducted at Fermilab proved the existence of the bottom quark.

--Experiments conducted on the SPEAR accelerator in 1974 confirmed the existence of the charm quark.

Some of the experimental results from the high-energy physics accelerators have received international recognition. For example, in 1974, scientists using the Brookhaven AGS accelerator and the Stanford SPEAR accelerator independently discovered a new particle which was called the J/psi. This discovery won Nobel Prizes in 1976 for Sam Ting of the Massachusetts Institute of Technology and for Burton Richter, now the Director of the Stanford Linear Accelerator Center, and was important because its existence supports the "standard model" and later led to several other discoveries. In addition, a 1980 Nobel Prize was awarded to Princeton University Professors Val Fitch and James Cronin for a discovery related to the decay of subatomic particles. This discovery was based on experimental work performed on the Brookhaven AGS accelerator and was important because it contradicted one of the most basic physics theories at that time. A detailed list of high-energy physics achievements--developed by DOE in 1979--is included as appendix III. A DOE-provided update for 1979 through 1984 is included as appendix IV.

According to DOE nuclear physics program officials, nuclear physicists are adding to man's knowledge of the interactions, properties, and structures of atomic nuclei, and each of the 11 facilities has made important contributions to nuclear physics. For example, 26 new nuclei have been discovered over the last 15 years on the Brookhaven electrostatic accelerators. In addition, experimental observations have been made at Lawrence Berkeley Laboratory's Bevalac facility of nuclear matter with densities three to four times greater than ordinary matter. Researchers observed that at those densities, nuclei behave in many ways like a liquid. The facility has also raised nuclear matter to temperatures hotter than those at the center of the sun. Two detailed lists of nuclear physics accomplishments--compiled by DOE--are included as appendixes V and VI.

The high-energy physics goal of understanding the forces of nature and the ultimate structure of matter also relates to astrophysics. Astrophysics is the branch of astronomy dealing with the physical and chemical properties of celestial bodies. According to DOE and accelerator laboratory officials, achievement of the high-energy physics objectives may contribute to understanding the origins of the universe.

The high-energy and nuclear physics accelerators also provide a training ground for physicists. While education is an important by-product of the high-energy physics accelerators, the emphasis on education of physicists is somewhat less than that at the nuclear physics accelerators. However, at hearings before the Subcommittee on Energy Development and Applications, House Committee on Science and Technology on February 22, 1984, DOE officials estimated that about 150 doctoral degrees are conferred annually on the basis of work done at DOE's high-energy physics facilities. The Chairman of the Nuclear Science Advisory Committee told us that education is the primary mission of the four university-based nuclear physics accelerators and an important goal at the seven national nuclear physics accelerator facilities. According to data provided by DOE at the same February 1984 hearings, 60 to 80 doctoral degrees are conferred each year on the basis of research conducted at nuclear physics accelerator facilities in the United States.

INDUSTRIAL APPLICATIONS

According to DOE and accelerator officials, although not an objective of DOE's high-energy physics and nuclear physics programs, many industrial applications have resulted from developments in accelerator physics. These applications include industrial uses of superconducting magnets and materials testing. In addition, commercial accelerators used in medical and industrial applications were developed on the basis of high-energy or nuclear physics accelerator research.

Two high-energy physics facilities have developed superconducting magnets for their accelerators. Application of this knowledge has been explored for more than 10 years at Brookhaven National Laboratory for electric power transmission. Brookhaven officials now believe they are close to a viable system of underground power transmission that is based on superconductivity. In January 1985 a private corporation submitted a proposal to the Empire State Electric Energy Research Corporation (an association of electric utilities in New York) to manufacture and test a transmission cable using the technology developed at Brookhaven.

In addition, Brookhaven and Fermilab officials stated that superconducting technology developed at those facilities has been used in Japan on an experimental train. Superconducting magnets propel the train and also allow the train to float above similar magnets in the "track." Speeds of up to 321 miles per hour have been attained in tests.

The Director of Fermilab also cited the current use of commercial (nonresearch) accelerators as a result of the DOE accelerator physics programs. Specific applications include the inspection of thick metal vessels and pipes, the sterilization of food, and the disinfection of sewage that is to be recycled as fertilizer. Commercial accelerators are also used in the manufacture of integrated circuits. According to the director, over 1,000 such accelerators are currently in use, annually producing circuits for about $8 billion in sales of calculators, computers, and microprocessors. Other facility officials cited cryogenic refrigeration[1] systems, high-speed computers, microwave science, high-level radiation handling equipment, and precision lasers as spin-offs from the accelerator programs.

MEDICAL AND OTHER SCIENTIFIC APPLICATIONS

In addition to the accelerator facilities' primary mission of experimental physics, several of the facilities also use the accelerators for medical purposes and other science research. For example, neutrons produced by the Fermilab high-energy physics accelerator have been used to treat about 1,000 cancer patients over a recent 5-year period. Similarly, heavy-ion beams produced by the Bevalac nuclear physics accelerator have been used to treat about 15 patients per day during 1984. Treatments utilizing the Fermilab and Bevalac beams have been effective in reducing or

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[1] Cryogenic refrigeration is used to obtain near absolute zero temperatures (about -273° Centigrade).

eliminating some malignant tumors. The Director of Fermilab stated that about 1,000 commercial accelerators also treat cancer patients in the United States. In recent years commercial accelerators have treated about 350,000 patients per year.

The production of radioactive isotopes[2] was also cited by DOE and accelerator facility officials as an application of DOE's accelerators. Radioactive isotopes are used to treat cancer patients, test functional performance of organs and diagnose illnesses. Accelerator beams at Brookhaven, LAMPF, and the Lawrence Berkeley cyclotron are currently used to produce isotopes for medical uses. Radioactive isotopes are also produced by commercial accelerators.

A specific example of a medical application of DOE accelerators occurred in 1976, when DOE was granted a patent for a Brookhaven development.' Using a radioactive isotope called technetium-99, red blood cells can now be freeze-dried and stored for up to 5 months. Previously, blood had to be withdrawn and labeled just prior to chemical study--a laborious and inconvenient task, according to Brookhaven officials. These officials estimated that sales of the technetium-99 isotope would be about $200 million in 1985.

Some DOE accelerators have been taken over partially or completely for research involving other sciences. For example, when a high-energy physics accelerator--the Argonne Zero Gradient Synchrotron--was shut down in 1979, the injector portion of the facility was transferred to a new research program. The resulting Intense Pulsed Neutron Source facility produces beams of neutrons for physics, chemistry, biology, and materials science experiments that study the position and motion of atoms.

In addition, an electrostatic accelerator at Oak Ridge National Laboratory is an example of a DOE-funded nuclear physics accelerator which is now used for other purposes. This accelerator was built in 1960 by DOE's nuclear physics program. DOE's construction of the Holifield Heavy Ion Research Facility in Oak Ridge made this accelerator expendable and it was transferred to DOE's atomic physics program; it is now used for fusion energy, astrophysics, and solid state physics research.

Accelerator-based facilities have also been developed for research in biology, chemistry, medicine, solid-state physics, and materials science using ultraviolet and x-ray beams. National facilities involved in these sciences are operating at the Brookhaven National Synchrotron Light Source and the Stanford Synchrotron Radiation Laboratory (utilizing the SPEAR accelerator). A third such facility has been proposed by Argonne at an estimated $120 million construction cost.

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[2] An isotope is one of two or more atoms having the same number of protons (which makes them the same chemical element) but having a different number of neutrons (which gives them different atomic weights).

