An Introduction to High-Energy Physics and the Stanford Linear Accelerator Center SLAC*

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I. Introduction

The type of research done at SLAC is called High Energy Physics, or Particle Physics. This is basic research in the study of fundamental particles and their interactions. Basic research is research for the sake of learning something. Any practical application cannot be predicted, the understanding is the end in itself. Interactions are how particles behave toward one another, for example some particles attract one another while others repel and still others ignore each other. Interactions of elementary particles are studied to reveal the underlying structure of the universe.

II. Ancient History

People have been wondering what the basic stuff of the universe is for a long time. Some of the ancient Greek philosophers believed that everything in the universe was composed of only four things, earth, air, fire, and water - which they called *elements*; they believed that by taking various combinations of these elements one could construct anything. Another school of philosophy believed that everything was made of tiny indivisible things called atoms. There were wood atoms, water atoms, and so on. A great disadvantage of philosophy is that it is passive, the theories are not tested. Physics, and science in general, is ultimately an *experimental science*, that is, no theory can survive if it fails to predict what happens in the laboratory. This self-correcting method is one of the great strengths of science.

III. The Renaissance

It wasn't until the Renaissance period that people began to experiment carefully with the world about them. The work of the Chemists in the eighteenth and nineteenth century led to the atomic theory of matter and the eventual discovery of 92 naturally occurring elements. Various combinations of the 92 elements could account for all the known substances. Physicists like to believe that the underlying structure to the universe is simple, that is, only a few particles and interactions. While 92 elements is many more than the Greeks had, and therefore not as esthetically pleasing, scientists appeared to have a good understanding of the basic constituents of the universe.

IV. Early Twentieth Century

By the early part of the twentieth century physicists started to make their mark on our knowledge of the fundamental structure of the universe. An early contribution was the discovery of electrical charges in the atom. Atoms now appeared to have negatively charged particles (called *electrons*) in them which could be removed. The rest of the atom had to be posi-

tively charged in order to maintain overall electrical neutrality of atoms. In England, in 1911, Rutherford performed an experiment which consisted of shooting charged particles (in this case ionized helium atoms) at a very thin foil of gold and noting the deflection of the particles after they passed through the foil. To everyone's great surprise the scattering angles were such that the positive charge appeared to be concentrated at the center of the atom (about 1/100,000 the size of the atom) and to have almost the entire weight of the atom. This was the beginning of the nuclear theory of the atom, that is, a small dense positively charged core (of *protons*) surrounded by a cloud of negatively charged electrons.

The apparatus shown here schematically was used in 1911 by Rutherford to study the structure of the atom. The beam consisted of a narrow stream of alpha particles (ionized helium atoms) which emerged from a radium source through a small hole in a block of lead. The beam was directed against a thin foil of gold only a few hundred atoms thick. Most of the alpha particles passed straight through the foil, but some were deflected, or scattered, in collisions with the gold atoms. The detector consisted of a zinc sulfide screen and a small microscope mounted together on a frame that could be rotated to different angles. When a charged particle such as an alpha particle strikes the zinc sulfide screen there will be a small flash of light which a person could see in a darkened room through the microscope.

Later, in 1932, an electrically neutral particle, the *neutron*, was also found to inhabit the nucleus. The basic constituents of matter in the early 1930's appeared to be the electron, proton, and neutron. Thus, only 3 entities were needed to make anything, a very simple formula indeed. Also in 1932 was the experimental discovery of *anti-matter*, in this case the *positron*, or anti-electron. This led physicists to believe that for every particle there is an anti-particle. Anti-particles have certain properties which are exactly the opposite to those of their corresponding particles. For example, electrons have a negative electric charge and positrons have a positive electric charge.

V. The Four Forces

There are four known forces, or interactions, that can act between particles. The effect of the force depends on the type of particles involved and on the distance between them. Each force has a range, that is, a distance over which the force can be felt by another particle. The Strong force is what keeps the protons and neutrons together in the nucleus and as we shall see even keeps the protons and neutrons in one piece. The range of the Strong force is about $1/10$ of a trillionth of a centimeter. Any electrically charged particle will interact with any other charged particle via the Electromagnetic force. The Electromagnetic force has an infinite range. The Weak force is responsible for certain types of nuclear decays. The range of the Weak force is extremely short, only about $1/10,000$ of a trillionth of a centimeter. All particles respond to the Gravitational force which has an infinite range. This force is over a trillion trillion times weaker than the Electromagnetic force. Because the Gravitational

force is so much weaker than any of the other forces its effect can be ignored in High Energy Physics applications. The reason gravity is so pervasive in our everyday lives is that almost everything around us is electrically neutral so that we don't feel the effects of the Electromagnetic force. Also the huge number of particles in the earth make up for the weakness of the Gravitational force.

