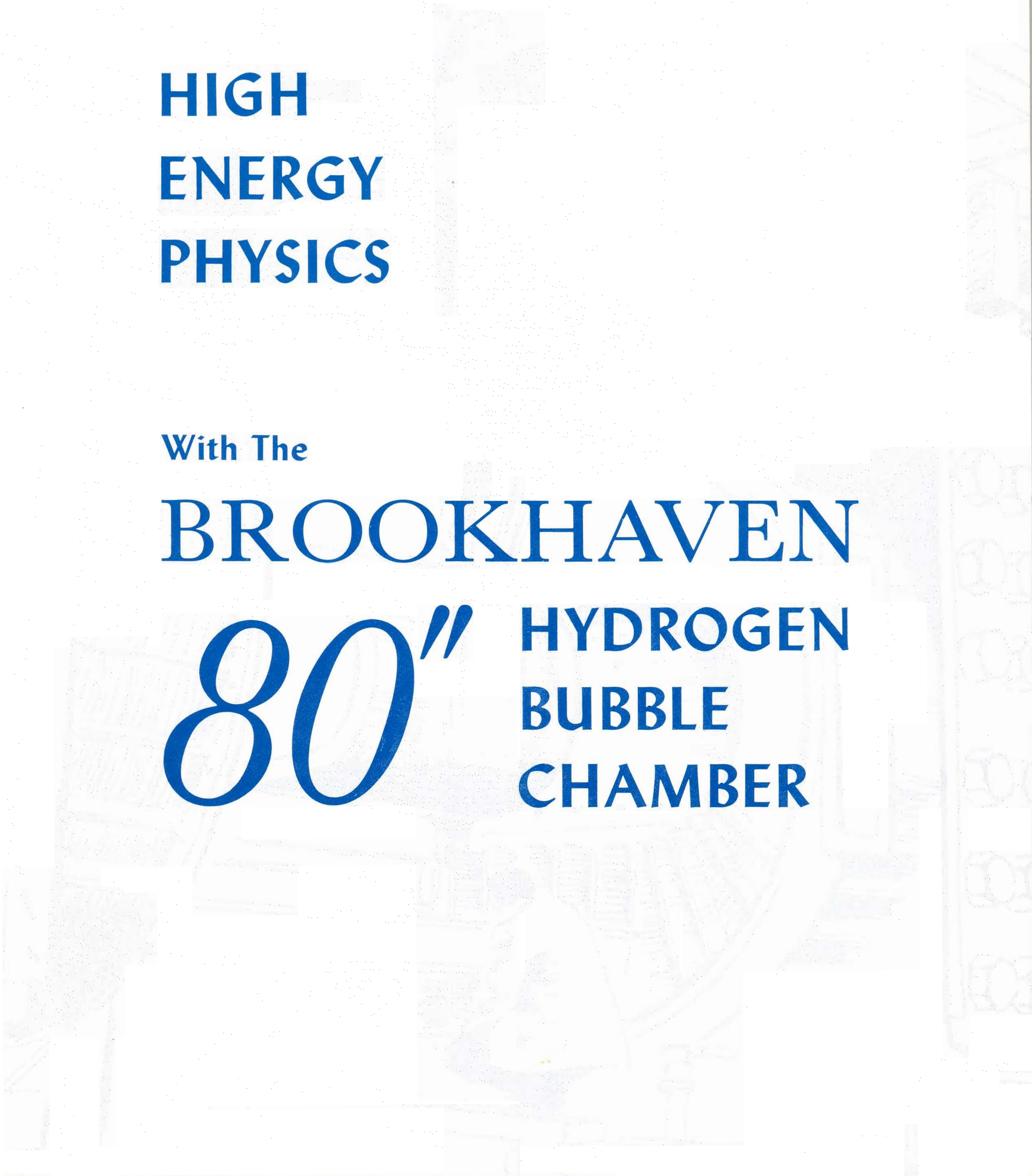
HIGH ENERGY PHYSICS

With The BROOKHAVEN 80" HYDROGEN BUBBLE CHAMBER



BROOKHAVEN NATIONAL LABORATORY

ASSOCIATED UNIVERSITIES, INC.
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Foreword

Members of Brookhaven National Laboratory's Bubble Chamber Group have prepared this booklet for those interested in the Laboratory's research efforts in high energy physics with bubble chambers. In this field, the funds and manpower required for design, construction, and operation of a large bubble chamber are exceeded only by those for the accelerator itself, which produces the high energy particles required for experiments. The chamber serves as a target and particle detector and provides data sufficient for many research teams at many universities and laboratories in the United States and in other countries. This booklet, then, describes some of the technical and scientific work of a large number of people during a period of several years.

Many illustrations have been included for clarity and to achieve some degree of completeness. An attempt has been made not only to describe a particular bubble chamber, but also to explain how the bubble chamber technique fits into an experiment's sequence: accelerator, beam, chamber, data processing, and interpretation.

We should like to thank Brookhaven's Photography and Graphic Arts Division for their many contributions and for their patience and cooperation.

R.P. Shutt
For the BNL Bubble Chamber Group
July 22, 1966

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Introduction

The physics of elementary particles, often called high energy physics, is concerned with the properties and interactions of nuclear particles. Experimental work in this field has two basic aspects, the production and the detection of the particles whose characteristics are being studied. High energy physics is one of the important branches of science today, and one of its basic research tools is the bubble chamber. Many kinds of apparatus and machines have been devised to extend man's knowledge of the universe. Enormous telescopes are used to observe phenomena in the sky too remote for direct observation, and microscopes enable the human eye to see minute objects and organisms. But the atom is far too small to be seen even with the most highly magnifying microscope. Various types of detectors have therefore been devised to study the atom and subatomic particles; among these, the bubble chamber is one of the most useful. The 80-inch liquid hydrogen bubble chamber at Brookhaven is the largest now in existence; it is used in conjunction with Brookhaven's Alternating Gradient Synchrotron (AGS), at present the world's most powerful accelerator.

In a bubble chamber, collisions and interactions between nuclear particles take place. If the particles come sufficiently close to each other, the collisions can cause them to generate new particles or to break up into other elementary particles, which, if electrically charged, produce tracks of bubbles along their trajectories through the liquid contained in the bubble chamber. Thus, although the particles cannot be seen directly, their tracks give evidence of their existence and provide information concerning their properties. From measurements and computations on observed events and the application of basic physical laws, a great deal of knowledge about nuclear particles can be gained from bubble chamber tracks. The geometry of the tracks and the curvatures produced by magnetic fields and also the observed number of bubbles along a track provide data from which the masses, electric charges, mean lives, and other more subtle properties of the particles can be determined. Insight into the nature of the forces that act between nuclear particles can then be gained from the types and numbers of particles observed and from the details of many events studied. An understanding, including a correct mathematical description, of these forces, and the formulation of laws explaining their properties are central goals of high energy physics. Experimental investigations now being done are leading the way to new theoretical concepts which in turn are used to predict further experimental results. Through this interplay between theory and experiment, the field of physics has come a long way; it probably has a long way to go before all the observed phenomena can be explained and understood.

Nuclear Forces and Interactions

When two billiard balls collide, their surfaces are slightly compressed at first and then spring back, and the balls are propelled in certain new directions; the balls are elastically scattered by the compression forces acting between them. Since the balls must touch each other before these forces can act, this might be called an interaction at *short* range. An elastic interaction at *long* range occurs when the path of a comet passing near the sun is altered by the gravitational force of the sun acting on the comet. A similar but very much stronger force, due to the electric charges, acts between atomic particles. An example of the action of this electric force is the elastic scattering of an electron by a proton. (The proton is the simplest existing nucleus, that of hydrogen. At low relative energies an electron and a proton can be bound together by the electric force to form a hydrogen atom.) Other kinds of forces include the magnetic force, which acts similarly to the electric force; the weak interaction force, which, among other things, plays an important role in radioactive decays; and the strong short-range nuclear interaction force, which, for example, binds protons and neutrons together to make heavier nuclei. The latter two forces are at present under intensive investigation.

If two billiard balls were to collide at high enough velocities, they would either crack and shatter immediately or oscillate violently for a brief period and then fall apart (decay) into several fragments; this would be an example of an inelastic collision. By studying the numbers, sizes, velocities, rotations, and directions of flight of the fragments it should be possible to draw conclusions about the forces that held each ball together before the collision and made them shatter afterwards. Similarly, the short-range nuclear forces can be studied by analyzing the products of inelastic collisions occurring at high velocities, near the velocity of light. According to the theory of quantum mechanics, forces between particles are due to the exchange of quanta (discrete packets of energy). For instance, the electric force between the proton and the electron is due to the exchange of light quanta called photons. Under proper experimental conditions the photons themselves behave as particles although they propagate as electromagnetic waves. The stronger and shorter-range the forces, the heavier the quanta, and the more clearly can the quanta be identified as particles. These quantum-particles themselves, if they live long enough, can collide with nuclei and produce still other new particles. So far almost 100 different such subatomic particles have been identified. Thus the field of high energy physics is also called particle physics – and it has become one of the most vexing, exciting, and scientifically rewarding areas of research.

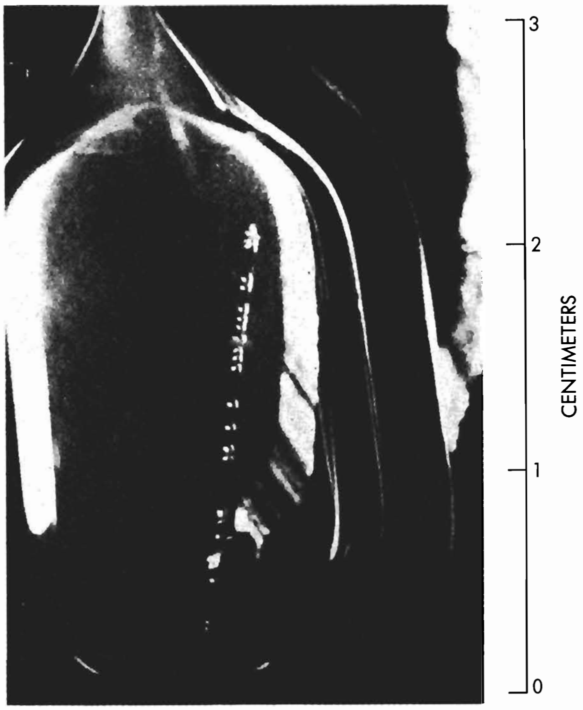
Particle Detectors and Accelerators

When few particles of interest are involved in an interaction, their paths and flight times can be recorded by letting them pass through recording devices such as electronic counters, and this is still an important technique. However, as more particles become involved, if details on every observed interaction are needed, the paths of the particles must be made visible to make detailed measurements possible. Until 1952 this was done with cloud chambers or with special photographic emulsions. In the latter the particles interact directly with the nuclei of the atoms contained in the emulsion. A cloud chamber consists of a box filled with a gas plus the vapor of a liquid and equipped with glass windows. By cooling the gas the vapor is supercooled so that it forms droplets where an electrically charged particle has passed. The resulting tracks are quickly illuminated and photographed.