SOCIETAL VALUE

The physics community often refers to the societal value of their fields. This value is--as with any basic science--impossible to fully quantify or, for that matter, render a judgment as to the significance of its worth. In our 1980 report on high-energy physics,[3] DOE officials provided us with the following view:

> "In the past two hundred years, mankind has found some truly fundamental causes for what is going on in the natural world and we have learned to penetrate below the surface of the phenomena that are ordinarily observed around us. Basic science has searched for and has found a regular world beneath the seemingly irregular flow of natural events and has studied its laws and interrelations. This search goes on and reaches ever deeper layers of nature finding at the same time new and unexpected forms of natural events. High energy physics is a spearhead in this endeavor, it tries to reach the deepest level of the material world.
>
> Basic science is one of the cornerstones of our Western civilization. No other civilization has created anything like it. It is probably the major contribution of our time to the great creations of the human spirit. It is one of the positive constructive elements in the time when so many values are undermined and overthrown.
>
> A vigorous basic science creates a spiritual climate which affects the whole intellectual life of the Nation by its influence on the way of thinking and by setting standards for many other intellectual activities. Applied sciences and technology adjust themselves to the highest intellectual standards which are strived for in the basic sciences. It is the style, the scale, and the level of scientific and technical work in pure research that attracts some of the most inventive spirits and brings the most active scientists to those countries where science is at its highest level. This is why many outstanding scientists have moved to the United States from other countries in the recent decades.
>
> The case for generous support for pure and fundamental science is as simple as this. Fundamental research sets the standards of modern scientific

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[3] Increasing Costs Competition May Hinder U.S. Position of Leadership in High Energy Physics (EMD-80-58, Sept. 16, 1980).

> thought; it creates part of the intellectual climate in which our modern civilization flourishes. It pumps the lifeblood of ideas and inventiveness not only into the technological laboratories and factories, but also affects other cultural activities. It is a most vital and active part of our intellectual life, a part which we all should regard with pride as one of the highest achievements of our century."

In a 1982 paper,[4] the Director of Fermilab stated that the knowledge and acceptance of science's cultural value is necessary in maintaining healthy science programs, as follows.

> "The earliest drive towards explanations of how things work was a cultural one. And it is the cultural appeal which has attracted the best minds into science. Whereas the guarantee of an economic and clean source of energy may be the most crucial scientific problem of our day, the bright high school student will more often be drawn to science by the puzzle of neutrino mass, antimatter and the big bang theory of creation. Not only is pure science a recruiting factor but its success sets standards and reaffirms confidence among workers throughout the spectrum of science.
>
> "If the cultural value of these sciences is not given its required weight in long range science policy planning, we will have a second rate enterprise--innovation and progress will slow . . . To appreciate the power of the cultural drive, one must spend enough years with undergraduates or, even more dramatically, with the high school students such as those who flood my laboratory each Saturday morning. It is out of these culturally agitated young people that the genius will come to solve our many problems in unexpected ways."

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[4] Viewpoint From Fundamental Science, by Leon M. Lederman, Revised Apr. 15, 1982.

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United States Senate
COMMITTEE ON APPROPRIATIONS
WASHINGTON, D.C. 20510

November 25, 1984

Mr. Charles A. Bowsher
Comptroller General of
the United States
General Accounting Office
441 G Street
Washington, D. C. 20548

Dear Mr. Bowsher:

The annual cost of the Department of Energy's nuclear physics and high energy physics programs is about $750 million. A sizeable portion of this cost is dedicated to the operation, maintenance and frequent upgrading of several large particle accelerators. During the past year, the Department requested about $250 million to construct a new facility, the Continuous Electron Beam Accelerator Facility (CEBAF). The Department also has preliminary plans for building another much larger accelerator, known as the super-conducting super collider. This device--a circular beam track with a circumference of between 60 and 120 miles--is expected to cost as much as $4 billion to construct and may cost more.

With these proposals in mind, the Subcommittee on Energy and Water Developoment of the Senate Committee on Appropriations is becoming increasingly concerned about the need for larger, more costly nuclear and high energy physics facilities. I am therefore asking the General Accounting Office to develop information related to the Department's nuclear and high energy physics programs and facilities. As part of that effort, I am requesting that GAO:

--compile an inventory of accelerators that have been built or are planned in the United States,

--identify the construction, operation, and maintenance costs associated with these accelerators, so that a clearer view of the appropriations that will be required to support the cummulative inventory of facilities and projects in future years will be available to the Subcommittee; and

--determine what benefit is being derived from the construction and operation of these accelerators.

Because the Subcommittee is concerned about upcoming funding requests for nuclear and high energy physics facilities, the Subcommittee will need this information in time for use during deliberations on the Department of Energy's Fiscal Year 1986 budget request--probably around April 1, 1985.

If you have any questions concerning this matter, please contact Mr. Proctor Jones of the Subcommittee staff.

Sincerely,

J. Bennett Johnston
Ranking Minority Member

JBJ:bcg

ACCELERATOR CAPABILITIES

The table on the following page was prepared by GAO based on information provided by DOE to show a representative mix of the capabilities of the accelerators supported by its nuclear physics program. As shown in the table, an accelerator can accelerate less massive particles to higher energies than it can accelerate the more massive particles. For example, the accelerator at Yale University can accelerate particles with an atomic mass unit (AMU)[1] of 1 to an energy of 27 MeV. If the particle to be accelerated has an AMU of 120, then the Yale machine could accelerate that particle only to 2 MeV per AMU.

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[1] Atomic mass unit (AMU) is a unit of measure used to compare the mass of atomic particles where AMU 1 is approximately equal to the mass of one proton.

SELECTED CAPABILITIES OF DOE-SUPPORTED NUCLEAR PHYSICS ACCELERATORS

Facility	Location	Accelerated Particles	
		Mass (AMU)	Maximum Energy (MeV per AMU)
A.W. Wright Nuclear Structure Laboratory Yale University	New Haven, Connecticut	1 16 120	27 8 2
Argonne Tandem/Linac Accelerator Argonne National Laboratory	Argonne, Illinois	1 16 127	30 20 6
Tandem/AGS Brookhaven National Laboratory	Upton, New York	12 to 32 63 238	14,000[a] 2 0.5
Cyclotron Institute Texas A&M University	College Station, Texas	1 12 40	55 26 8
88-Inch Cyclotron Lawrence Berkeley Laboratory	Berkeley, California	1 16 84	55 35 6
Superhilac/Bevalac Lawrence Berkeley Laboratory	Berkeley, California	1 56 238	4,900 2,100 960
Clinton P. Anderson Meson Physics Facility Los Alamos National Laboratory	Los Alamos, New Mexico	1	800
Bates Linear Accelerator Massachusetts Institute of Technology	Middleton, Massachusetts	electrons	750 MeV maximum energy
Nuclear Physics Laboratory University of Washington	Seattle, Washington	1 16	18 5
Holifield Heavy Ion Research Facility Oak Ridge National Laboratory	Oak Ridge, Tennessee	10 197	26 3
Triangle Universities Nuclear Laboratory	Durham, North Carolina	1 4	32 24

[a] Upon completion of transfer line project in FY 1986.

US MAJOR ACCOMPLISHMENTS IN HIGH ENERGY PHYSICS SINCE 1945

June 1979

Prepared by:

Division of High Energy Physics
US Department of Energy
Washington, D.C. 20545

FOREWORD

This chronological list is the result of an effort to give a short account of major achievement milestones in the evolution of high energy physics in the United States since 1945. Assembled in this form, it illustrates the rapid development of our conceptions of the basic nature of matter and energy, the importance of technological developments to this field, and the strong interleaving of experimental and theoretical discoveries.

The listing is meant to include only major highlights and the selection of items is necessarily somewhat arbitrary. It is also likely that new discoveries and the power of hindsight would result in a different selection in future such lists.