VI. Wave-Particle Duality

When physicists looked into the atom they found the nucleus and when they looked into the nucleus they found protons and neutrons. In order to probe such small distances one needs a very good microscope. An ordinary microscope works on the following principle; visible light is aimed at an object, the light scatters off the object and is focused into the eye. However, there is a limit to how small an object one can see. The limit depends on the wavelength of the light. If the object is much smaller than the wavelength of the wave then the wave won't see the object, it doesn't scatter enough. Then, to look at objects which are nuclear or sub-nuclear in size one needs to use a wavelength much smaller than that of visible light. One could use very short wavelength light, but such short wavelength light is not readily available. One very important discovery of the 1920's was that so-called "particles" have so-called "wave" properties, and vice-versa. The distinction between particles and waves is now fuzzy, it depends on how you look at them. It turns out that the higher the energy a particle has the shorter the wavelength it has. Thus, **high energy particles** can be used to probe very small objects.

How a microscope works. A visible light source illuminates a specimen on a microscope slide (left). If there are structures in the specimen which are comparable in size to the wavelength of the light then the light will scatter by a large angle. The scattered

light is then focused into an eyepiece, thus providing a magnified image. In a similar way, particles can be used as a probe (right). High energy particles have very short wavelengths and so can "see" very small objects.

VII. The Need for Particle Accelerators

In the 1930's and 1940's particle accelerators (cyclotrons and electrostatic generators) were used to study the nucleus, the particle energies needed to do this are in the range of millions of electron-Volts. To get an idea of what an electron-Volt is, consider a picture aloft in a color TV; when the electrons hit the screen their energy has been increased by about 40,000 electron-Volts. In order to do sub-nuclear physics one needs much higher energies. One naturally occurring source of very high energy particles are cosmic rays. Many experiments were done and are still being done with these high energy particles from space. A typical experiment might consist of a block of material with properties similar to that of photographic film which is sent aloft in a balloon. When the balloon is lowered, the material is etched and examined under a microscope to see how the cosmic rays interacted with the material. Many particles were discovered using cosmic rays. The problem with cosmic rays are that they have a very low intensity and their energies are spread over a wide range. These problems were overcome with the advent of the high energy particle accelerator. A particle accelerator is a device which increases the energy of, or accelerates, particles. The high energy particles are in a beam or in bunches under the control of the experimenter, who can direct it as needed to various experiments.

VIII. SLAC Pre-History

In the late 1940's and early 1950's work on a linear electron accelerator powered by microwave amplifiers was underway on the Stanford campus. Stanford Professors Hansen and Ginzton were instrumental in these early days of electron accelerators. The culmination of the work at the Stanford campus resulted in the 300-foot-long "Mark III" accelerator (1 billion electron Volt maximum energy). The experiments done at the Mark III under the direction of Stanford professor Robert Hofstadter resulted in his being awarded the Nobel Prize. His experiments used the high energy electron bunches from the Mark III for scattering off of protons and neutrons. These experiments measured the size of the proton.

During the 1950's plans for a much larger linear accelerator at Stanford were developed. In 1959 President Eisenhower recommended to the Congress that the Federal Government finance construction of what was to be SLAC's two-mile accelerator. Ground breaking took place in 1962 with a budget for construction of \$114 million. The accelerator was completed in 1966 on a 480 acre tract of Stanford University land leased to the government. SLAC is operated

by Stanford University for the Department of Energy. There are very few laboratories in the world which do High Energy Physics. SLAC has the longest linear accelerator in the world and can still make the highest energy intense electron beams in the world.

IX. The Linear Accelerator

There are two kinds of high energy accelerators in use today, the synchrotron (circular) and the linear accelerator. The latter is the type in use at SLAC and will be discussed here. To get high energy particles, energy must be transferred to the particles. This energy usually comes from microwaves. The microwaves come from a device called a *klystron* (*klyzo* is the Greek verb for the breaking of water on the beach). The klystron was invented at Stanford by the Varian brothers. The klystron is a very important part of radar technology. The high power microwaves from the klystron travel through a "waveguide" (a metal pipe) until they reach the accelerator tube. The microwaves enter the accelerator tube which resembles many tuna fish cans stacked together (80,000 copper cylinders and disks for SLAC's 2-mile long accelerator). Each klystron supplies the microwave power for a certain length of the accelerator. At SLAC, 240 high power klystron tubes placed every 40 feet provide the power to accelerate bunches of electrons up to an energy of more than 30 billion electron Volts. In principle one could build a linear accelerator even longer and get even higher energy (over 60 billion electron-Volts in 4 miles, etc.), the limitations being money, real estate, and power.

