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# Radiation Laboratory

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# FACT SHEET
# BEVATRON

University of California, Berkeley
Public Information
(Wilkes)

The following is a fact sheet describing details of the history, operation and projected research with the Bevatron.

## Initial Operation

Dr. Edward Lofgren, physicist in charge of the Bevatron, was credited with bringing the machine into successful operation. He said that most of the effort of the laboratory staff in the next few months will be devoted to a "shake-down" of the machine. Attention will be concentrated on perfecting the machine's operation and determining the nature of its powerful beam and the kinds of particles the beam generates.

Among other things, these early routine studies will tell the physicists how best to place concrete shielding to soak up radiation generated in the Bevatron. At present no shielding is necessary and personnel can work in the building while the machine is in operation. The reason is that very few particles are being accelerated at present. The beam is such intensity that a person could stand in it for some time without running any risk.

Later, when more particles are accelerated, the thickness of the shielding around the machine will be increased at points where radiation is intense.

## Research

Early research with the machine, Dr. Lofgren said, will be devoted to the identification of nuclear particles generated when protons from the machine smash into target atoms.

In addition to the proton beam, a secondary beam of neutrons, ranging in energy up to 6.25 billion electron volts (Bev), is generated. These neutrons are dislodged when the protons strike target nuclei. The neutron beam can be used for special research bombardments.

Attention will be focused especially on mesons created by the collision of high energy protons with particles in target nuclei. The production of mesons is one of the chief missions of all modern high energy particle accelerators.

Mesons are a growing family of secondary cosmic rays. In Nature they are generated mostly at great altitudes when high energy primary cosmic rays, similar to the protons of the Bevatron, shoot from space into the earth's atmosphere. There the primaries interact with gas atoms, liberating mesons and other particles.

Mesons are sometimes called the glue of the atomic nucleus. Physicists have found them to be intimately involved with the powerful but elusive forces that hold nuclei together, forces that are ultimately responsible for the form and order of the physical world and for the atom's great energy. For this reason, physicists for over a decade have looked to studies of mesons as the most promising source for understanding the nature of matter.

Mesons were trapped first in 1937 in Nature, in cloud chambers of the cosmic ray hunters. Like other charged particles, they make easily photographed tracks, resembling the vapor trails of high-flying aircraft, in cloud chambers. They make similar tracks in photographic emulsions, and these records are also studied to learn the nature and role of mesons in atoms.

But physicists encountered severe handicaps in the study of mesons in Nature. Mesons have very brief lifetimes --- the longest known have a lifetime of only about 2 millionths of a second. Moreover, they are found only when high energy particles interact with a nucleus. Also, the processes of <u>primary</u> cosmic ray production are in the upper atmosphere --- beyond convenient reach of physicists. It is these production processes, now available in the Bevatron, that are of greatest interest to physicists.

In 1939 Professor Lawrence aspired to build a cyclotron powerful enough to generate mesons in the laboratory. With such a machine, it would be possible to create meson-producing cosmic ray events at will and to control the conditions. The result would be more information, in greater detail, and faster.

The 184-inch cyclotron, the first cosmic ray machine, was not completed until 1946. In 1948 mesons were detected for the first time in bombardments with the machine.

Since that time more powerful cosmic ray machines have been completed, such as the cyclotrons at Columbia University (385 million electron volts --- Mev) and the University of Chicago (430 Mev); a 500,000 Mev synchrotron at California Institute of Technology; the 2.3 Bev Cosmotron at Brookhaven National Laboratory.

In all of these machines except the Cosmotron, only light mesons, of which 5 are known ranging in mass from 210 to 276 (times the mass of the electron), have been made. In addition to light mesons, two other "families" have been found in Nature: heavy mesons, ranging in mass up to the mass of the proton; and "super-heavy" mesons (hyperons), with masses greater than protons.

Scientists working with the Cosmotron have reported the detection of one of the "super-heavy" mesons. This is the only meson outside the "lightweight" class so far generated in atom-smashers.

The Bevatron should extend the spectrum of laboratory meson production still farther. Dr. Lofgren says it should be possible to make a number of different types of heavy and "super-heavy" mesons in addition to all those now generated in other machines. Whether it will be possible to observe all of the roughly 20 species of mesons now known in Nature, and possibly discover new ones, will be determined in future research.