Until 1952 the only source of particles with energies high enough to cause interactions of special interest was cosmic radiation. Particles, often from outer space, entering the atmosphere from all directions, made many interesting studies possible. But it was not easy to separate any special kind of particle for study, and there were not very many to select from. Then the advent of large particle accelerators such as the Brookhaven Cosmotron enabled experimenters to select particles by their masses, velocities, or momenta and to collimate or focus them to obtain precisely the right conditions for an experiment. The Cosmotron could produce particles with energies up to 3 billion electron volts (BeV), much higher than the *average* energy of cosmic radiation. (A particle with one electron charge acquires one electron volt of energy when it passes through a potential difference of one volt.) The particles from the Cosmotron were sent through cloud chambers, and many interesting events were observed due to collisions between an incident particle and a nucleus of an atom contained in the chamber gas. Hydrogen was an especially interesting gas for use as a target because, since the hydrogen nucleus is simply a proton, the collisions were not obscured by secondary effects due to the other particles present in heavier nuclei. Deuterium gas was also useful, since its nucleus contains only one neutron bound to the proton. To produce more collisions, cloud chambers could be made to contain more target nuclei by increasing the gas pressure. But for reasonably good operation the pressure could not be very high, and the number of events of special interest remained too low.

Since liquids are much denser than gases and gas bubbles are certainly visible in liquids, a number of researchers considered the possibility of using liquid targets in which bubbles would form along the paths of electrically charged particles. Donald A. Glaser at the University of Michigan invented the bubble chamber in 1952 (just when the first experimental results were being obtained at the Cosmotron) and received the Nobel Prize for this achievement in 1960. Glaser's first chamber consisted of a very well-cleaned small glass bulb, but he and other experimenters soon found that for practical purposes the chamber walls need not be extremely clean. Thus it was possible to construct chambers with metal walls, glass plates, gaskets, pipe lines, and other standard engineering materials, and the way was open for construction of chambers of almost unlimited size.

Many different liquids can be and have been used in bubble chambers. Hydrogen is perhaps the most universal one, but propane, Freon, liquid xenon, and more recently neon-hydrogen mixtures, all have properties that may be desirable in some experiments. Specifically, the heavier liquids produce more events because their nuclei, being larger, are more easily struck by an incident particle. Events in heavier liquids usually are difficult to analyze, but neutral particles from an event are fairly easily detected because secondary reactions in these liquids yield charged particles.



The 3-cm × 1-cm-diameter glass bulb in which bubble tracks of charged particles were first observed by Donald A. Glaser.

No two bubble chambers are constructed exactly alike, but all operate on the same basic principle. The first large liquid hydrogen chamber, 72 inches in length, was designed and built at the University of California in Berkeley, where the Bevatron, a 6-BeV accelerator, had come into operation. As will be shown later, the higher the energies to be investigated, the larger the desirable chamber size. Many special low-temperature (cryogenic) techniques had to be developed, since liquid hydrogen (also deuterium or neon) must be kept at temperatures below −400°F. At Brookhaven two chambers, one 14 inches in diameter and the other 20 inches long, were completed in 1959 for use at the Cosmotron.

Design and construction of the Brookhaven AGS, a proton accelerator employing a strong-focusing principle and designed to accelerate protons up to energies of about 33 BeV, was begun in 1952. Satisfactory operation started in 1960. This machine is described in another booklet called *The Brookhaven Alternating Gradient Synchrotron.* In order to exploit the opportunities offered by the AGS, design was begun in 1959 on a liquid hydrogen bubble chamber 80 inches in length.

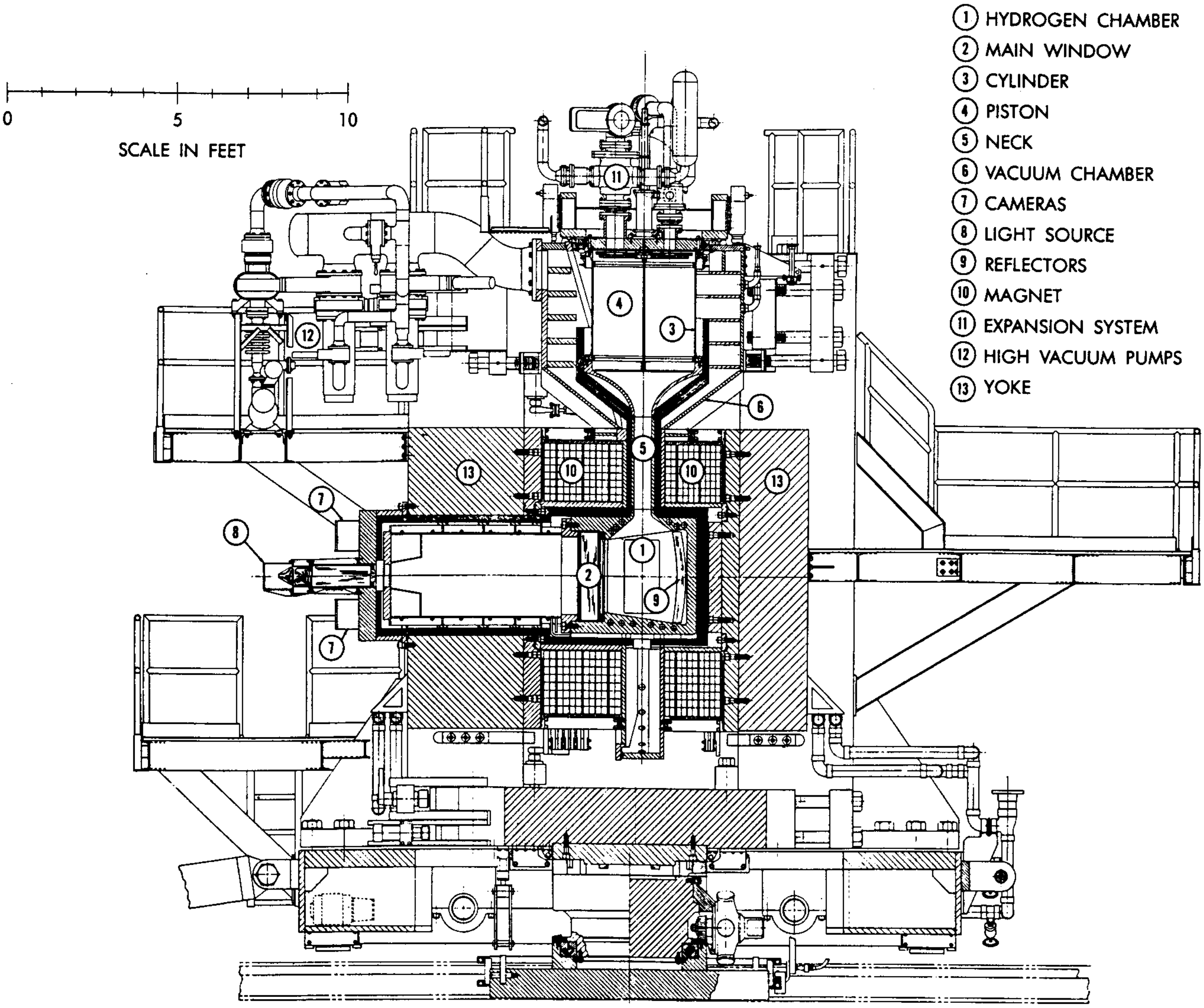
How a Bubble Chamber Works

The mechanism by which a bubble chamber operates may be explained as follows. Every liquid gives off a vapor. If the liquid is enclosed in an insulated, sealed container, it exerts a vapor pressure, which depends on the temperature of the liquid. If the volume of the container is subsequently increased, liquid evaporates to fill the additional space with vapor. This occurs almost instantaneously: the liquid boils briefly with bubbles forming at the container walls. Inside the liquid there is much less boiling because its molecules cling together very tenaciously (if they didn't, only gases would exist, not liquids or solids) and because heat must be transferred to the bulk of the liquid. For a bubble to form, some special condition is needed to start an extremely small "break" in the liquid. For instance, a dust particle or some other mechanical irregularity can break the coherence of the liquid; this is one reason why boiling occurs easily along container walls that are not perfectly smooth. Or a tiny amount of extra energy in the form of heat might be localized in a minute space in the liquid, only a few billionths of an inch in size. Heat means motion of molecules, and extra heat means extra agitation counteracting the coherence of the molecules. Thus a local hot spot can cause a "break" resulting in bubble formation. If a microscopic heat spike is produced somewhere in the liquid simultaneously with an increase in the container volume, then a bubble will form at that point and continue to grow until equilibrium is restored.

This process occurs in a bubble chamber by the following mechanism: When an electrically charged particle travels through any material, its moving electric field causes motion of some of the charged particles (electrons and nuclei) in the material. Sometimes these particles are bounced fairly far from their original positions, but most frequently the collisions are less energetic, and only a few hundred electron volts of energy are transferred from the incident particles to the particles in the material. When this material is the liquid in a bubble chamber, the resultant agitation is quickly shared among the local molecules and forms the heat spike necessary for bubble formation. If the container volume is expanded, and the charged particle passes through the liquid at the correct instant during this expansion, then the string of heat spikes left along the particle's path produces a track of very fast-growing bubbles. A light flashed shortly after the passage of the particle allows a photograph of the track to be taken. If an incident particle hits one of the nuclei in the liquid, then its own track may stop abruptly at the point of collision, and other tracks caused by the fragments may start there. This nuclear interaction may turn out to be one of the events to be studied in detail. For practical reasons and to allow frequent repetition of the process, the liquid is rapidly returned to its compressed condition so that the bubbles are forced to collapse and return to the liquid state.