The interior of the Klystron Gallery, the longest building in the world. There are 240 klystrons (barrel shaped object) spaced every 40 feet for the entire length of the accelerator.

Schematic drawing of two of the forty-foot-long accelerator stages.

Let's follow in detail the 10 millionths of a second journey of a typical electron through SLAC's accelerator. The electrons come from a hot wire filament similar to the one in a TV set. The heat boils the electrons off the filament. A positively charged grid then attracts the electrons away from the hot wire so that they can be formed into a bunch. Several thousand bunches are formed for every millionth of a second this electron gun is turned on. The gun can fire up to 360 times per second. After about 20 feet the electrons have a speed over 99 percent the speed of light. The rest of the journey doesn't add much speed (the speed of light is never attained by massive particles like the electron), just energy. This non-intuitive phenomenon is a consequence of Einstein's *Special Theory of Relativity*. After 40 feet the electron bunch has been properly focused and shaped (to about a millimeter in length) and is ready to enter the accelerator. The electron bunch now gets its kick via microwaves from each of the 240 klystrons in turn. Each klystron feeds its microwaves into the accelerator in four locations spaced 10 feet apart. The reason for this is that after 10 feet just about as much energy as possible has been extracted by the electrons or gone into heating the accelerator pipe. The old wave is taken out and a fresh one enters the accelerator pipe. Each klystron must be timed so that its microwaves will arrive at the same time as the electron bunch. This basic 40 foot cycle is repeated until the electrons reach the end of the accelerator.

Cut-away of the accelerator pipe. Microwaves are slowed down by the presence of the discs to the speed of the electron bunches. The electron bunches pass through the hole, absorbing energy from the microwaves while travelling between the discs.

The accelerator housing as it actually appears. The accelerator pipe is wrapped inside the insulating material. The large cylinder at the bottom is for structural support.

X. Early Experiments at SLAC

By the late 1960's experiments with accelerators had found hundreds of fundamental, or elementary particles. This large number was distressing to physicists who like to believe that things are fundamentally simple. Also at this time, SLAC was operating the two-mile long accelerator. The early experiments at SLAC were called *fixed target experiments*. In this type of experiment, the particles coming from the end of the accelerator are steered by electromagnets to one of two large buildings ("End Stations"). In these buildings are housed the *target* and the *detector*. The target for these types of experiments usually consists of liquid hydrogen, which is almost entirely composed of electrons and protons. A typical experiment consisted of a target and beyond that a large detector weighing perhaps thousands of tons. The detector is sensitive to the passage of certain types of particles. By swinging the detector to different angles one can study the *angular distribution* of the outgoing particles. In this way

a "picture" of the target can be made in a similar way that a microscope does. Another type of detector is to have the liquid hydrogen as the target and the detector. This is possible because charged particles will leave a visible trails in the liquid hydrogen which are later scanned to see if any interactions occurred. These early experiments showed that the proton and neutron had structure; even **they** were not fundamental! Theorists soon came up with a theory that was able to account for all the hundreds of particles, including the proton and neutron, using only three building blocks. These building blocks were new particles called quarks. Various combinations of two or three quarks or anti-quarks could account for all the known particles except for the few particles related to the electron (which still seem to be fundamental). A great breakthrough had been made, a great leap into a deeper level of understanding.

This type of experiment revealed the structure of the proton. The large object on rails is the detector. The target is located in front of the small lead wall. By swinging the detector to different angles a "picture" of the target is obtained.

In High Energy Physics there is always a great push for higher energies in order to search for ever more massive fundamental particles. A drawback to the type of fixed target experiments done at SLAC is that much of the energy of the colliding electron goes into the motion of the final state particles. Only some of the energy goes into the possible production of new particles. This again a result of Einstein's *Special Theory of Relativity*; $E = mc^2$ means it is possible to create a new particle of mass m if the energy E is supplied. If a 20 billion electron-Volt electron strikes a stationary proton

only about 6 billion electron-Volts (30 % "efficiency") of energy will be available for new particle production. In order to get around this problem, which gets worse as the energy gets higher, physicists sought a more efficient method. If one could collide particles and anti-particles of equal energy head-on, then the energy available for the creation of high mass particles is just the sum of the two energies. The machine that was built to do this is called a **storage ring**.