APPENDIX III

APPENDIX III

US Major Accomplishments in High Energy Physics Since 1945

1945	Synchrocyclotron principle (phase stability) suggested, removing the last technical barrier to unlimited particle energies attainable by orbital or linear accelerators.
1946	184" synchrocyclotron began operation with 350 MeV protons at what is now the Lawrence Berkeley Laboratory. This machine, which by 1957 had reached 720 MeV, was used to study in detail the pions which were discovered in cosmic rays in 1947.
1947	Muon identified as lepton, i.e., as a particle which does not experience the strong nuclear force. First observed in the late 1930's, the muon had been thought to be the meson carrier of the strong force postulated by Yukawa in 1935. The finding that it did not interact strongly led to a successful search for a heavier particle, the pion, which decayed into the muon. The pion was found to interact strongly and hence identified as the Yukawa meson.
1948 a	Universality of weak interactions suggested, i.e., weak interaction recognized as a fundamental force. This force is responsible for the decays of radioactive nuclei, of muons and many other particles and for neutrino interactions with matter, which have been extensively studied in the 1970's and are important in astrophysical processes.
1948 b	Quantum electrodynamics renormalized. Stimulated by measurement of the Lamb shift, a very small splitting of two quantum states of the hydrogen atom which had been thought to have identical energies, new calculations showed how to resolve the long-standing divergence problems of QED and established it as the correct relativistic theory of the electromagnetic force. This theory has withstood 30 years of extremely rigorous experimental testing, and is still our most precise field theory, serving also as a model for other gauge theories presently being developed for the strong interaction. J. Schwinger shared the 1965 Nobel Prize for his contributions to QED.
1949 a	Berkeley Synchrotron began operation with electrons of 330 MeV. This accelerator, which utilized the principle of phase stability, produced in its first year the discovery of the neutral pion and played an important role in determining the properties of pions.

1949 b	Neutral pion discovered at the Berkeley Synchrotron, completing the triplet of charge states, $\pi+$, π^-, and π°, which mediate the strong force binding neutrons and protons in atomic nuclei.
1949 c	Feynman diagram approach to field theory invented, and applied to quantum electrodynamics. This graphical way of describing interactions has been a powerful language for both quantitative and qualitative calculations in all areas of particle physics and in other fields of physics as well. Feynman shared the 1965 Nobel Prize for his work on quantum electrodynamics.
1950	High Power Klystron first used in the Stanford Mark II linear accelerator. These power amplifiers are the heart of modern electron accelerators, supplying radiofrequency power to the cavities which accelerate the electrons.
1951	Resonant beam extraction developed for accelerators. This technique of extracting the particle beam from the machine in a slow "spill" is crucial for many electronic experiments.
1952 a	Associated production hypothesis proposed: that the Λ and K particles, which had been discovered in cosmic ray interactions, are produced only in association with each other. The hypothesis was experimentally confirmed and led to the discovery of a new property of certain particles called "strangeness" (see 1953 e).
1952 b	Δ discovered at the Chicago Cyclotron. The delta was the first detected particle "resonance", or very short-lived particle formed as a resonant combination of two or more other particles, in this case the pion and proton. Many other resonances have since been discovered, leading physicists to seek a more fundamental set of building blocks of matter (see for example 1961 a and 1964 b).
1952 c	Strong focusing (alternating gradient) principle discovered. This method of using magnetic field gradients alternating in direction to focus a beam of charged particles had two important consequences: it greatly reduced the cost of accelerators by allowing much smaller magnet apertures (since the beam could be focused to a small diameter), and it provided a means of transporting extracted or secondary beams (produced by interactions of the primary beam with a target) to experimental apparatus located far from the accelerator.

1952 d Cosmotron began operation at Brookhaven National Laboratory with 2.3 GeV protons, later raised to 3 GeV. The first multi-GeV accelerator, it had sufficient energy to produce the strange particles which had been observed in cosmic rays. The associated production hypothesis was confirmed, several additional strange particles were discovered and their properties studied.

1953 a CPT Theorem proved - any local field theory is invariant under the combined operation of particle-antiparticle exchange (C), mirror reflection (P), and time reversal (T), if the theory of relativity is correct. This very general invariance principle has important consequences, e.g., that a particle and its antiparticle have equal masses and lifetimes.

1953 b Bubble chamber invented at the University of Michigan. This device records the passage of a charged particle as a trail of small bubbles in a medium such as liquid hydrogen. Photographs of the tracks allow detailed studies of the interaction of an incident particle in the liquid and any subsequent decay processes. The bubble chamber became the dominant experimental high energy physics technique for many years and is still a powerful tool for exploratory research and very detailed studies of complex processes.

1953 c Σ^+ discovered in a cosmic ray experiment: the first member of a new family of "hyperons" similar to the lambda hyperon, a strange baryon. The other two members of the sigma family were subsequently discovered at the Cosmotron.

1953 d Experimental confirmation of associated production of strange particles, at the Cosmotron (See 1952 a).

1953 e Strangeness quantum number proposed to explain associated production. Hyperons and kaons have a charge-like property, called "strangeness" for the "strange" behavior of strong production and weak decay. Strangeness is conserved in strong interactions such as those which produce lambdas and kaons. However, these particles are not massive enough to decay to other strange particles, so their decays must proceed through the weak interaction which does not conserve strangeness. (Heavier strange particles have since been discovered which do decay via the strong interaction.)

1954 a Bevatron began operation at Berkeley with 4.9 GeV protons, later increased to 6.2 GeV. The antiproton and many other particles and antiparticles were discovered with this accelerator.

1954 b Ξ^- (Ksi) discovered: the first of a pair of hyperons with two units of strangeness.

1954 c Yang-Mills theories - a method of constructing field theories invariant under a local gauge group was invented. This class of "gauge theories" has been important in theoretical developments such as recent advances in developing a theory of strong interactions (see 1973 b).

1954 d Derivation of dispersion relations from quantum field theory. These relations provided support for field theory, independent of perturbation theory (the usual method of field theory calculations based on successive approximations), and formed a basis for a detailed understanding of pion physics.

1954 e Cornell BeV Synchrotron began operation. This 1.3 GeV electron accelerator demonstrated the practical application of the strong focusing principle.

1955 a Discovery of the antiproton at the Bevatron, confirming the 1928 prediction of relativistic quantum mechanics that for every basic particle there must be an antiparticle, i.e., a particle with all charge-like quantum numbers (such as electric charge, strangeness, baryon number) reversed in sign. E. Segre and O. Chamberlain received the 1959 Nobel Prize for the discovery.

1955 b K_L^0 predicted. The neutral K meson was predicted to decay through two states, K_S^0 and K_L^0, with different decay modes and lifetimes. Each would be a quantum mechanical mixture of particle and antiparticle but a definite state of CP (see 1953 a).

1955 c First indications of structure within the proton, now understood to be composed of quarks. Studies of large angle scattering of electrons by protons showed that the proton had a finite size and hence must have structure. Hofstadter shared the 1961 Nobel Prize for this and related work.

1956 a Neutrino observed, confirming the hypothesis of its existence made by Pauli in 1933. The existence of an uncharged, massless particle having only weak interactions seemed essential to an understanding of nuclear beta decay, yet these properties made its experimental observation a very difficult matter until recent high energy accelerators were built.

1956 b Parity violation predicted to occur in weak interactions. One of the most challenging problems of the 1950's was the so-called $\tau-\theta$ puzzle; there seemed to be two particles which were identical in every respect except that they decayed into states of opposite parity. A radical alternative was suggested, that they were in fact the same particle (the K^+) but parity was not conserved in the weak interaction which governed its decay. It had long been assumed that parity, the mirror reflection operation, was conserved in all physical processes. Parity violation was quickly confirmed in a nuclear physics experiment, and T. D. Lee and C. N. Yang won the 1957 Nobel Prize for their bold prediction.