Dr. Lofgren pointed out that all of the known mesons but one were first discovered in Nature. The one exception is the neutral pi meson discovered with the Berkeley 184-inch cyclotron. Historically, however, the properties of mesons discovered in Nature remain hazy until they are artificially generated in atom-smashers, and subjected to analysis under controlled laboratory conditions. Too few mesons can be observed in Nature and the conditions of their observation are too difficult. Thus, detailed and precise knowledge of the properties of the light mesons has been filled in by atom-smasher studies.

The properties of the heavy and "super-heavy" mesons remain very hazy. With the generation of a number of these two "families", their now-unknown properties can be determined, and the interrelationships of mesons and their association with nuclear forces will be better understood, Dr. Lofgren said.

## Research Methods

Observations of mesons and other high energy nuclear phenomena will be made by a variety of methods.

Cloud chambers, both the continuous type and those with a strong magnetic field for bending particles, will be used.

Photo emulsions will be used, as they are in the 184-inch cyclotron and other high energy atom-smashers, to record similar events.

Counters and various arrangements for scattering experiments in which nuclear forces are tested will also be used.

## Origins of the Bevatron

The origins of the Bevatron go back to 1929. At that time, with the Cockroft-Walton voltage multiplier it was possible to impart only one electrical push to nuclear particles. With the electrical equipment then available, particles for atom-smashing could be accelerated to only about half a million electron volts.

In 1929 Dr. Lawrence, then a 28-year-old professor of physics at Berkeley, conceived the cyclotron. His idea was to place a vacuum chamber in a magnetic field. The magnetic field would guide particles in the chamber in a circular path. With an electrical apparatus placed inside the chamber, the particles would be given energy boosts. After each boost, the magnet would guide the particles in a circle back to the region where they could receive another push. As they gained energy the particles would spiral out gradually,until they emerged from a slit in the chamber.

In this way, using a small voltage source over and over again, it was possible to achieve high energies. In 1930 Lawrence built the first working model of the cyclotron --- a tiny 4-inch instrument of the "sealing wax and string" variety, with an energy of only 80,000 electron volts.

Lawrence and his colleagues built successively larger cyclotrons: in 1936, an 85-ton, 37-inch machine for deuterons (nuclei of heavy hydrogen atoms) of 8 Mev and alpha particles of 16 Mev; in 1939, a 225-ton, 60-inch cyclotron for, at present, 22 Mev deuterons and 44 Mev alpha particles. With the latter instrument the trans-uranium elements --- 93 through 98, and including plutonium --- were discovered.

At the time Lawrence made plans for the 184-inch cyclotron in 1939, it was believed that the laws of Nature would prohibit the construction of a cyclotron of greater energy than about 100 Mev for deuterons. In all cyclotrons built up until that time, the accelerating electrical impulses were applied to particles at a constant frequency. In the 60-inch cyclotron, for example, the impulses come at regular intervals --- there is no variation. Moreover, the magnetic strength remains constant.

But the theory of relativity says that as particles gain energy they gain weight. As they gain weight they tend to lag in a constant frequency cyclotron, and cannot be accelerated at the same rate as at lower energy. At about 100 Mev, it was believed the particles in a cyclotron would fall out of step with the regularly spaced electrical pushes. At that point no more energy could be imparted to them.

In 1945 Dr. Edwin M. McMillan, a colleague of Dr. Lawrence and also a Nobel Laureate, conceived a theory to circumvent this limitation of relativity. He called it the theory of phase stability. At about the same time, independently, a Russian scientist, V. Veksler, conceived the same idea.

The theory made it possible to do two new things with particle accelerators. It suggested that the intervals between electrical impulses could be varied --- the frequency could be modulated --- to accomodate the pace of the particles. Thus, with freedom from fixed frequency, accelerators would be built for much higher energy.

Second, McMillan's theory said that the magnetic field of an accelerator could be varied for the guidance of particles. As particles gained higher energy, particles could be kept in a constant orbit by increasing the strength of the magnetic field. Thus solid core magnets, required by a spiral orbit, would not be necessary to guide particles. Ring-shaped magnets could be built.