As described below in more detail, most bubble chambers are mounted in magnets. A magnetic field deflects moving charged particles. The resultant curvatures in the tracks are used to determine the momenta of the particles. The momentum depends on a particle's mass and velocity and is needed for calculations to be performed on events.

After a series of photographs has been taken, the photographs are scanned on projectors for events of interest, and then the tracks of the events are measured very accurately – to an accuracy of a few ten-thousandths (10^{-4}) of an inch. Because of the very high precision required, bubble chambers themselves must be precision instruments. The photographed bubbles must be small, and their size and average density along the tracks must be uniform; this requires great accuracy in timing the photographic process and controlling the temperature. Precise and uniform temperature control throughout the chamber is also required to prevent distortion of the tracks by turbulence. Furthermore, since the tracks must not be distorted by optical effects, the optics of the chamber camera and illumination system must be nearly perfect. Maintenance of picture quality without variation from one photograph to the next requires accurately reproducible operation of the whole chamber complex from cycle to cycle. Since the magnetic field must be very well determined over the entire chamber for later correct calculation of track curvatures, it must remain very constant and must be measured precisely. A further important consideration is safety of operation, since all liquids so far used in bubble chambers are flammable or toxic or require high pressure for satisfactory operation.

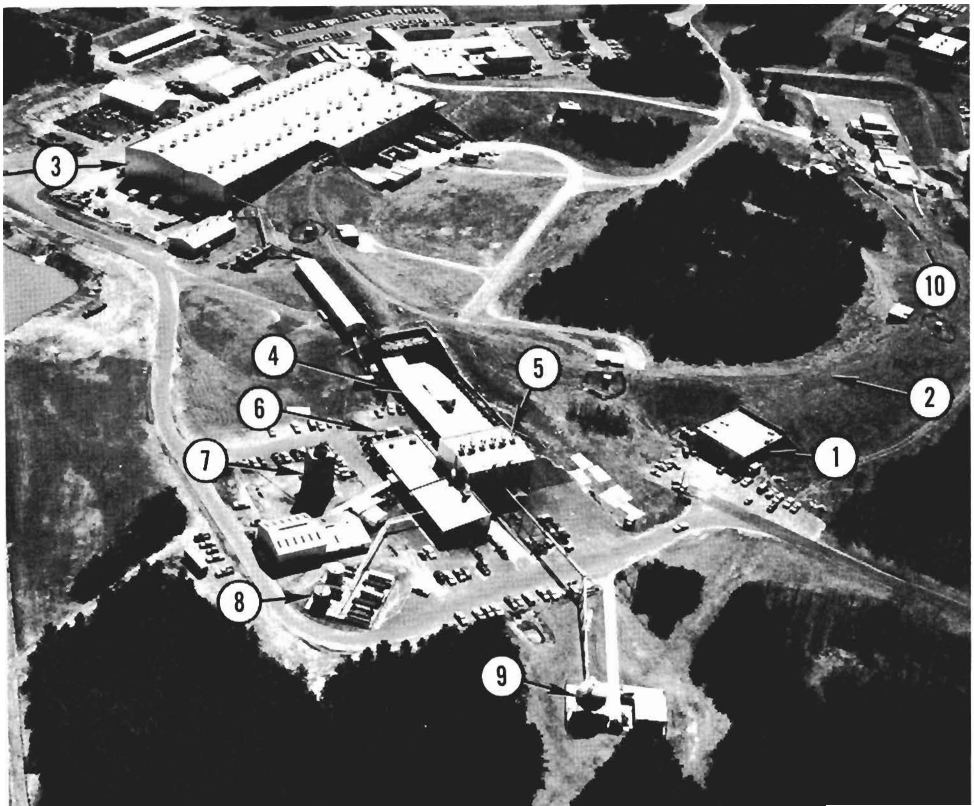


Schematic cross section of the 80-inch liquid hydrogen bubble chamber showing major components.

The 80-Inch Liquid Hydrogen Bubble Chamber

Design work for the 80-inch bubble chamber was started at Brookhaven in 1959. The entire project, including engineering design, purchasing, manufacturing, assembly, building and facilities, required a total of 250 man-years and cost almost $6 million. Four years later, on June 2, 1963, the first tracks were photographed in the chamber on the first trial run. After a number of improvements and modifications, the chamber was put into operation for physics experiments in October 1963. To date 3.3 million pictures have been taken for 29 experiments scheduled for groups of physicists from 17 universities and laboratories, including Brookhaven. Fifty people including technicians, engineers and physicists are required to operate and maintain the chamber 24 hours a day, 7 days a week.

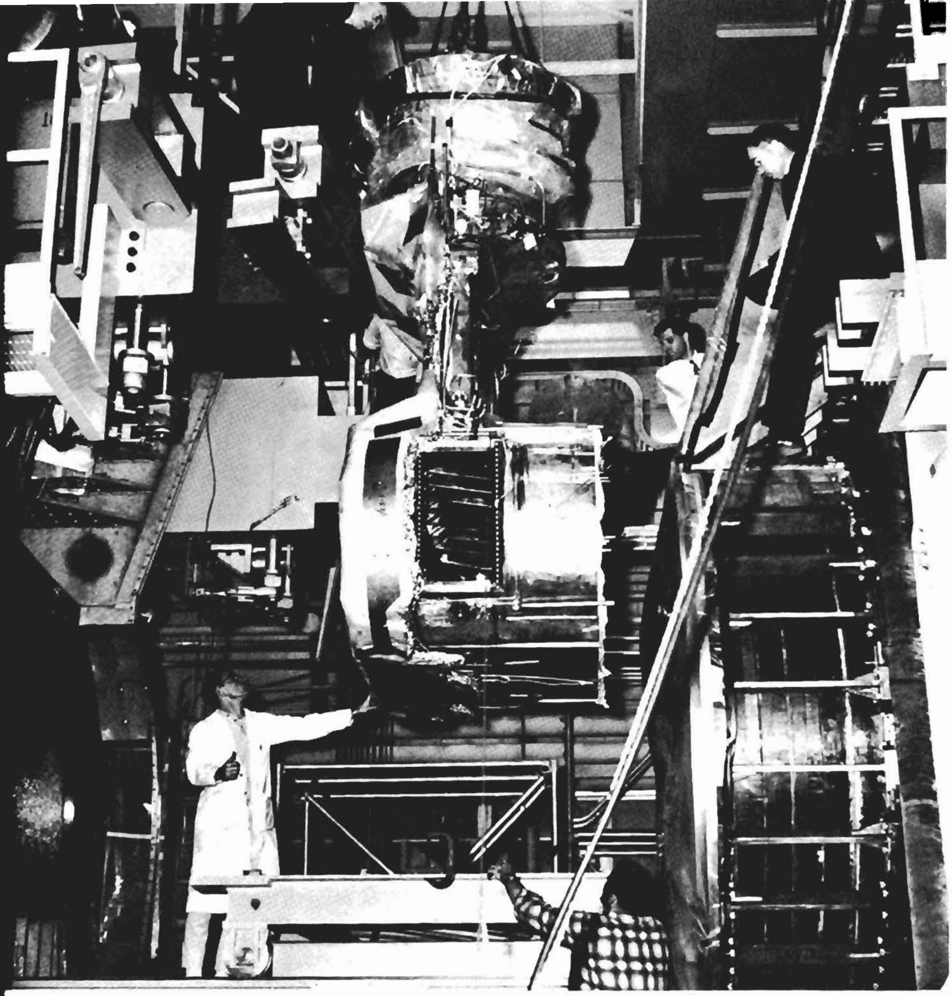
The 80-inch bubble chamber is located in a high-bay area in a 62 by 74-foot building 41 feet high, equipped with a 40-ton overhead crane and provided with adequate ventilation for a fast air change in case of undesired hydrogen release into the room. One-foot-thick concrete walls separate the high-bay area from the compressor and control rooms. Located outside, in addition to the gas storage area and the safety sphere, is a redwood cooling tower 47 feet high which cools the recirculated water carrying off the heat dissipated by the bubble chamber magnet and the beam magnets, a total of 12 megawatts.



Aerial view of the Brookhaven Alternating Gradient Synchrotron (AGS) and 80-inch bubble chamber complex. (1) AGS injector building housing the Cockcroft-Walton machine and section of linear accelerator; (2) circular tunnel containing the 843-foot diameter AGS magnet ring; (3) main experimental area; (4) particle beam array for 80-inch bubble chamber; (5) 80-inch chamber building; (6) transformers for electric power for the 80-inch chamber magnet and other major components; (7) water cooling tower; (8) gas storage area; (9) safety sphere; (10) beam direction in AGS.

The chamber body containing the liquid hydrogen is made of a special stainless steel (Kromarc 55) and weighs 11 tons. It is about 27 inches wide and 80 inches long with rounded ends, and 26 inches deep. Visible to the stereoscopic cameras are 240 gallons (900 liters) of liquid hydrogen. At its top, the chamber has a wide neck leading to a 36-inch-diameter cylinder containing a piston 32 inches high. The piston is constructed of Inconel sheet metal brazed together in a hexagonal cell (honeycomb) structure, which makes it very strong yet light (250 pounds) for its large size. The bottom of the piston, being in contact with the liquid hydrogen, is kept at about −412°F. There is a temperature gradient along the height of the piston, since its top surface is surrounded by gaseous hydrogen at room temperature; the insulating properties of the honeycomb structure minimize heat losses. The equilibrium pressure above the piston is controlled at the normal chamber pressure, 80 psia. Expansion of the liquid is accomplished by rapidly venting the hydrogen gas above the piston by means of high-capacity, fast-acting valves. This produces a pressure difference between the chamber and the top of the piston which causes an upward movement of the piston of about ½ inch and increases the chamber volume by ½%.