1956 c K^0_L (long-lived neutral kaon) discovered at the Cosmotron, confirming the prediction of 1955 that there be a long and a short-lived state. The short-lived state K^0_S had long been known, from the earliest cosmic ray "vee" particles. These mixtures of particle and antiparticle are unique to the neutral kaons.

1958 a V-A theory of weak interactions proposed, explicitly incorporating parity violation. This theory, extended in 1963 to include strangeness-changing processes, has successfully explained a wide variety of weak interaction processes.

1958 b Neutrino helicity determined. The massless neutrino always has its spin directed opposite to its momentum; it is said to be "left-handed" or to have negative "helicity". (The antineutrino has positive helicity). The observation of the neutrino's helicity was an important confirmation of the V-A theory.

1959 72-inch bubble chamber began operation at the Bevatron with a liquid hydrogen fill. Luis Alvarez received the 1968 Nobel Prize for particle discoveries using this device and the extensive system developed to analyze the photographic data.

1960 a Brookhaven Alternating Gradient Synchrotron (AGS), a strong focusing accelerator, began operation with protons of more than 30 GeV, a factor of five higher than previous machines. Among the most important discoveries made at the AGS are the ν_μ, the Ω^- and the Ψ/J. (1962 a, 1964 a, 1974 a).

1960 b Y^* (1385) discovered at the Bevatron, the first of a family of pion-hyperon resonances.

1960 c Spontaneous symmetry breaking proposed as the determining mechanism by which the strong interactions manifest themselves in nature. This work has had an influence on current thinking about quark interactions and on the efforts to unify all interactions within a single theory.

1961 a	SU(3) theory proposed independently by scientists in the US and in England. Known mesons and baryons were grouped into families, in a manner analogous to the periodic table of the elements. SU(3) led directly to the idea of quarks (1964 b). M. Gell-Mann received the 1969 Nobel Prize for this and other work.
1961 b	η (eta) meson discovered at the Bevatron, completing one of the SU(3) families (that of the spin 0, odd parity mesons) and thus giving important support to the theory.
1961 c	ρ (rho) meson discovered at the Cosmotron, the first pion resonance, and the first member of a new SU(3) family, the spin 1 nonet.
1961 d	ω (omega) meson discovered at the Bevatron, a pion resonance which occurs as a quantum mechanical mixture with the ϕ meson (1962 c).
1961 e	K* (890) discovered at the Bevatron, the first strange meson resonance, also a member of the spin 1 nonet.
1961 f	Matched long straight sections proposed for circular accelerators. A way was shown to insert straight sections without disturbing the operation of the machine, thus greatly enhancing its utility. Straight sections allow efficient systems for injection and extraction of the beam at high energy and are very important for colliding beam machines.
1962 a	ν_μ discovered at the AGS: a new type of neutrino, associated with the muon, The experiment showed that neutrinos produced in association with muons are distinct from those produced with electrons.
1962 b	On-line digital computer applied to data handling for a large array of scintillation counters, allowing much higher complexity of experimental apparatus and a higher rate of data acquisition. This technique and its further developments led to the present generation of very powerful electronic experimental facilities.
1962 c	ϕ (phi) meson discovered at the AGS, the first kaon resonance and a member of the spin 1 family, this meson mixes with the ω. The ϕ is now understood as an $s\bar{s}$ combination of quarks analogous to the $c\bar{c}$ quark combination which forms the J/Ψ (see 1964 b and 1974 a).
1962 d	Application of Regge theory to high energy physics: a sophisticated way of understanding scattering which has proved very powerful in explaining particle interactions at high energies.

1962 e Proposal of current algebra, a set of relations which set the scale for weak interactions of hadrons, clarified the weak interactions of hadrons with leptons and provided support for the quark hypothesis. Current algebra is also playing a role in estimating quark masses and other modern topics.

1963 a Argonne Zero Gradient Synchrotron (ZGS) began operation with protons of 12.7 GeV. Accurate and systematic studies using advanced experimental techniques such as superconducting analyzing magnets and polarized targets, have been the forte of the ZGS program. Experiments in the 60's demonstrated the successes and limitations of Regge theory and confirmed duality (1968 a). More recently, the unique ZGS capability to accelerate polarized protons and deuterons (1973 a) has been exploited to study the spin dependence of proton and neutron interactions with complete spin information.

1963 b Polarized proton target developed, allowing investigations of the spin dependence of the strong force. This type of target (with proton spins aligned) is widely used and is especially valuable at the ZGS, where experiments can now be done with both beam and target polarized (see 1973 a).

1964 a Ω^- (omega) discovered at the AGS: a new hyperon with 3 units of strangeness which had been predicted by SU(3). The discovery of this particle completed the baryon decuplet and was a crucial confirmation of the theory.

1964 b Quark hypothesis proposed: that the known hadrons (mesons and baryons) are composed of constituents called "quarks". At this stage, there were to be only 3 quarks, denoted by u, d and s. Mesons are made of a quark and an antiquark combination; baryons, of 3 quarks. During the 1970's, the quark hypothesis has been dramatically confirmed and extended to include two new kinds of quarks, the c and the b, and a sixth, the t, is predicted.

1964 c CP violating $K_1^0 \to \pi^+\pi^-$ decays observed at the AGS, implying (by the CPT theorem) a violation of time reversal invariance and suggesting the possible existence of a new fundamental force.

1964 d Charm hypothesis proposed: that there exists a fourth quark (c) with a new property called charm, a charge-like quantum number analogous to strangeness (such quantum numbers are now referred to by the generic term "flavors"). The basis for the charm hypothesis at this time was somewhat speculative; a stronger argument was offered in 1970. The existence of charmed quarks was demonstrated by the very exciting discoveries of 1974-76.

1965 a	Color hypothesis proposed: that each "flavor" of quark (e.g., u, d, s, c), comes in three types or "colors". This distinction offered a way to place three identical fermions in an antisymmetric state inside a baryon in agreement with the Pauli exclusion principle which forbids such states. The color property is not interpreted as having a greater significance; the source of the strong force which binds the quarks into hadrons.
1965 b	First application of a superconducting magnet to bubble chambers, using the 10" helium-filled chamber at Argonne National Laboratory. The use of the superconductors in magnets is of great importance in modern high energy physics facilities including accelerators and polarized targets as well as bubble chambers.
1966	Stanford Linear Accelerator (SLAC) began operation with electrons of 20 GeV. Discoveries at SLAC include ep scaling, the tau lepton, parity violation in neutral currents and, via SPEAR (1972 b) much of the new physics of charmed quarks.
1967	Weinberg-Salam theory proposed by scientists from the US and abroad with the aim of unifving wht weak and electromagnetic interactions. The theory has since been strongly supported by theoretical and experimental developments. It may be comparable in importance to Maxwell's unification of electricity and magnetism in 1865, and points the way to a possible unification of all the forces.
1968 a	Duality: resonance formation and particle exchange models of hadron scattering were shown to be equivalent. This relationship has provided important insight into scattering processes.
1968 b	ep scaling observed at SLAC: large angle electron-proton scattering behaves like that expected if the proton contained free (non-interacting) pointlike constituents.
1969	Parton model proposed to explain ep scaling as due to constituents of the proton called "partons". Partons are now interpreted as being quarks and "gluons" (carriers of the strong force between quarks).
1970	12-foot bubble chamber began operation at the ZGS, using a large superconducting magnet. This was the first of the very large hydrogen bubble chambers and was used especially to study neutrino interactions.
1972 a	Fermi National Accelerator Laboratory (Fermilab) began operation with 200 GeV protons, reaching 400 GeV later in the year. This beam energy was considerably higher than that of any other accelerator. Major Fermilab discoveries include a wealth of information about neutrino and hadron interactions at very high energies, charm production, and the upsilon, made up of b quarks.