Frequency modulation was incorporated into the 184-inch cyclotron following the war, and it is capable of accelerating protons to 350 million electron volts and deuterons to 200 Mev --- about twice the design energy.

In 1947 William Brobeck, assistant director of the Radiation Laboratory and one of the foremost accelerator engineers, using McMillan's theory, conceived the Bevatron. A similar design was used for the Cosmotron at Brookhaven, and the two laboratories have collaborated in the evolution of the two atom-smashers.

Brobeck has been in charge of the design of the Bevatron and its construction. Theoretical computations incorporated in the design were made by Lloyd Smith, physicist.

## Construction

The Bevatron was authorized and funds allocated by the Atomic Energy Commission in the spring of 1948.

In the course of design and construction, a quarter scale model was built and tested successfully in 1949. These tests advanced the operation of both the Cosmotron and Bevatron. The 25-foot magnet for the test model is now at the California Institute of Technology, where it has been converted into the world's most powerful synchrotron.

## Components and Principles of Operation

The Bevatron is not only the world's biggest nuclear research instrument; its complexity is rivaled only by the Cosmotron at Brookhaven. The machine itself cannot accelerate particles from a "standing start" or even at low energy. Therefore, particles have to be accelerated to relatively high energy --- 10 Mev --- in stages.

The following is a description of the components of the Bevatron and their operating principles.

## The Ion Source

The first component of any atom-smasher is an ion source. This is the mechanism which provides the particles for acceleration --- the ammunition of the atom-smasher.

The ion source for the Bevatron is similar to that for a cyclotron. It consists of a small chamber filled with hydrogen gas and containing an electrical arc. When the arc is discharged, electrons are torn off the hydrogen atoms. The resulting hydrogen nucleus is a proton, with a positive charge.

These protons are guided electrically into position in the accelerating tube of the Cockroft-Walton machine.

## The Cockroft-Walton

Interestingly enough, one of the subsidiary components of the Bevatron is a stream-lined model of the first effective atom-smashing machine, the Cockroft-Walton. This machine was developed by J. D. Cockroft and E. T. S. Walton, of the Cavendish Laboratory in England, in 1929. The first artificial disintegrations of atomic nuclei were conducted with such a machine. Cockroft and Walton received the Nobel Prize for their work, in 1951.

In a Cockroft-Walton a number of electrical power sources are linked together to build up a large potential difference. A potential difference exists when two bodies are charged oppositely, creating an electrical field between them. When a particle crosses this field toward the body of opposite charge, it receives an amount of energy equal to the potential difference.

The Cockroft-Walton for the Bevatron is much more compact than early versions of the machine. In the early days tubes and condensers were huge, and some had to be made by experimenters themselves. Now, smaller and more efficient tubes and other parts are manufactured and readily purchased.

The Cockroft-Walton starts the protons on their long but rapid journey. In the accelerating tube the protons receive a 500,000 electron volt push.

## The Linear Accelerator

From the Cockroft-Walton the protons are fired into a linear accelerator. The idea for this machine was originated by Ernest Lawrence at about the same time he conceived the cyclotron. In those days, however, electronics was not sufficiently advanced to make the machine practical.

Following the war, Dr. Louis W. Alvarez, professor of physics in the University of California, using advanced electonic methods, developed a practical and useful linear accelerator. This machine, now operating in the Radiation Laboratory, has an energy of 32 Mev, and is 40 feet long.

The linear accelerator for the Bevatron is a smaller version of the same instrument. It consists of a steel tank, 3-1/2 feet in diameter' and 19 feet long, containing a copper cavity. In the center of this cavity are small "drift tubes" through which the protons are aimed. High frequency electrical charges on the drift tubes cause the flying protons to gather speed and energy.

When the protons emerge from the linear accelerator, they have an energy of 10 Mev.

## Focusing Magnets

When the protons leave the linear accelerator, they pass between two strong focusing magnets which bunch the particles together. If the particles were allowed to scatter, many would be lost in the long journey ahead.

## The Inflector

The next problem is to get the fast-moving protons into the circular orbit of the Bevatron accelerating chamber in the right position and moving at the right angle to be caught by the magnetic field. The big magnet itself is not designed to do this. If left alone, the 10 Mev protons would sail through the chamber and into the inner side of the magnet yoke.