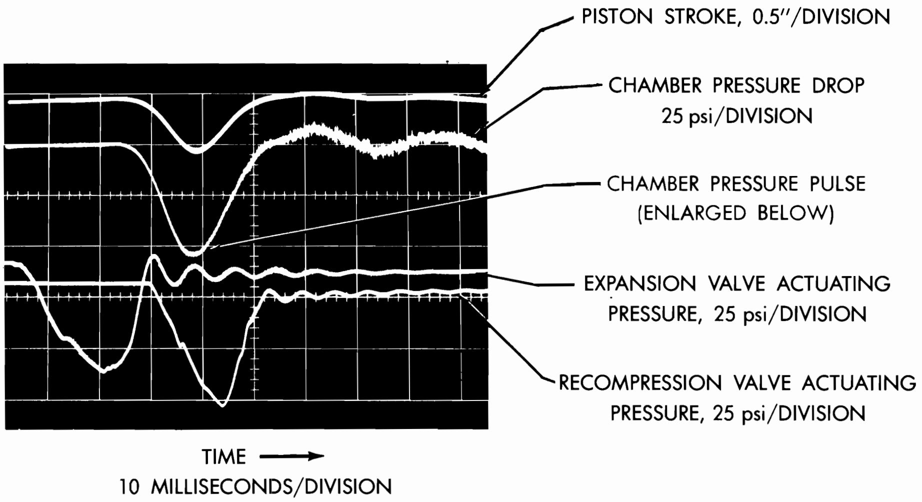
The expansion that occurs in about $^{15}/_{1000}$ of a second results in a 50-psi drop in chamber pressure, which makes the liquid track-sensitive. At this time, charged particles are sent into the chamber through a thin-metal beam window in its side, and the resultant bubble tracks are photographed. The bubbles are then quenched by the recompression stroke of the piston, which is also controlled by fast-acting valves. The whole cycle is completed in less than $^{30}/_{1000}$ of a second and can be repeated once a second. To keep the chamber cycling at this high frequency requires faultless functioning of the expansion system. Expansion and recompression valves must be accurately cycled to provide sufficiently fast expansions reliably and to avoid overtravel of the piston in either direction. A continuous supply of pure gaseous hydrogen, needed to drive the expansion system, is provided by a 3-stage hydrogen compressor supplying 250-psi hydrogen gas and driven by a 150-horsepower motor.



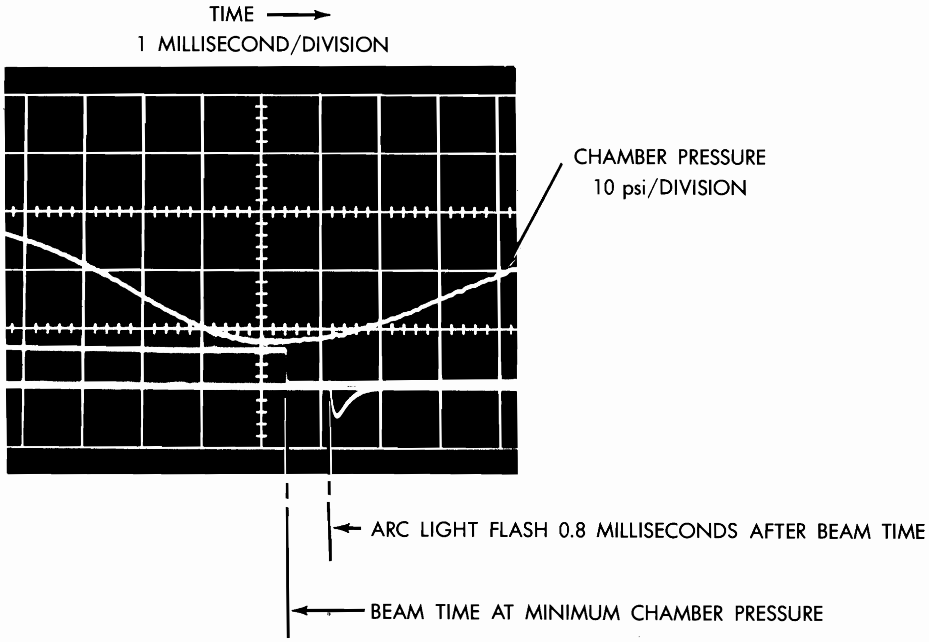
Body of the 80-inch bubble chamber being lowered onto a fixture for insertion in the stationary section of the vacuum chamber, visible at the left. The bottom part of the neck through which the chamber is expanded can be seen through the still-open beam window. A portion of the multiple-layer insulation is already mounted on the chamber.

Thirty-six-inch-diameter piston for the Brookhaven 80-inch liquid hydrogen bubble chamber. Inconel sheet metal 0.003 inches thick has been corrugated and brazed together with 36-inch-diameter face sheets to form a cellular structure. Also brazed to the assembly are the rings at top and bottom carrying high-density polyethylene seal-and-wear rings. A rod at the top of the 250-pound piston leads to a pneumatic control for positioning it between expansions.

EXPANSION SYSTEM PULSE



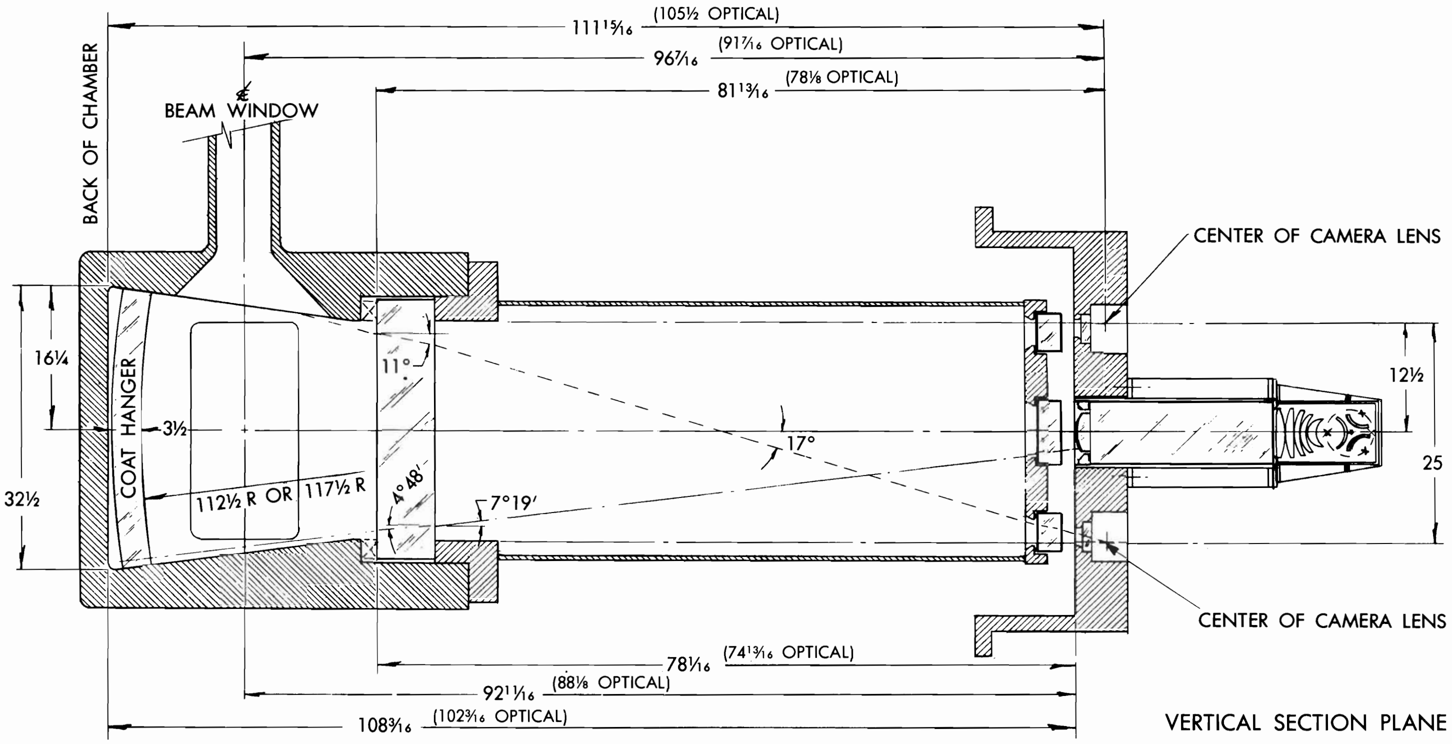
ENLARGED PORTION OF CHAMBER PRESSURE PULSE



Oscilloscope photographs of the expansion system pulse showing the time functions of the piston motion, chamber pressure, and actuating valves. The lower figure shows the chamber pressure near its minimum and the beam timing and light delay on an expanded time scale.

A light source located 8 feet in front of the chamber is flashed approximately 1/1000 of a second after the particles have passed through the chamber. The light is reflected back from the rear of the chamber toward the light source, but some of it is scattered by the bubbles toward 4 ports for cameras spaced around the light source and causes the images of the bubbles to be formed on 70-millimeter photographic film. The light passes through several glass windows, among them a glass plate 6½ inches thick, 81 inches long, and 30 inches high that weighs 1500 pounds and is precision-ground to optical tolerances. A magnetic field of about 20,000 gauss, acting in a horizontal direction parallel to the optical axis, deflects the charged particles in the vertical direction and produces curvature of the tracks. The magnet coils consist of 31 tons of copper bus bar, about 2 by 2 inches in cross section, with a central hole for cooling water, wound in a race-track shape to fit around the chamber. A current of 16,000 amperes, supplied to the coils through a series of transformers and a large group of rectifiers, is produced by a potential difference of 250 volts and results in a power consumption of 4 megawatts. The copper coils alone would not produce the required 20,000-gauss field; they are aided by an iron yoke which facilitates the return of the magnetic flux. This iron yoke, including a heavy undercarriage, weighs about 400 tons and is strong enough to act as the support structure for the entire apparatus. The undercarriage permits translation of the magnet assembly on rails and allows the magnet structure to be opened for easy access to the chamber body and associated equipment. The magnet structure is propelled by a 100-ton-capacity hydraulic pusher, and it can be elevated by four 200-ton-capacity synchronized jacks and rotated on a large roller bearing.