1972 b SPEAR began operation: an electron-positron colliding beam storage ring at SLAC with energies of 2.5 GeV in each beam, later raised to 4.1 GeV per beam. Charm was discovered and studied in great detail with this facility. SPEAR is the prototype of PEP at SLAC and PETRA at DESY, both higher energy e^+e^- colliding beam facilities.

1973 a ZGS accelerated polarized protons to 6 GeV (later increased to 12 GeV) a unique capability which allowed the study of the details of proton-proton scattering with both proton spins polarized.

1973 b Asymptotic freedom demonstrated as a property of Yang-Mills theories. This theoretical advance was important to the development of quantum chromodynamics (QCD), a gauge theory which treats the strong force that binds the quarks into hadrons as arising from the color "charge" of the quarks. The force decreases asympotically to zero as the momentum transferred in collisions increases without limit; thus the quarks behave as if they were free particles in very high energy collisions such as the ep scaling experiments (1968 b).

1974 a Ψ(psi)/J discovered: a new particle composed of a $c\bar{c}$ combination, i.e., a bound state of the predicted charmed quark (1964 d) and its antiquark. This dramatic discovery, which occurred independently at the AGS and at SPEAR, opened a new era in high energy physics. It put the quark model on a very solid foundation, confirmed the charm hypothesis, led to the discovery of a large family of charmed particles and encouraged a search for still other possible quarks, one of which has subsequently been found (the b; see 1977a). S. Ting and B. Richter shared the 1976 Nobel Prize for this revolutionary discovery.

1974 b Ψ' discovered at SPEAR: an excited state of $c\bar{c}$. This and many other excited states form a detailed energy spectrum of "charmonium" which provides a rigorous test of detailed theoretical predictions and strikingly confirms the quark hypothesis.

1975 a Λ_c (lambda) observed at the AGS and at Fermilab: a charmed baryon, i.e., a 3-quark combination with one of the quarks being the c. Finding particles like this with "naked" charm (as opposed to the hidden charm of the $c\bar{c}$ states) was a crucial confirmation of the quark model.

1975 b τ(tau) discovered at SPEAR: a new charged lepton, the first since the muon. The existence of this lepton and its associated neutrino provide a strong suggestion that there must also be another pair of quarks called the b and t, since quarks and leptons have so far occurred in matched pairs, e.g. (u, d) and (e, ν_e)

1975 c	Particle jets observed in e^+e^- collisions at SPEAR. Jets are clusters of particles moving in the same general direction; their existence is evidence for parton-parton collisions. The existence of jets has subsequently been confirmed in hadron collisions.
1976	D, D* mesons discovered at SPEAR: charmed mesons, i.e., quark-antiquark combinations with one of the two being a c (or $\bar{c}$). These naked charm particles provided important support to the charm hypothesis and the quark model.
1977 a	T(upsilon) discovered at Fermilab: a new particle composed of $b\bar{b}$, where b is a fifth quark. The existence of this new quark had been suspected since the discovery of the τ lepton in 1975. Finding the b gives strong encouragement to search for its anticipated partner, the t quark.
1977 b	T' discovered at Fermilab: an excited state of the $b\bar{b}$ combination. This discovery provided important confirmation of the existence of the b quark and further tests of the quark theory.
1977 c	Strong spin dependence of proton-proton interaction discovered in ZGS experiments using polarized proton beam and target. At 1.5 GeV, protons with parallel spins interact far more strongly than protons with spins opposed. This effect, not yet fully understood, could be the first indication of a new kind of particle composed of six quarks.
1978	Parity violation in neutral currents observed in polarized electron-deuteron scattering at the SLAC linac. This observation of a very small scattering asymmetry provided one of the most striking confirmations of the Weinberg-Salam theory unifying the weak and electromagnetic interactions (1967).

APPENDIX III

APPENDIX III

REFERENCES

REFERENCES

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U.S. Major Accomplishments in High Energy Physics Since 1945

Addendum to June 1979 Edition

1979-82 - Particle Physics connection with cosmology expanding. Early moments in the evolution of the universe are controlled by ultra-high energy particle interactions. The observed preponderance of matter over antimatter in the universe has been related to the unification of weak, strong, and electromagnetic forces and to the phenomenon of CP violation. New cosmological models for the universe have been proposed to explain the origin of large scale effects in the universe as seen today.

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1979 - First evidence for gluon jets at DESY/PETRA (with participation of U.S. groups). The standard model of elementary particles that emerged after the discovery and interpretation of the J/ψ particle asserted that all observed strongly interacting particles were made of charged particles called quarks held together by particles called gluons. Although all strong interactions were attributed to gluons, there had been no direct, active evidence for their existence until these experiments, which observed jets of particles associated with high-momentum gluons produced in electron-positron collisions.

S. L. Wu et al., Z. Phys. C 2, 107 (1979)
R. Brandelik et al., Phys. Lett. 86B, 243 (1979)
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1980 - Discovery of the charmed counterpart of the eta particle, called eta-c, at a mass of 2.98 GeV at SLAC/SPEAR. When the J/ψ particle was discovered, it was hypothesized to be made of a new kind of particle, called a charmed quark, which was heavier than the known quarks, but had identical strong interactions. The hypothesis required that there be a whole new spectrum of particles, including one, the eta-c, lighter than the J/ψ . Its discovery, at the expected mass, was an important confirmation of the existence and properties of charmed quarks.

T. M. Himel et al., Phys. Rev. Lett. 45, 1146 (1980)
R. Partridge et al., Phys. Rev. Lett. 45, 1150 (1980)

1980-82 - Monte Carlo methods in Lattice QCD yield hadron mass estimates from first principles. Quantum chromodynamics (QCD) had become recognized as a viable candidate for a theory of strong interactions because of its successes in describing some very high energy processes. The Monte Carlo calculations were the first direct, if approximate, application of the fundamental theory to that most basic of strong interaction phenomena, the spectrum of particles and resonances. This work is influencing condensed matter physics and is having important consequences for advanced computer design.

M. Creutz, Phys. Rev. Lett. 45, 313 (1980)
D. Weingarten, Phys. Lett. 109B, 57 (1982)
J. Kogut et al., Phys Rev. Lett. 48, 1140 (1982)

1981-84 - Precision measurement of the anomalous magnetic moment of the electron; calculation of the eighth order quantum electrodynamic contribution to the magnetic moment. The anomalous magnetic moment of the electron and its gyromagnetic ratio can both be measured and calculated to extraordinarily high precision, and they permit the most careful comparison of theory with experiment of any physical system. The agreement of theory and experiment is now known to be correct to within a few parts in a trillion for the magnetic moment.

A. Dehmelt et al., Phys. Rev. Lett. 47, 1679 (1981)
T. Kinoshita, Phys. Rev. Lett. 47, 1573 (1981); 52, 717 (1984)

1982 - Electro-weak interference observed in electron-positron collisions at DESY/PETRA (with U. S. teams participating) and SLAC/PEP. This discovery confirms energy-dependent predictions of the unified theory of weak and electromagnetic interactions up to the highest energies available.