XI. The Storage Ring

A storage ring is a roughly circular vacuum pipe in which bunches of particles are constrained by magnets to circulate in. One of the first and certainly one of the most successful storage rings was built at SLAC. The Stanford Positron Electron Asymmetric Ring (SPEAR) began operation in 1973. SPEAR is about 200 meter in circumference. In SPEAR a pencil size bunch of electrons circles clockwise at nearly the speed of light with energies up to 4 billion electron Volts per particle. Circulating counterclockwise is a bunch of positrons. Since positrons are anti-matter and we live in a matter universe SLAC must produce its own anti-matter. This is done by inserting a special target into the accelerator about 2/3 of a mile from the beginning. After the electrons strike the target some of the particles coming out the other side are positrons which are then accelerated the rest of the way down the accelerator. At the end of the accelerator the electron or positron bunch is steered with powerful electromagnets into its injection line, one for positrons and one for electrons. From the injection line the bunch enters SPEAR. Once inside SPEAR the electron bunch is bent around the ring again by electromagnets. After SPEAR has been filled with its complement of electrons and positrons the ring magnets are tuned so that the bunches will pass through each other. The bunches can circulate for several hours after which time it becomes uneconomical to continue the experiment due to loss of particles from the bunches. This loss is due to misfocusing and collisions with residual gas molecules in the vacuum pipe and not due to electron-positron collisions. When the intensity becomes too low the SPEAR operators ask the accelerator operators to "top up" SPEAR with new particles from the accelerator and the experiment resumes.

When the bunches pass through each other (each bunch contains billions of particles) it is possible for an electron to come close enough to a positron so that they will *annihilate* forming, for a brief moment, pure energy. This pure energy quickly rematerializes into pairs of particles. The pair of particles may go through several transformations resulting in a dozen or so par-

In a storage ring, such as SPEAR, electrons and positrons circulate for hours at a time at nearly the speed of light. Detectors are placed at the two places in the ring where the bunches collide.

ticles reaching the detecting apparatus. A detector sensitive to the passage of most particles surrounds the "interaction region". Most particles will leave some kind of trail telling where its been and how it interacted with the detector material. This information is recorded electronically and later analyzed by computer. Since many kinds of pairs can be produced initially one must use a computer to help select the sample that one is interested in looking at. The analysis involves looking at various quantities for each "event" in order to determine what happened at the interaction point. By analyzing a large number of events, comparisons can be made with theory and any differences noted. The differences or agreement with the theory can indicate

the inadequacy or adequacy of the theory.

SPEAR has made many contributions to our understanding of the sub-nuclear world. Two discoveries in particular stand out. One year after SPEAR started running Burton Richter and his collaborators discovered a new particle which is called the ψ . The ψ appeared to contain a new kind of quark. Previously only 3 quarks were thought to exist (theorists now think there are 6 quarks with 5 discovered so far). Professor Richter shared the Nobel Prize for co-discovering the ψ and for his work in the development of SPEAR. Also, Martin Perl and his collaborators found a particle similar to the electron but much more massive. He called the particle the τ , the Greek letter "tau".

With the great success of SPEAR physicists decided to build a much larger storage ring. This ring was finished in 1979 and is called PEP (Positron Electron Project). PEP is a mile and a half in circumference and has six interaction regions, or places where the electron-positron collisions occur. The energy of the electrons and positrons in PEP is about 15 billion electron-Volts for a combined energy of 30 billion electron-Volts. Thus far no truly unsuspected results have come from PEP, but the precision measurement of certain quantities and searches for very rare or exotic processes continues.

In PEP, 3 bunches of electrons and positrons circulate at nearly the speed of light. There are over 400,000 bunch crossings per second at each of the six interaction regions.

If an electron and positron get close enough to each other they can annihilate and form, very briefly, pure energy (top). This energy is unstable and very quickly rematerializes into pairs of particles, one particle and one anti-particle (bottom). One cannot know beforehand what type of pair will rematerialize, only the probability that a particular type will rematerialize. If quark pairs are produced, they will undergo several transformations before reaching the detector.

This is a computer drawn reconstruction of an "event" in the MAC (MAGnetic Calorimeter) detector at PEP. The electrons are going into the page and the positrons are coming out. This event has all the characteristics of an electron-positron annihilation which rematerialized into quark pairs which then transformed into many more particles before reaching the detector. The innermost part of MAC is sensitive to charged particles. The computer has drawn lines from

the annihilation point to the edge of the "drift chamber", following the trails of the charged particles. The tracks curve because of a magnetic field in the chamber. Outside the drift chamber are two types of energy measuring devices (calorimeters). The location of the stubby lines indicates that a particle passing through that region has lost energy there. The amount of energy lost is given by the length of the line, the longer the line the more energy.