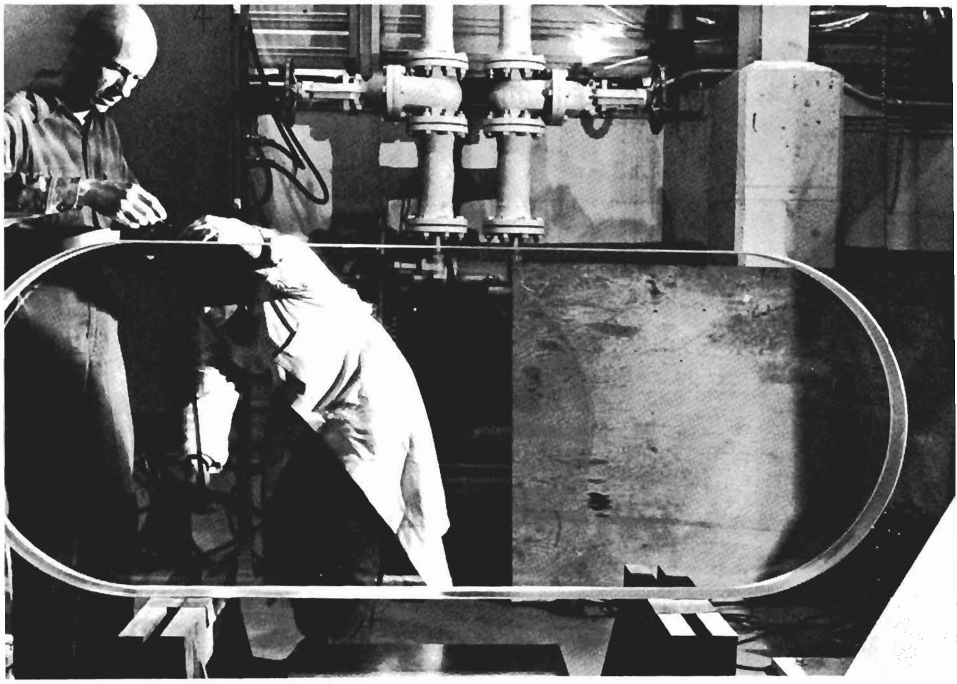
The hydrogen chamber is insulated by several hundred layers of thin aluminized plastic sheets (Mylar®) to shield it from the large amount of heat radiation due to the large temperature difference between the inside and the outside. Since heat conduction and convection must also be drastically reduced, the chamber is placed inside another chamber that is evacuated to a high degree of vacuum (like a thermos bottle). This vacuum chamber, which must fit around the entire

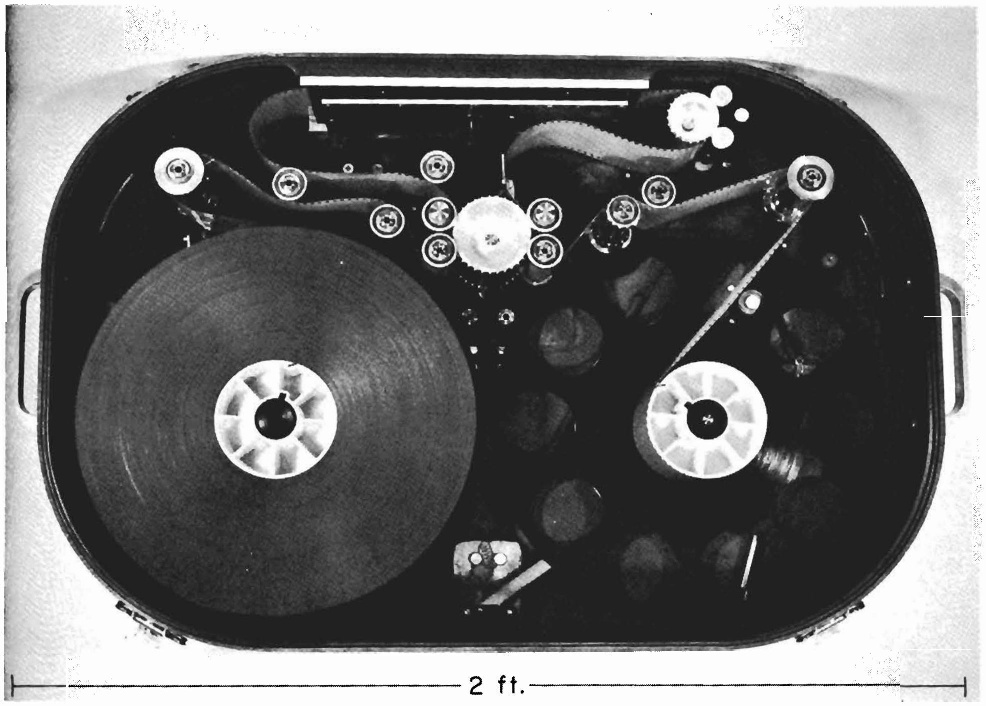


Schematic showing the light source assembly (right) consisting of a xenon-filled quartz tube and an optical condenser system to focus the light through an opening in the vacuum chamber. The light then travels toward the "coat hangers" (left), where it is reflected back toward the source. Some of the light is scattered by the bubbles toward the camera windows, where an image of the bubble can then be produced.

Installing the coat hangers inside the 80-inch chamber body. This must be done with very high precision to insure uniform chamber illumination. The plastic coat hangers are shaped almost like cylindrical lenses focusing light on a silvered reflecting surface on their back side. This system eliminates the mirror images of bubbles which would be seen if, for instance, a large open mirror were installed to reflect the light back toward the source.

The glass window for the 80-inch bubble chamber. It weighs 1500 pounds and is 6½ inches thick, 81 inches long, and 30 inches high. For added strength this glass is tempered by a heating and subsequent rapid cooling procedure. Since pictures are taken through this window, it may deviate from flatness by only a few light wavelengths per inch. The optical quality of the glass must be excellent, free of bubbles, inclusions, or other sources of distortion.



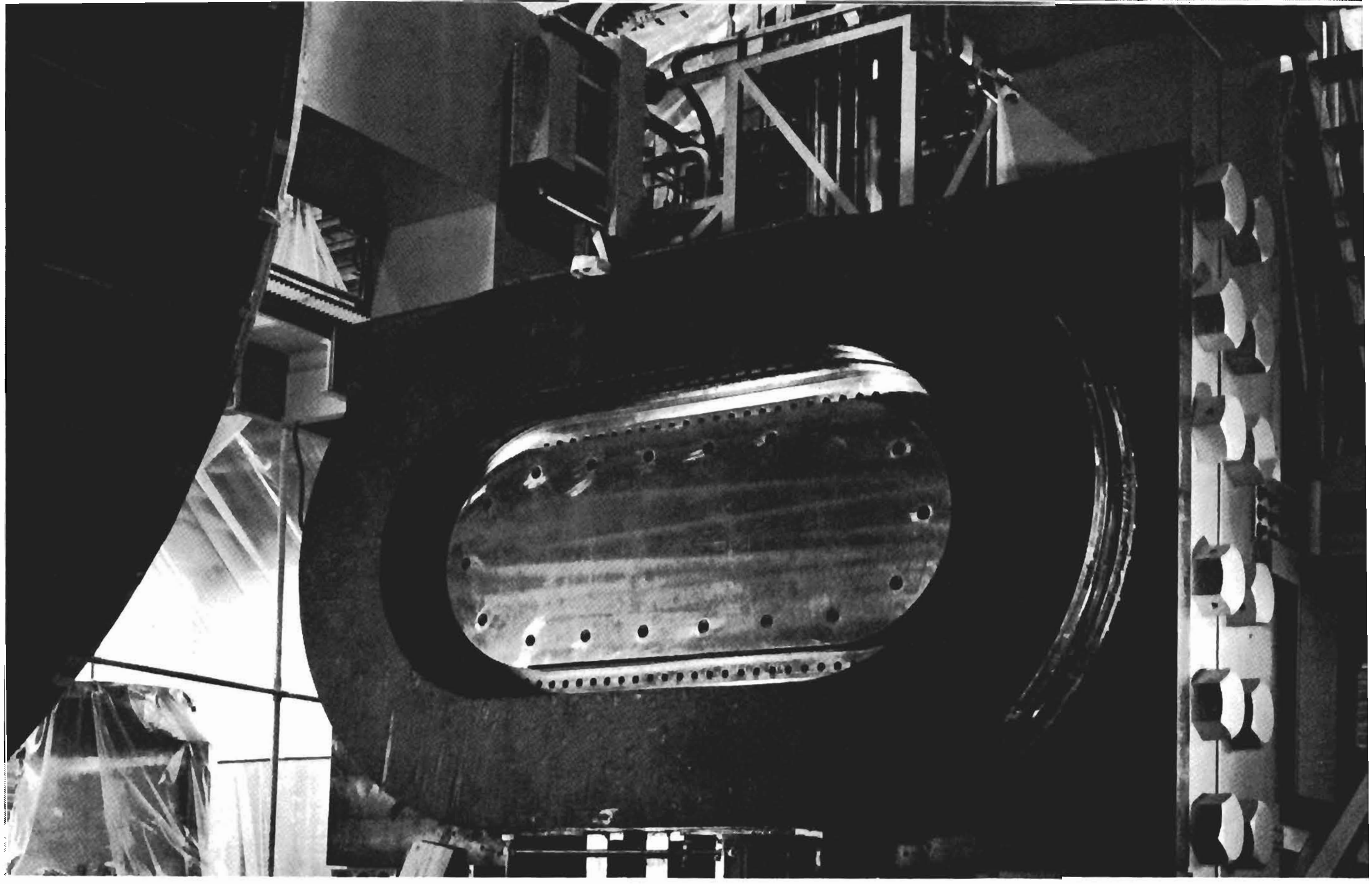


Loaded camera magazine. Film from the spool at the left is guided through mechanical drives past the opening at the top, where it is exposed to the bubble images provided by a photographic lens. The mechanism must advance ≈ 6 inches of 70-mm film every second. The film must be very flat in order to avoid distortion; it is therefore pulled back against a metal plate by a vacuum.

bubble chamber body and within the magnet, is necessarily of complicated shape and intricate design.