B. Adera et al., Phys. Rev. Lett. 48, 1701 (1982)
R. Brandelik et al., Phys. Lett. 110B, 173 (1982)
W. Bartel et al., Phys. Lett. 108B, 140 (1982)

1983 - Discovery of the W, the charged carrier of weak interactions, and the Z, the neutral carrier, at CERN (with participation of U.S. groups). Since the 1950's, there have been attempts to unify the weak and electromagnetic interactions. By the beginning of the 1970's, the very attractive Glashow-Weinberg-Salam theory was formulated, and it enjoyed many successes. Its most definitive prediction was the existence of the W and Z particles. Their discovery is powerful evidence for this theoretical understanding of unified weak and electromagnetic interactions.

G. Arnison et al., Phys. Lett. 122B, 103 (1983); 126B, 398 (1983)

1983 - Discovery of new stable meson with fifth-quark (b-quark) quantum number at Cornell/CESR. This discovery confirms expectations that such particles should exist based on previous discovery of the Upsilon particle at Fermilab in 1977.

S. Behrends et al., Phys. Rev. Lett. 50, 881 (1983)

1983 - Proton decay experiments have succeeded in raising the lower limits on the proton decay lifetime to $\geq 10^{32}$ years. On this basis, the simplest model of grand unification of weak, strong, and electromagnetic forces has been excluded and new theoretical work is proceeding to incorporate the proton decay experimental limits. Before grand unification ideas emerged, theories allowed only for the possibility that the proton (the nucleus of the hydrogen atom) was absolutely stable.

R. Bionta et al., Phys. Rev. Lett. 51, 27 (1983)

1983 - World's first superconducting proton synchrotron at Fermilab accelerated protons to 512 GeV, a world's record, and subsequently to 800 GeV in 1984. This achievement results from an extensive U.S. R&D effort on superconducting magnets and is a forerunner of worldwide use of this technology. A vital component has been the development, construction, and operation of the world's largest helium refrigerator.

1983 - Longer than expected lifetime for B-meson measured at SLAC/PEP which constrains parameters for CP violation and the top-quark mass. This measurement utilizes new high precision experimental techniques to measure directly very short particle lifetimes.

E. Fernandez et al., Phys. Rev. Lett. 51, 1022 (1983)
N. Lockyer et al., Phys. Rev. Lett. 51, 1316, (1983)
D. Klem et al., Phys. Rev. Lett. 53, 1873 (1984)

1983-84 Nuclear dependence of nucleon internal structure seen in lepton beam experiments. These experiments establish that quarks within nucleons in nuclear matter behave differently than quarks in free protons and neutrons.

J. Aubert et al., Phys. Lett. 123B 275 (1983)
A. Bodek et al., Phys. Rev. Lett. 50, 1431 (1983)
R. Arnold et al., Phys. Rev. Lett. 52, 727 (1984)

1984 - For many years there have been several inconsistent experimental results, obtained from various difficult experiments worldwide, on the beta decay of the Sigma Minus hyperon. The latest results from Fermilab are considered to resolve these inconsistencies and to be definitive verification of the Cabbibo theory of beta decay.

S. Y. Hsueh et al., Phys. Rev. Lett. (1985)

1984 - Brookhaven National Laboratory accelerated polarized protons at the AGS to the highest energy yet attained-16 GeV. First experiments studied the elastic scattering of unpolarized protons on a polarized target. This scattering was found to depend very strongly on the spin alignment. How these results depend on the quark structure of protons is yet to be determined.

1984 - Observation at Cornell/CESR of the F meson, carrying both charmed and strange quarks, at 1970 MeV mass. This elusive particle was predicted to exist at about this mass by dynamical theories of heavy charmed quarks.

1984 - Development of superstring theories that promise unification of all forces including gravity. The goal of finding a unified description of all the fundamental interactions in nature has been a powerful theme in elementary particle physics. Superstring theories, although their development is just in its infancy, have the possibility for the first time of providing such an "ultimate theory of everything."

M. B. Green and J. H. Schwarz, Phys. Lett. 149B, 117 (1984).

1984 - Radio Frequency Quadrupole (RFQ) linac first used in Brookhaven National Laboratory. This table-top-size facility accelerates polarized particles to 750 kilovolts for injection into the 200 MeV linac which in turn serves as an injector for the 30 GeV Alternating Gradient Synchrotron. The RFQ serves the function of the very large and relatively unreliable Cockcroft-Walton electrostatic pre-injector and marks the beginning of a world-wide conversion to RFQ's.

PROGRAM ACCOMPLISHMENTS AT THE NUCLEAR PHYSICS ACCELERATOR FACILITIES[1]

ATLAS
Argonne National Laboratory
Argonne, Illinois

Scientists at Argonne have been instrumental in identifying the contributions of second-order collective excitations to the single-particle states made in transfer reactions. They have been leaders in the effort to understand the limits governing the fusion of two complex nuclei at intermediate energies. The dependence of incomplete fusion on projectile type and on mass asymmetry in the entrance channel have been established. They have contributed heavily to the investigation of resonance phenomena in di-nucleon quasi-molecular formation. Of special interest has been the work on collective states which investigates the way that nuclei deform, sometimes prolate and sometimes oblate, under the addition of large amounts of angular momentum. The prominence of quasi-elastic reaction channels and its influence on other reaction channels has been established for very heavy collision systems.

TANDEM/AGS HEAVY ION FACILITY
Brookhaven National Laboratory
Upton, New York

Pioneering studies of heavy ion induced direct reactions encompassing inelastic scattering and particle transfer have led to a quantitative theory for the reaction mechanism. The gamma-ray spectroscopy of very high spin states in many new isotopes has led to a better understanding of how collective nuclear behavior changes over to independent particle behavior as higher spins and excitations are reached. The complex structure of back angle elastic scattering of heavy ions has been extensively studied at Brookhaven. High energy resolution studies of heavy ion radiative capture unexpectedly demonstrated that giant resonances, both quadrupole and dipole, could be built on highly excited nuclear states.

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[1] This material was excerpted from DOE's publication entitled Nuclear Physics Accelerator Facilities, January 1985.

CYCLOGRAAFF ACCELERATOR
Triangle Universities Nuclear Laboratory
Duke University
Durham, North Carolina

TUNL measurements of the fine structure of analog states and of amplitude correlations are unique. These are the only charged-particle data of sufficient quality to test new statistical theories and provide valuable information to complement neutron studies. These measurements have provided protron strength functions obtained from individual resonances. The charged-particle program has recently used polarized deuteron beams to initiate reactions which probe the nonspherical nature of the wave function for ^{4}He. On the tandem accelerator, an efficient three-stage bunching system has been constructed which facilitates measurements with pulsed, polarized beams. Up to 80 percent of the DC beam can be obtained in pulses on target with 2 ns burst width. A major achievement of the capture program in the past few years has been the production of high quality, polarized fast-neutron data, using this pulsing system, from which the collective E2 strength in the capture reaction can be deduced. In addition, Cyclograaff beams have been used to study the nature and properties of giant resonances built on highly excited states. The neutron program has provided neutron polarization information for the characterization of the spin-orbit interaction of neutrons with nuclei ranging from ^{1}H to ^{208}Pb. As a result, improved neutron-nucleus optical models have been developed to describe cross-section and polarization data over the 8-40 MeV range.

During the existence of this laboratory, 131 graduate students have earned Ph.D. degrees in experimental nuclear science. A large fraction of these are now in academic institutions and national laboratories. At present, some 29 graduate students are in residence at TUNL and working towards the Ph.D. degree.

SUPERHILAC/BEVALAC
Lawrence Berkeley Laboratory
Berkeley, California

The Bevalac scientific program has been able to delve deeply into new regions of nuclear equations of state by making high-temperature compressed matter. Measurements have been made of the size of "hot spots" created when heavy nuclei collide. In addition, studies of nuclear collisions in which all (100 or more) secondary charged particles are characterized have revealed the phenomena of collective energy flow--a phenomena in which high pressures deflect many particles away from the beam direction. Other studies of central collisions of relativistic heavy ions have uncovered a puzzle in the production of mesons. Pions are produced several times less abundantly than predicted, but kaons are produced several times more copiously than expected.