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A positron bunch is denoted by e^+ , an electron bunch by e^- . The Linac is the two-mile linear accelerator.

1. First a positron bunch and two electron bunches are extracted from the damping rings. The damping rings are for shaping the bunches for SLC. 2. The trailing electron bunch is extracted for production so the next positron bunch.
3. The remaining electron and

positron bunches are separated by magnet. into their respective arcs. 4. After being focused to a small size the bunches pass through each other producing occasional interactions which are recorded by the surrounding detector. 5. The positron bunch is reinjected into the Linac. 6. The electron gun injects two bunches into the damping ring completing the cycle.

XII. SLC

High Energy Physics is a very rapidly advancing field, the quest for higher energy requires a laboratory like SLAC to keep an eye on the future. To this end SLAC has started development of a new type of colliding beam machine. This new machine will be called the SLC Linear Collider. A collider is not the same as a storage ring, the particle bunches are used only once. Modification to the 2-mile long accelerator will raise the energy of its bunches to 50 billion electron-Volts. The cycle for the SLC starts in two small storage rings, one for electrons and one for positrons. First a positron bunch is extracted from its storage, or "damping" ring, then two electron bunches are extracted from their ring. After travelling two-thirds of the way down the accelerator the trailing electron bunch is extracted and sent to a positron production target. The remaining positron and a electron bunches are accelerated the remaining part of the accelerator and when they reach the end have attained an energy of 50 billion electron Volts. The two bunches are separated by magnets and sent through an elaborate system of magnets and finally focused down to a spot about $1/10,000$ of an inch across. The reason for such stringent focusing is to make up for the fact that the bunches in SLC will collide only 180 times per second opposed to over 400,000 times per second in PEP. Surrounding the one interaction spot will be a detector. After the bunches pass through each other the bunches are sent to a "beam dump" where their energy is dissipated.

Let's not forget the bunch of electrons extracted from the linear accelerator. They have hit a target and produced positrons that will be used in the next cycle of SLC. After being bent by magnets the positrons are sent through a vacuum pipe and into the positron damping ring for shaping prior to injection into the linear accelerator. Now the electron gun will inject two new bunches of electrons into the electron damping ring. The cycle is now complete.

XIII. High Energy Physics today

To conclude this brief discussion of High Energy Physics and SLAC let us turn to today's theories and experiments and the outlook for tomorrow. One of the greatest ambitions of theorists is trying to "unify" the four basic forces of nature. So far, only the Electromagnetic force and the Weak force have been shown theoretically to be different manifestations of the same force, the Electro-weak force. Other outstanding problems include the actual number of fundamental particles and the masses of the fundamental particles. On the experimental front, the accelerators and storage rings of the mid- to late- 80's will be larger and

larger, with diameters of tens of miles. The detectors will weigh thousands of tons with hundreds of physicists involved in each experiment.

XIV. How one becomes a Physicist

To become a physicist requires years of training in mathematics and physics. Preparation begins in high school and by the time you finish high school you have probably taken some advanced mathematics and maybe even a physics course. During the college years more mathematics and physics is taken. Physics courses emphasizing theoretical (problem solving) and experimental (experimental design, data analysis) techniques are taken throughout your college career. If you have shown promise as an undergraduate, graduate school is the next step. The first year or two in grad school is spent mostly with the course work, which will serve as the final foundation in your career. After that time, you proceed into research, theoretical or experimental. Theorists provide theories which give experimentalists an idea of what to look for. Not every experiment confirms what theorists have predicted. For this reason theorists also spend a lot of time trying to explain unexpected experimental results. Experimentalists must not only design and operate an experiment, but must also be able to interpret the experimental results. The typical time to get a Ph.D. is about 5 years. With a Ph.D. in hand you have many opportunities for jobs in various fields. If you decide to continue in basic research there is the post doctoral Fellowship for which you work for a national laboratory or a university. This phase usually lasts two or three years. Finally you have attained enough skills and experience to obtain a more permanent position.

Additional Reading

Some of the information used in this document came from the following sources:

SLAC-Pub 62 "The Story of Stanford's Two-mile Long Accelerator", by D. Dupen, 1966.

SLAC Beam Line "High Energy Physics: An Introduction", April 1978.

Testing of the SLC damping rings is a major step in the development of SLAC's newest project, the Linear Collider. The damping rings will extract a bunch of particles from the linear accelerator and after shaping the bunch will reintroduce the bunch into the linear accelerator, a feat never before achieved with any accelerator.

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