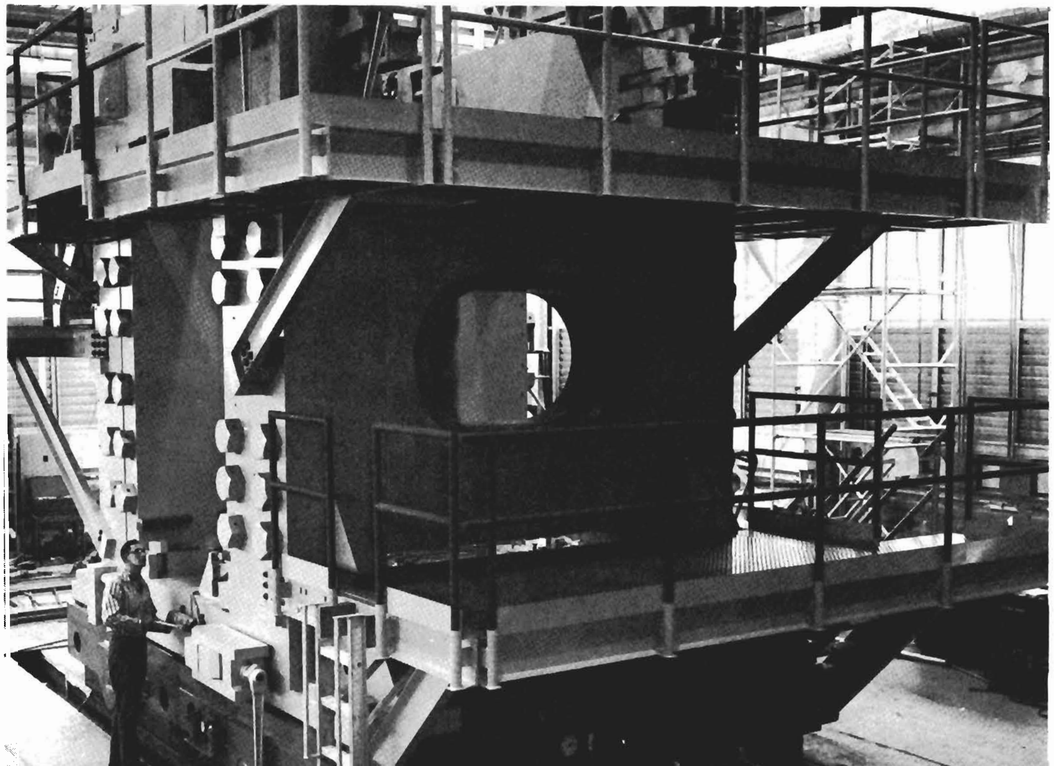
The chamber body is kept at a constant low temperature by means of a hydrogen refrigerator which circulates hydrogen at a controlled low temperature through passages drilled along the chamber walls. The hydrogen refrigerator is a closed recirculating system in which refrigeration is produced by expansion of high-pressure hydrogen gas through orifices (Linde cycle). The hydrogen gas is compressed to 2000 psi by two 5-stage compressors that together require 250 horsepower. Then, after passing through a series of room-temperature and low-temperature purifiers and heat exchangers, it is expanded through variable orifices, which serve to control the pressure in the refrigeration circuits and by this means to control the temperature. The still cold hydrogen returning from the chamber refrigeration circuits passes through heat exchangers to precool the incoming hydrogen gas and thus improve the efficiency of the refrigeration cycle. The refrigerator has sufficient capacity to carry off 2500 watts of heat at −412°F.

All the controls for the expansion system, the refrigerator and compressors, the high vacuum system, the magnet, the pulsed lights, the cameras, and many other smaller systems are located in a central control room, where the status of every unit in the machine is displayed on instrument panels. (More than 140 miles of wire were used for the connections.) Temperatures, pressures, flow rates, magnet current, vacua, valve positions, and number of pictures taken are among the items of information indicated. The control room is also the center of a communication network for the entire complex. An on-line electronic computer automatically logs statistics and data vital to effective operation of the chamber. Audible and visual alarms are actuated immediately if a malfunction occurs anywhere in the chamber complex. A crash button enables the operator to empty the chamber rapidly in case of emergency. The chamber contents are dumped either through a vent line and stack into the atmosphere or into a 28-foot-diameter safety sphere that can safely store all the hydrogen or deuterium gas.

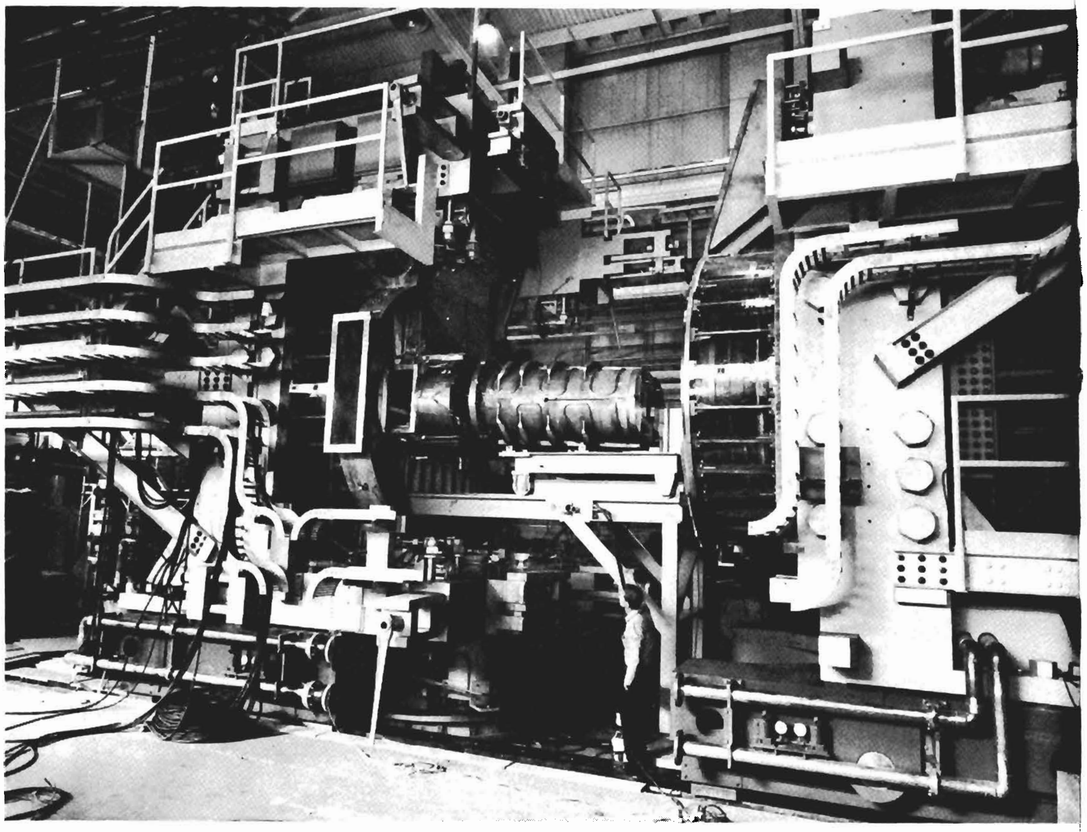


Magnet coils installed on back part of steel yoke. These copper coils are "potted" in epoxy so that several similar units of great strength are produced, which facilitates their handling and support. The magnet is designed to withstand the very large forces produced by the magnetic field. The most significant force is one that tends to pull the coils into a circular shape.

The magnet yoke with platforms attached for support of auxiliary equipment. The magnet carriage at the bottom permits the yoke to separate and slide on rails. The entire chamber assembly can be pushed or pulled along by a hydraulic piston at the lower right.



Installation of the safety chamber in front of the chamber body. The safety chamber shields the liquid in the bubble chamber from thermal radiation; equally important, it would catch glass fragments and liquid hydrogen if the large glass window should ever break.



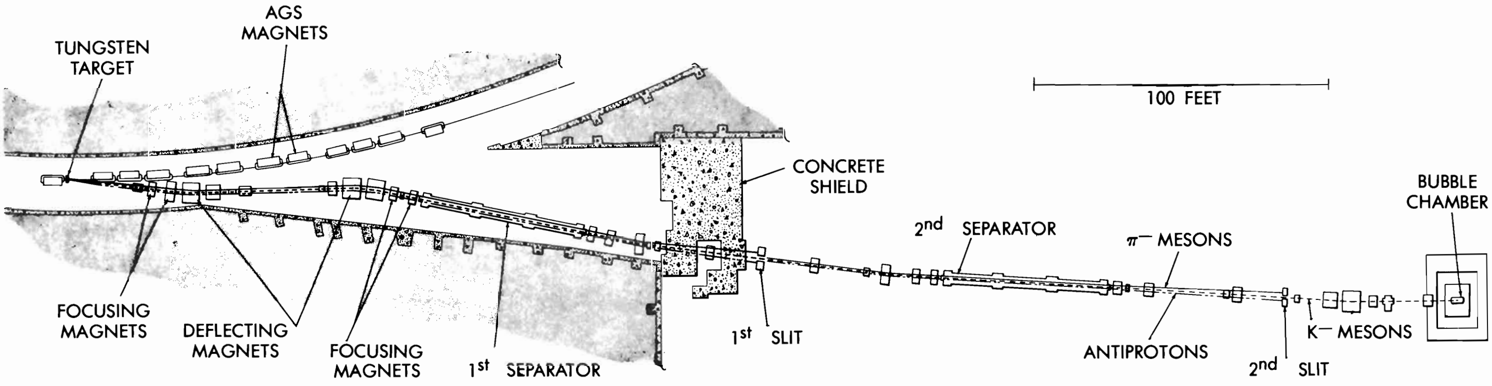
Particle Beams for the Bubble Chamber

The source of incident particles for the 80-inch bubble chamber is the AGS complex, but selection of the desired particles and directing them into the chamber require considerable manipulation. The AGS produces per pulse over 10^{12} protons with energies up to 33 BeV, far too many to be accommodated in the chamber, where only 10 to 20 particles per pulse are usually admitted. Also, the most exciting results may not necessarily be obtained from protons colliding with protons in the chamber. Other particles may be more interesting even if they have lower energies. Therefore, the AGS proton beam is allowed to hit a solid target and thus produce a very large number of secondary particles, which fly off in all directions and with many different velocities. This creates a situation as chaotic as in the case of cosmic radiation except that the particles come toward the chamber from one source only, and their intensity is high enough that there is a good chance of screening out a sufficient number of the desired particles.