The SuperHILAC has long been a world center for research with very heavy ion beams. The pioneering program in deep-inelastic scattering studies continues with a new generation of particle and gamma-ray detectors and coincidence experiments, and the relationship between the evaporation of particles and fission is also being explored. Electromagnetic moment measurements via Coulomb excitation and Doppler-shift techniques are providing stringent tests of today's nuclear models. Heavy-element isotopes and nuclei near the proton drip line are being studied with new isotope separators.

88-INCH CYCLOTRON
Lawrence Berkeley Laboratory
Berkeley, California

Recent research accomplishments include: (1) observation of a new radioactive decay mode--beta-delayed two proton emission from the exotic nuclei ^{22}Al and ^{26}P; (2) discovery of a giant dipole resonance built on highly deformed, high angular momentum states; (3) observation of nuclei with moments of inertia approaching the rigid-body value; (4) studies of the emission of heavy, complex fragments by highly excited nuclei; (5) the separation of transfer and breakup processes in heavy ion reactions utilizing a very large solid angle plastic scintillator array; and (6) studies of the properties of the transfermium nuclei produced by heavy ion beams and a highly radioactive target of einsteinium.

CLINTON P. ANDERSON MESON PHYSICS FACILITY (LAMPF)
Los Alamos National Laboratory
Los Alamos, New Mexico

Recent research accomplishments at LAMPF include: (1) use of the pion charge exchange reactions to excite isotopic analog states, i.e., states of the nucleus showing strong symmetry between neutrons and protons; (2) discovery of an isotopic monopole giant resonance (i.e., neutron-proton breathing mode oscillation); (3) first observation of free muonium; (4) observation of the Lamb shift in muonium; (5) a stringent new limit on the rare decay, muon decaying to 3 electrons, namely 1×10^{-10}; (6) an experimental demonstration of the need for using the full Dirac wave function to describe polarized nucleon-nucleus scattering; and (7) evidence found with the pion double-charge-exchange reaction on ^{14}C at 50 MeV which showed that a six-quark cluster component is required in the nuclear wave function.

BATES LINEAR ACCELERATOR CENTER
Massachusetts Institute of Technology
Middleton, Massachusetts

Recent research achievements include: (1) stringent tests of nuclear mean field theories by precision measurements of electromagnetic structure near closed shells and by the systematic study of nuclear stretched states (elementary excitations resulting from the maximum possible angular momentum transfer in a one-step process); (2) demonstration of the importance of meson exchange currents in the nucleus, particularly in the short distance structure of nuclear magnetization; (3) measurements of the nuclear response functions at large energy transfer resulting in total strengths unexplainable in the conventional framework of static nucleons; (4) measurement of the nuclear interaction of the lowest nucleon excited state (the delta) by means of coherent photoproduction of neutral pions, photon scattering, and deep-inelastic electron scattering; (5) studies of the mechanism for pion production in nuclei; and (6) (e,e'p) coincidence studies of proton knockout which demonstrate the importance of multinucleon contributions to the electromagnetic current.

HOLIFIELD HEAVY ION RESEARCH FACILITY
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Changes in nuclear shapes, the role of rotational alignments, and the crossing of bands have been established through studies of discrete high-spin states and states in the continuum that are populated in both compound nuclear and transfer reactions. Lifetimes measured for the discrete states are especially important in determining their character. Isomer shifts and quadrupole and magnetic moments have been determined for the ground and isomeric states of short-lived Tl nuclei from the hyperfine structure resulting from laser-induced optical pumping. Gamma-ray decay branches have been measured from the giant quadrupole resonance in ^{208}Pb and provide, for the first time, microscopic composition of the resonance. The sharing of excitation energy among fragments has been explored under varying conditions between the two extremes of equal energy and of temperature equilibration. Evidence for a localized hot source in the nucleus has been established from small angle p-p correlations and from spectra of energetic protons and neutrons emitted in heavy ion induced reactions. The decrease of fusion cross section and corresponding increase in incomplete fusion channels have been studied as a function of energy and correlated with the impact parameter and entry channel. Lifetimes of reaction processes around 10^{-18} seconds have been measured through blocking of emitted particles by crystal lattices. Observation of neutral pi mesons at projectile energies of 25 MeV/AMU (the lowest energy to date for production of pions) has established the importance of cooperative action of many nucleons.

TEXAS A&M CYCLOTRON
Cyclotron Institute
Texas A&M University
College Station, Texas

Texas A&M scientists have conducted an extensive series of high precision studies of giant resonance states in nuclei. From these experiments, giant monopole resonances (the entire nucleus contracts and expands as a unit) and their possible splitting have been identified and measured providing new and unique information about nuclear compressability. In a systemmatic study of nuclear stability, the masses of nuclei near the limits of particle stability have been determined and the need for a charge-dependent nuclear force demonstrated. Experimenters at Texas A&M have demonstrated that "massive transfer" (a large part of the projectile transfers to the target) occurs quite generally in heavy ion reactions and populates nuclear states within a narrow angular momentum window, providing a new tool for nuclear spectroscopy. Studies of x-ray emission in heavy ion collisions have demonstrated the importance of fast electron rearrangement in highly ionized atoms and have led to the discovery of a resonant electron transfer process in ionic solids. The protocol for treatment of human cancer with neutron therapy was established in a program which treated over 500 patients in an 8-year period. Texas A&M scientists were the first to obtain quantitative determination of oxygen and boron at the 10^{-11} grams per gram of sample and 10^{-13} grams per gram of sample levels, respectively, using charged particle activation analysis and the first to profile gold by means of heavy ion backscattering. The Cyclotron Institute has been a significant source of scientific manpower with 45 students receiving Ph.D. degrees and 23 receiving M.S. degrees from cyclotron-based research from 1970 to 1984. Fifty-four scientists received their postdoctoral training during the same period.

TANDEM/SUPERCONDUCTING BOOSTER ACCELERATOR
Nuclear Physics Laboratory
University of Washington
Seattle, Washington

Recent difficult and innovative experiments include studies of the weak nucleon-nucleon and electron-nucleon force by nuclear and atomic parity mixing, of nucleon charge conservation, and of the breakdown of isospin symmetry in nuclei. High precision investigations of deviations from Rutherford scattering in sub-Coulomb heavy ion scattering have permitted the observation of the dynamic effects of relativistically invariant wave equations as well as the effects of electron screening and dynamic nuclear polarization. Other examples of recent research include the study of the effect on atomic ionization of "time delay" in nuclear reactions, evidence which indicates the absence of the "low 1-value window" predicted in heavy ion fusion reactions, and the demonstration that back-angle analyzing powers observed in the inelastic scattering of polarized protons to the continuum arise from orbiting.

TANDEM VAN DE GRAAFF ACCELERATOR
A.W. Wright Nuclear Structure Laboratory
Yale University
New Haven, Connecticut

Recently, the laboratory reported: experimental evidence for the first supersymmetry observed in nature centering on ^{193}Ir; an entirely new form of dipole nuclear collectivity; a spectrum generating algebraic approach to the understanding of nuclear molecular interactions; nuclear astrophysical cross sections pertinent to the formation of the solar system; and emission of monoenergetic positrons in supercritical Coulomb fields.

In applied areas, fundamental new information on the physics of the sputtering process induced by both keV and MeV beams has been reported as well as new techniques for beam induced adhesion of thin films, contacts, and the like, of importance in microelectronics. The quantitative, nondestructive characterization of hydrogen in solids that was reported several years ago has been further refined for use in many areas of technology including fusion energy research.