Positioning of the protons is achieved by the inflector. The inflector consists of two strips of steel, precision machined in a circuit of 18-foot radius with a 35 degree arc, or angle. The two Strips are placed parallel in vertical position. They are 7/8 of an inch apart, and are charged with 70 kilovolts.

As the protons travel between these two plates, their paths are bent gradually by the electrical field. By the time they have the inflector, the protons have been guided to precisely the right angle and position for their entry into the Bevatron accelerating chamber. At this point the gaint Bevatron magnet takes over further guidance of the particles.

## The Magnet

The job of the giant Bevatron magnet is to guide the protons in their long journey. The protons must circle the chamber inside the magnet some 4,000,000 times, the astronomical distance of 300,000 miles, in approximately 1.85 seconds. They cannot be allowed to wander off a precisely prescribed orbit more than a few inches. For if they do, they will crash into the side of the chamber, and never reach the end of the journey.

When the protons enter the accelerating chamber, the magnetic field is relatively weak --- about 300 gauss. It is just strong enough, however to guide the protons around the chamber in the right orbit. As the protons pick up speed and energy, they would tend to "peel off", and crash into the sides of the chamber if the magnetic field remained the same. Therefore, as the particles gain energy, the magnetic field is strengthened accordingly by the build-up of electrical power (see "Power Source", below) in the magnet coils.

As a result, the particles are forced to remain in their prescribed orbit. The magnetic field reaches a peak strength of 15, 500 gauss at the end of the journey of the protons.

The magnet is built in four sections, or quadrants. Between each quadrant are spaces which allow access to the accelerating chamber for auxiliary equipment.

The outside diameter of the magnet, believed to be the largest in the world, is 135 feet; the diameter at the center of the accelerating chamber is 120 feet. It stands 14 feet high, and is roughly doughnut-shaped. The steel yoke is 20 feet wide. The total weight of the magnet is approximately 10, 000 tons.

The steel yoke of the magnet is composed of laminated pieces of steel that are bolted together. The horizontal yoke members each weigh 24 tons. The vertical yoke members each weigh 4. 5 tons.

A total of 140, 000 feet of 2-inch copper cable, weighing 350 tons has gone into the winding of the magnet. The cable is wound around the pole pieces of the magnet. When electrical current is fed into the copper cable, the steel of the magnet is energized, and the magnetic field is created.

The magnetic field was almost perfect from the beginning of operations. Errors in the field were minute, and in such a big magnet this indicates remarkable engineering.

Some 17, 400 tons of force are exerted when the magnetic poles begin to pull together. Yet the noise that is inevitable from the forces exerted is barely a hum. In the testing stage, however, its power was attested by a big crash in the Bevatron building when it was first turned on. This was due to the realignment of loose pieces of iron around the floor of the building. The iron was magnetized, and moved to accommodate the powerful magnetic field.

## The Accelerating Chamber

The accelerating chamber provides free space in which the protons can travel inside the magnet. It is an evacuated chamber made of stainless steel. It forms a complete circle inside the magnet. In cross section it is rectangular in shape. The gap in which the particles travel is approximately one foot high and four feet wide.

It is evacuated (see vacuum system, below) so that the protons can move freely, without bumping into atoms of air. The orbit in which particles circle the chamber is 400 feet long.

## The Accelerating System

Boosts of energy are given to the protons by means of an electrode inside the accelerating chamber, controlled by an oscillator which feeds power to it. The electrode and oscillator are located at one of the interspaces of the magnet.

The electrode is a kind of electrical "paddle" which gives the particles a boost of energy every time they go by it. The amount of energy the particles receive from the electrode on each circuit averages about 1300 electron volts --- the same as that used by Lawrence in the first working cyclotron.

The high frequency oscillator which feeds power to the electrode is unique. Only the Cosmotron requires an oscillator with such a wide frequency range. It is built also with an eye to precision timing where a millionth of a second is of vital importance.

What is meant by wide frequency range? In handling alternating current, the oscillator switches through a cycle from positive to negative charge. When protons are let into the accelerating chamber, the oscillator switches the charge on the electrode from positive to negative some 400, 000 times per second. By the time the particles end their journey, the oscillator goes through this cycle 2.5 million times per second.