The selection process starts at a wall of heavy metal with a small slit in it, mounted near the target struck by the protons. A number of particles pass forward through the slit, toward the chamber. Next, particles with the desired momenta and sign of electric charge are selected by a magnet which deflects them further toward the chamber. At this point the beam of particles, as defined by the target and the slit, has diverged to such an extent that not enough particles may be left to enter the chamber. Therefore, a focusing magnet, which may be compared to a lens focusing light, is used to gather together (or focus) the particles to prevent further divergence. These various magnets have the same effect as the large 80-inch chamber magnet: they curve the trajectories of the particles and thus alter their directions of flight in a precisely determined manner.

At this point particles of selected momenta are traveling at high speeds toward the chamber, but the selection process is not yet complete because particles of different masses can have identical momenta since momentum depends on both velocity and mass. To select the desired masses the particles are passed through a beam separator, where a strong electric field is applied in a direction perpendicular to the flight path of the particles. The electric field is produced between two metal plates, which may be 4 inches apart and 15 feet long, and may amount to a gradient of 100,000 volts per inch between the plates. Since an electric field deflects the particles according to the product of their velocities and momenta, for selected momenta the heavier particles are deflected more than the lighter ones, and the trajectories are again altered so that the particles emerge from the beam separators in slightly different directions corresponding to their masses. All that remains is to focus the particles on another heavy metal wall where a slit is located in the correct position for passage of the desired particles, and a separated beam of particles of the desired mass, electric charge, and momentum emerges. Sometimes only a few such particles are left when those of interest for an experiment are separated from the many more common ones. Also, the array of magnets and separators can become so long that many of the desired particles decay long before they reach the chamber. Nevertheless, beams of protons or antiprotons ($p, \bar{p}$), positive or negative pi mesons (π^+, π^-), and positive or negative K mesons (K^+, K^-) have been successfully produced. In the future, new kinds of beam separators will allow separation of particles at higher momenta.

Beams of neutral particles present quite a different problem. Since they cannot be deflected electromagnetically, they can only be collimated by slits, with little possibility of momentum selection. However, arrangements can be made that will produce neutral K-meson beams, for instance. Of special interest for high energy physics, and for bubble chambers in the future, are beams of the very elusive neutrinos, which do not produce tracks directly since they have no charge. Their interactions are extremely rare but are of great interest in the studies of weak interactions. For instance, although they have no mass at rest, they participate in decays of many particles into electrons (β decay), where their spin (see Glossary) is required in the angular momentum balance. A beam of high energy neutrinos obtained from the decays of fast-moving pi mesons can produce mesons, hyperons, and possibly entirely new particles, when colliding with protons.



Schematic diagram of a 5-BeV K-minus beam arrangement. The proton beam is deflected after acceleration into the tungsten target (left). Focusing magnets gather secondary particles from the target; deflecting magnets select, on the basis of momentum, the particles to be passed on to the electrostatic beam separator. This separator then deflects the particles according to their mass and focuses them on a slit (1×0.05 inch) that blocks most pi mesons and most antiprotons. Before the slit the ratio of K-minus mesons to pi-minus mesons to antiprotons is 10 to 800 to 10. As the beam enters the bubble chamber, after another separation stage, the ratio is 10 to 1 to 0.

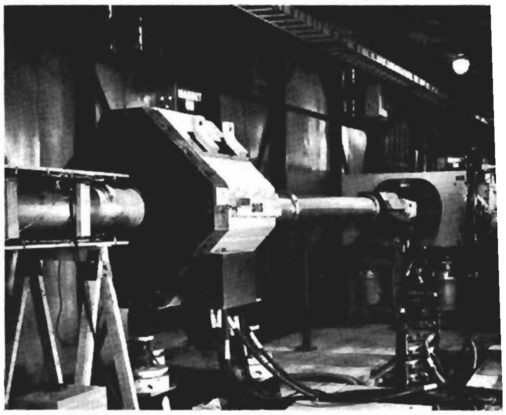
A machine used to measure bubble chamber tracks, which can be seen projected on a translucent screen. A device called a track follower makes it possible to "drive" along the tracks, and suitable points along the way are recorded for later use by a large digital computer which computes the positions of the tracks and their curvatures and then attempts to fit events to various hypotheses.

How Bubble Chamber Photographs Are Used in Physics

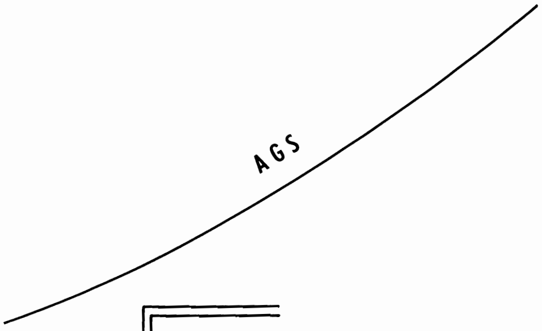
Photographs may be considered the output of a bubble chamber – they store the information required for the analysis that is part of an experiment. A particular experiment may require a great number of photographs, since the interaction (or event) being sought may be very rare, or many pictures may be required for reasons of statistics. With the 80-inch chamber as many as 250,000 stereoscopic pictures have been taken per month – three million pictures per year to be processed.

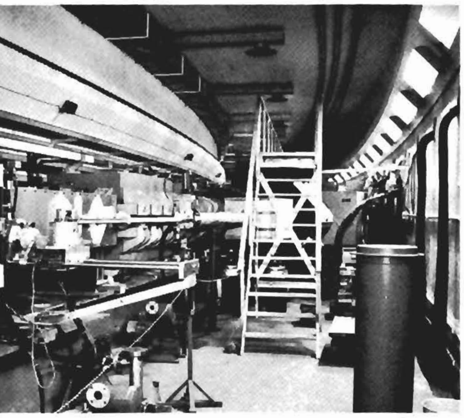
A typical bubble chamber photograph shows the incoming particle tracks, many of which often traverse the chamber without producing any interactions. Of interest are those tracks that stop, change direction, or produce secondary tracks due to interactions. The first step in analysis is to find the photographs showing the particular type of event sought in the experiment. For this purpose the photographs, which are on continuous reels of film, are projected onto scanning tables. It requires many trained scanners and many scanning machines to inspect each frame carefully to select those of interest. Next, the chosen pictures, sometimes