For more than 20 years, Yale has graduated more Ph.D.'s in experimental nuclear physics than any other institution in the world. Currently, 31 graduate students are working in the Wright Laboratory.

SOME MAJOR U.S. ACCOMPLISHMENTS IN NUCLEAR PHYSICS SINCE 1945

Prepared by:

Division of Nuclear Physics
U.S. Department of Energy
Washington, D.C. 20545
March 15, 1985

SOME MAJOR U.S. ACCOMPLISHMENTS IN NUCLEAR PHYSICS SINCE 1945

1945-1949

Nuclear shell model successfully describes systematics of low lying nuclear states in spherical nuclei throughout the periodic table. In this picture nucleon interactions within a nucleus are assumed to depend mainly on an average potential generated by all the other nucleons. Inclusion of a spin-orbit component in the potential made this model reproduce the order of the single particle levels in the nucleus. Other spectroscopic data such as binding energies of closed shell nuclei and spins of nuclei find a unified explanation in this model.

Pion is discovered in cosmic rays and identified as the particle postulated by Yukawa as the carrier of the strong force. The long range part of the nuclear force is still theoretically described in terms of the exchange of pions.

1950-1959

Nuclear optical model sucessfully represents nuclear scattering as a wave moving through a complex potential. Along with its generalizations, the distorted wave Born approximation and the coupled channels Born approximation, it forms the basis for quantitative experimental studies of nuclear properties such as size, shape, and excited state configurations.

Collective model of the nucleus is developed to describe nuclear excitations involving rotation and vibration. The idea that some nuclei could be intrinsically deformed in their ground state gave the conceptual basis for understanding their low lying excitations.

Electron scattering program on nuclei at Stanford and at other electron accelerators provide precision measurements of nuclear sizes and shapes (charge and current distributions) for nuclei throughout the periodic table.

Discovery of the neutrino confirms the existence of the massless, uncharged particle that was postulated in 1933 in order to understand the observed properties of nuclear beta decay.

Prediction of parity non-conservation confirmed in the detected angular distribution of beta decay electrons from a polarized Cobalt-60 nucleus. This result showed that the laws of physics need not be invariant under space reflection.

Helicity of the neutrino is determined by the detection of the nuclear gamma decay of Samarium-152 subsequent to its production in beta decay from Europium-152. This determination of the "left-handed" nature of the neutrino was very important in the understanding of the weak force.

Nuclear astrophysics provided the understanding of the basic mechanism of the evolution of the structure of the elements of the universe. Detailed development of the scheme of nuclear synthesis in stars continues.

Nuclear many body theory achieved crucial technical breakthroughs to allow it to treat the strongly interacting nucleons in a theory of nuclear matter. Three decades later the difficulties of this field have been sufficiently overcome to allow the seperation of two-body and three-body effects.

1960-1969

Nuclear reaction theory develops on a number of fronts to the point where it can be used to obtain spectroscopic information from direct nuclear reactions such as inelastic scattering and nucleon transfer.

Isobaric analog states are discovered. Sharp nuclear resonances seen in proton reactions correspond to a new type of nuclear state which is identical to a neighboring nucleus state except that a neutron is replaced by a proton.

New elements and new isotopes are discovered in ongoing nuclear science programs at a number of laboratories.

User accelerator facilities are developed. A new generation of large nuclear physics accelerators are developed, including sector focused cyclotrons, proton and electron linacs, and heavy ion tandems. These shared facilities set the stage for the nuclear physics discoveries of the 1970's and 1980's.

Shell effects in deformed nuclei were worked out in a theoretical model to understand deformed nuclei in terms both of a liquid drop and shell model corrections. This model led to the prediction of isomeric states decaying by spontaneous fission and to a quantitative description of the fission process.

1970-1979

Discovery of the giant quadrupole resonance began a new effort to study the fundamental vibrations that can be excited in the nucleus as a whole. Subsequent studies of giant resonances included the first measurements of nuclear compressibility.

Intermediate energy nuclear physics became a dominant subfield with the opening of the Los Alamos Meson Facility which provided intense high energy proton beams and secondary beams of pion, muons, and neutrinos. The role of the pion within the nucleus has been elucidated.

Interacting boson model is developed to provide a unification of different types of nuclear collective excitations (rotation, vibaration, and symmetric behavior that falls between these two extremes).

Transuranic elements up to element 106 are discovered at Berkeley by irradiating heavy targets with heavy ions. Discovery of tranuranic elements continues a program which has been active for decades.

Solar neutrino experiment challenged the understanding of the nature of the neutrino and of solar models. The unexpectedly small number of neutrinos observed is still not completely understood.

Deep inelastic scattering of heavy ions is observed. Study of this process, in which two heavy nuclei collide violently but do not fuse, has been important in the development of an understanding of nuclear mass and energy transfer mechanisms.

1980-1984

Role of quark substructure of nucleons on nuclear properties is measured at SLAC. Electron scattering gives results complementary to the European Muon Collaboration (EMC) result, namely that the quark structure of nucleons in nuclei differs significantly from that in free nucleons.

Sub-threshold pion production observed in heavy ion reactions demonstrates a surprising collectivity in the energy taken from the nucleons to produce the pions.

Quark-gluon plasma is predicted. Based on the current quantum chromodynamic (QCD) theory of the strong interaction, it was predicted that in a modest nuclear volume (e.g. order of a hundred nucleons) at very high densities and temperatures, it should be possible to effectively dissolve the underlying nucleon substructure of nuclei and create a plasma of the quark and gluon constituents of nucleons.

Giant Gamow-Teller strength in nuclei is measured using the (p,n) reaction. The amount of strength seen suggests the necessary role of the delta particle in nuclear structure.

Electron type neutrino elastic scattering from electrons is observed at the Los Alamos Meson Facility. This development provides a new capability for sensitive tests of electroweak theories.

Accelerator technology advances physics capabilities at a number of laboratories: the Bevelac accelerates uranium to relativistic energies; the Argonne ATLAS superconducting accelerating cavities become operational; LAMPF achieves beams of 1.2 mA, 20% above design current.

Nuclear liquid flow is observed in relativistic heavy ion experiments.

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Molecule	A unit of matter made up of two or more atoms.
Muon	A particle in the lepton family with a mass that is 207 times the mass of the electron and having other properties very similar to those of the electron.
Negative charge	The opposite of positive charge. Electrons carry negative charge. Protons carry positive charge.
Negative ion	Ion that has more electrons than protons.
Neutron	An uncharged particle, within the atom's nucleus, with a mass slightly greater than that of the proton. The neutron is a strongly interacting particle and a constituent of all atomic nuclei except hydrogen.
Neutrino	An electrically neutral, perhaps massless, particle in the lepton family. The only force experienced by neutrinos is the weak force. There are at least three distinct types of neutrino: one associated with the electron, one with the muon, and one with the tau.
Nucleon	A proton or neutron.
Nucleus	The central core of an atom, made up of neutrons and protons held together by the strong force.
Particle	A constituent of matter.
Photon	A quantum or pulse of electromagnetic energy. A particle, perhaps massless, that carries the electromagnetic force.
Pion	One of the family of mesons. It is thought to be the main mediator of the strong force in nuclei. Pions can be electrically charged (positive or negative) or neutral, and have a mass that is about 270 times that of the electron.
Positive ion	Ion that has fewer electrons than protons.
Positron	The antiparticle of an electron.
Proton	A particle with a single positive unit of electrical charge and a mass that is approximately 1,840 times that of the electron. It is the nucleus of the hydrogen atom and a constituent of all atomic nuclei.