The reason for build-up in the speed of the oscillator operation? As the protons travel faster, they make the trip around the chamber quicker. Therefore, the electrical pushes must come at shorter and shorter intervals. This is known as frequency modulation.

When they enter the accelerating chamber, the protons travel at a speed of 27,.200 miles per second. They reach a speed of about 184, 400 miles per second --- 99.2 per cent of the speed of light at 6.25 Mev. Thereafter their speed hardly increases at all, but as they continue around the chamber their energy keeps on increasing.

## Pulsing

The Bevatron does not operate continuously, but rather in pulses. The acceleration of each pulse of protons requires about 1.85 seconds.

Each pulse contains about 100 million protons, and there are about 10 pulses per minute.

In the first few hundred turns around the magnet, many of the protons orginally injected are lost. However, enough remains to yield an intense beam.

## Vacuum System

In order that they may be accelerated, the protons must travel in a vacuum. All of the components through which the protons travel are evacuated. That is, as much air as possible is removed.

The Bevatron vacuum system is believed to be the largest and most complex high vacuum system now operating. It is one big vacuum, from the Cockroft-Walton accelerating tube through the accelerating chamber of the Bevatron. Its different components are sealed together with a large number of gaskets.

The total volume of the vacuum system is about 12, 000 cubic feet --- about the size of a 1500 square foot house. The vacuum achieved is about 1/100 millionth of an atmosphere --- that is, all but about one air molecule in a hundred million are removed.

This vacuum is achieved by 7 mechanical pumps and 24 big oil diffusion pumps. The oil diffusion pumps are capable of pumping about 16, 000 cubic feet per minute.

## Electrical Power Source

The operation of the electromagnet requires enormous amounts of electrical power. Two generators, each having a 65-ton flywheel for storing power, make available 100, 000 kilowatts of power to the magnet eachtime a bunch of protons is accelerated.

This power, of course, is needed only during the 1.85 second intervals of particle acceleration. So the stored energy is used to build up the magnetic field during this period. About 80 per cent of the power is returned to storage in the flywheel during each cycle. Losses in power occur, and these are made up by two 3500 horsepower motors drawing continuously on a 12, 000 volt, 600 amp, 7200 kilowatt line supplied by Pacific Gas and Electric Company.

The 100, 000 kilowatts, if expended continuously, would be enough to light a city of 00000 people.

## Cooling System

Considerable heat is generated in the magnet by the electrical current which energizes it. This heat must be withdrawn.

For this purpose, two giant blowers, each capable of providing 310,000 cubic feet per minute, are used. The blowers suck air through an air filter in the wall of the Bevatron building, and blow it through a big tunnel under the magnet. This tunnel is 8 feet high and 20 feet wide. In this tunnel, the blowers generate a wind of 30 miles per hour. The wind escapes through the interspaces of the magnet, and goes out louvers in the roof of the building.

## The Shielding

Researchers and workers in the building must be protected from radiations generated in the Bevatron. This is not necessary in early operations, since the number of particles accelerated will be small.

In anticipation of the use of a higher intensity beam, shielding is now being constructed around the machine. This will be a wall of extra heavy concrete blocks stacked 15 feet high and varying in thickness from 5 to 10 feet. The foundations for this shielding --- caissons sunk some 30 feet into the ground --- are now being built. It is estimated that the concrete wall will weigh some 1000 tons.

A second purpose of the shielding will be to cut down on the background radiation that is generated when the protons smash atoms of air. This background radiation, if not absorbed by the concrete, would confuse experiments.

## Emergence of the Beam

In cyclotrons, the beam is deflected out of the accelerating chamber by magnetic and electrical means. In the Bevatron, no system has been developed for deflecting such a powerful beam.

Instead, at a strategic moment the oscillator is turned off while the magnetic field continues to increase. Then the protons are forced by the field to spiral inward, striking a target at the inner side of the accelerating chamber. The powerful protons knock protons and neutrons and mesons out of target nuclei, and these particles sail through a thin window in the steel wall of the chamber. Some of the original protons also scatter out along with secondary particles.

## Detection and Experimental Apparatus

Apparatus set up to detect the beam --- and which will be used in future experiments --- included counters, photographic emulsions, and cloud chambers.

The continuous cloud chamber built especially for Bevatron work is the largest in the world, and was built especially for use with the Bevatron. It is of the continuous type; that is, it operates continuously. It is 4 feet by eight feet, and 7 inches high.

The bottom of the chamber is cooled by 500 pounds of dry ice. On top are trays from which alcohol evaporates. The alcohol vapor travels down toward the dry ice, getting cooler and cooler.

When an atom passes through a 3-inch layer just under the alcohol trays, the cooling alcohol vapor will condense into vapor trails along the path of a charged nuclear particle.

In preliminary operations, the cloud chamber is a center of brilliant nuclear fireworks. It is possible to see atoms explode as Nature's cosmic rays crash into them. Great cosmic showers with hundreds of bright trails appear. Thousands of cosmic ray particles can be seen crossing the chamber.

These Natural cosmic ray showers run in a vertical direction. The particles generated by the Bevatron travel in a horizontal direction, and in that way it is possible to distinguish them from Nature's cosmic ray events.

This cloud chamber will be moved around in the Bevatron beam, to determine its characteristics, the scattering of the beam, and thus where shielding needs to be heaviest.

The instrument will also play an important part in future research with the Bevatron, along with photo emulsions and counters.

The cloud chamber was built primarily by Kenneth Relf, physicist, under the supervision of Dr. Wilson Powell, Professor of physics and a cloud chamber expert.

## Summary of Operation of Components

The following is a brief summary of the operation of the machine, as detailed in the description of the components listed above.

Protons from an ion source, are accelerated in a Cockroft—Walton generator to 500,000 electron volts. The protons' energy is increased to 10 Mev in a linear accelerator. By means of an "inflector", thebeam is brought into the accelerating chamber of the Bevatron at such an angle that the particles are caught by the magnetic field.

The particles circle the accelerating chamber some 4,000,000 times, traveling about 300,000 miles.

During this journey the particles are guided by the magnetic field over a precise orbit. As the particles gain energy, the increasingly strong magnetic field forces them to remain in this prescribed orbit.

The particles receive an average of about 1300 volts of energy on each trip around the chamber. The frequency of the oscillator (pushes) is increased to compensate for the increasing speed of the particles.

Thus the machine incorporates both frequency modulation and variation of the magnetic field.

The protons emerge from the Bevatron at an energy of 6.25 billion electron volts. At this energy, the particles are cosmic rays of the medium energy range. Twenty pulses of protons a minute, each containing about 100 million particles, emerge from the machine.

The beam of protons knocks neutrons and protons out of atoms. It generates showers of mesons and other synthetic secondary cosmic ray particles.

These cosmic ray events are detected and studied by means of counters, photographic emulsions, and cloud chambers.

## The Building

The Bevatron is housed in a circular building that rests in a depression of Charter Hill, some 710 feet above sea level and directly above the Berkeley campus of the University. The building has a total area of 74,000 square feet, and is composed of two principle parts: a circular structure 215 feet in diameter and 75 feet high at the center; and an attached rectangular section housing electrical and other auxiliary equipment.

The building is surrounded by a complex of other Radiation Laboratory structures which sprawl all over "the hill". These structures contain other accelerators, laboratories and offices.

## Scientific Personnel

Only a few of the scores of individuals who helped bring the Bevatron into successful operation can be mentioned. These include Dr. E. O. Lawrence, laboratory director, Dr. Donald Cooksey, associate director, W. B. Reynolds, managing engineer, Dr. Edwin M. McMillan, professor of physics, discovered the basic principle of the Bevatron. William Brobeck, assistant director, conceived and designed it. Lloyd Smith, physicist, made the theoretical computations for the design. Dr. E. J. Lofgren, physicist, brought the machine into operation.

Those primarily involved in designing and testing the magnet were Wilson Powell, Glenn R. Lambertson, and Duane Sewell, physicists. Associates of Dr. Lofgren in operations are Bruce Cork and Warren Chupp, physicists. Those chiefly responsible for mechanical design include Ralph Peters, Hayden Gordon, and James Bell, engineers. Leaders in mechanical construction were the late William Twitchell and Cedric Larson, engineers. Engineers responsible for phases of the complex electronics equipment are Dick A. Mack, Clarence A. Harris, George Farly, Quentin Kerns, and William Baker.