MAJOR COMPONENTS OF THE BUBBLE CHAMBER COMPLEX

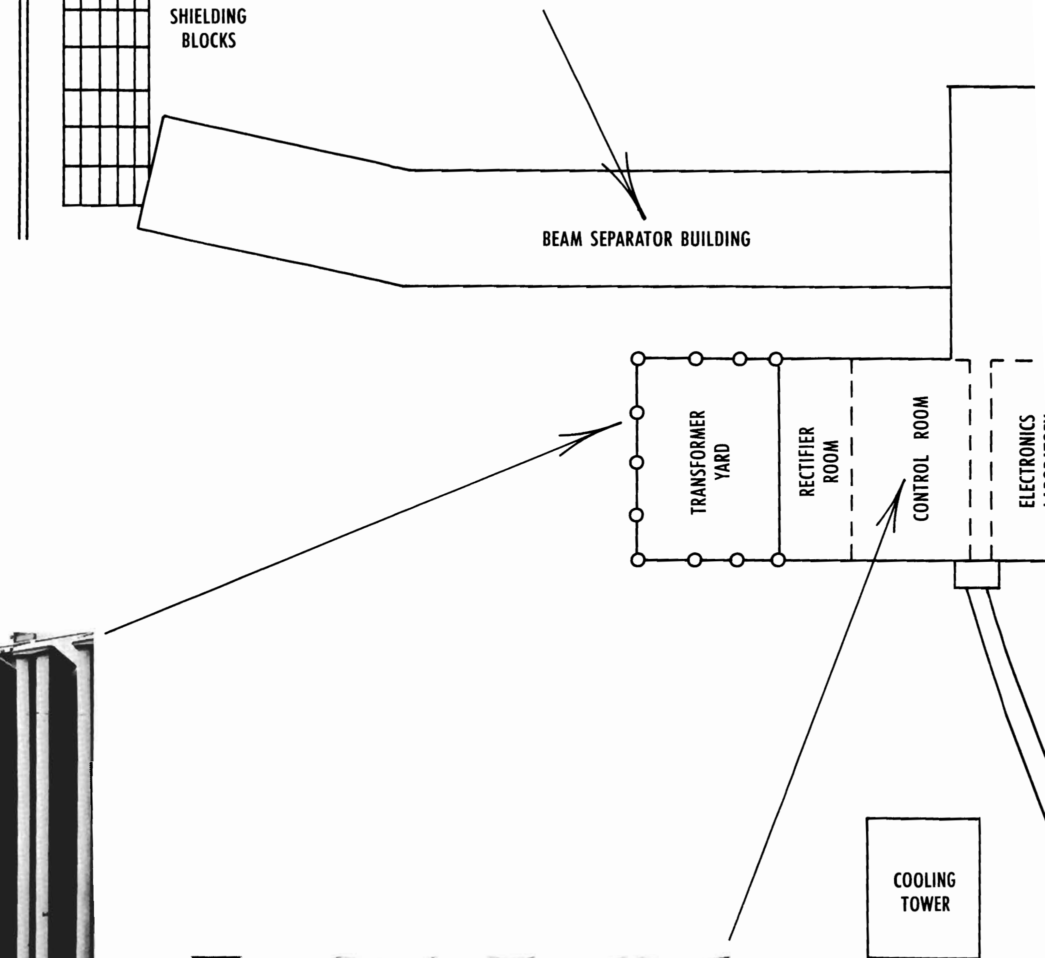


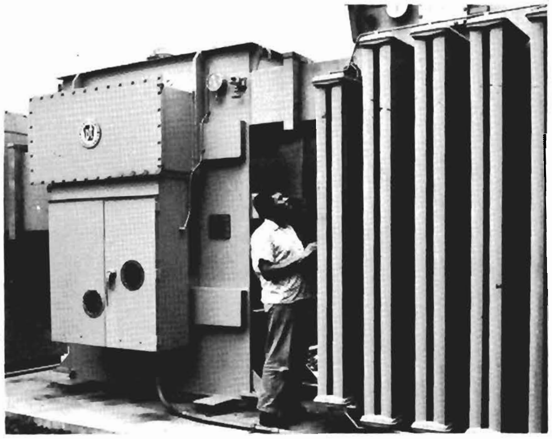
BEAM SEPARATOR





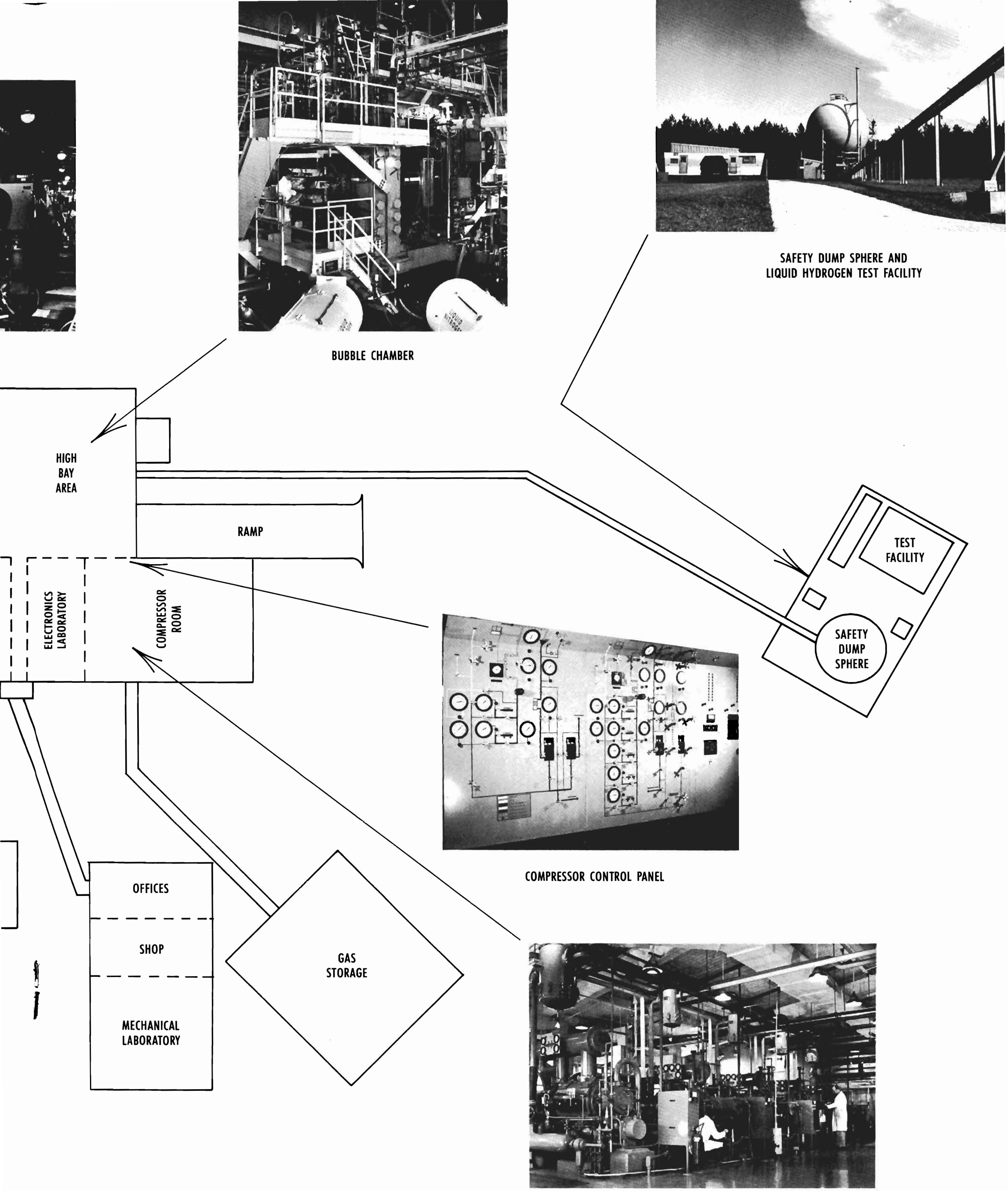
AGS BEAM EJECTOR





MAGNET POWER SUPPLY

MAIN CONTROL ROOM



BUBBLE CHAMBER

SAFETY DUMP SPHERE AND
LIQUID HYDROGEN TEST FACILITY

COMPRESSOR CONTROL PANEL

COMPRESSORS

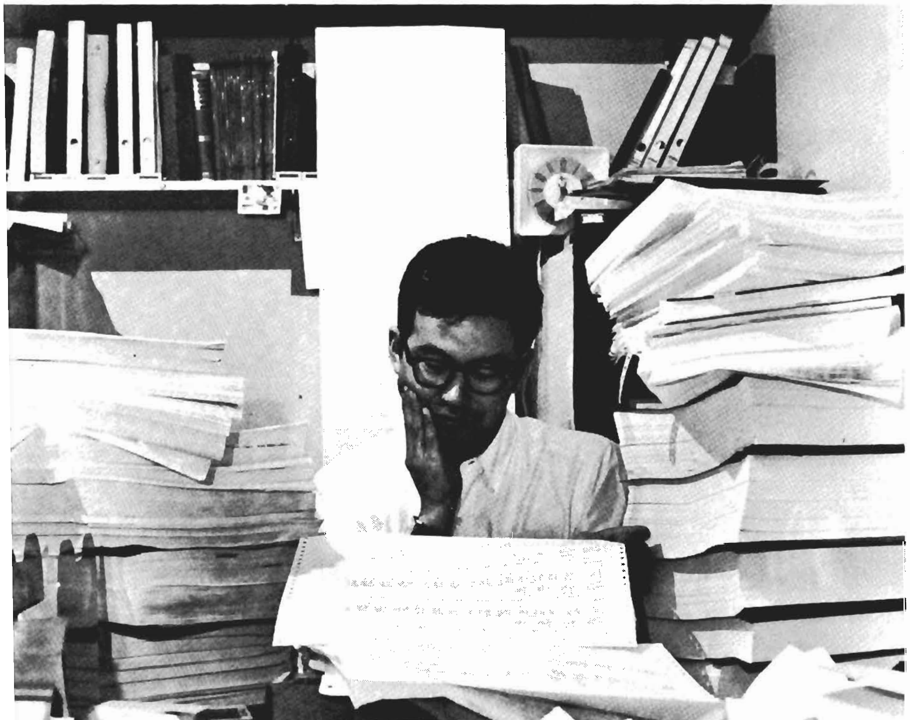
many thousands and sometimes very few, are mounted on measuring machines. Similar to measuring microscopes, these machines contain traveling stages, usually driven by very accurate micrometer-type screws, so that the positions of points along every track of an event can be measured to an accuracy of a few ten-thousandths of an inch on the film, corresponding to an accuracy of about 2/1000 of an inch in the bubble chamber. The track positions are measured in relation to reference points in the chamber called fiducial marks. All this information establishing track positions is stored on computer tape prepared for use in an electronic computer programmed to perform the necessary geometrical reconstruction and physics calculations.

The measuring process has been especially time consuming, but more automatic measuring machines have recently been introduced. The one at Brookhaven is a flying-spot digitizer in which a very small light spot is made to scan each photograph within a few seconds. The light passes through the film to a photosensitive vacuum tube, and less light is transmitted whenever the flying spot crosses a bubble track on the film; thus an electric signal can be given whenever a bubble is encountered. The actual position of the flying spot is automatically determined by having some of its light diverted and focused on a finely calibrated scale with another phototube behind it; the correlation between the bubble images on the film and the fixed scale serves as an automatic measuring and locating process. The information thus obtained is fed directly to an electronic computer. Since every photograph contains many tracks of no interest, such as incoming beam tracks producing no interactions or events irrelevant to the experiment being done, considerable time can be saved if the computer processing is confined to tracks of interest. This is done by programming the computer to ignore all information outside certain boundaries surrounding each track, called roads, which are fixed when an event is found and located during scanning. The flying spot digitizer with on-line electronic computer is now able to process 100 events per hour.

Some of the events seen in bubble chamber photographs turn out to be interactions well known by now, but interesting new ones remain to be studied. The only particles whose identities are known are the incoming one that has been selected through the beam separator system and the target particle in the chamber liquid; the others are unknowns. Further information is gained by measuring all the angles between the tracks on a photograph; the actual angles in space can be determined from the stereoscopic photographs. Also, it has been experimentally shown that the number of bubbles along a track (the bubble density) is significant: slower particles produce more bubbles in a given length than faster ones because their electric fields have more time to disturb the molecules in the liquid. This is true up to a point: since no particle can travel with a velocity faster than the speed of light, as a particle's velocity approaches this limit the bubble density becomes almost constant. Thus, in addition to the angles of the tracks, the velocities of some particles can be analyzed.

It is well known from electric motors that a magnetic field exerts a force on a wire carrying an electric current caused by electrons flowing through the wire. Similarly, the magnetic field in the bubble chamber exerts a force on a charged particle moving through it and thereby deflects it from its initial straight path to a circular one. The stronger the magnetic field, the more curved the path, and the more precise the measurements. Practically all particles have some weight, however little. Their weight is related to their mass, which is a measure of their resistance to deflection from a straight path. Therefore, the heavier a charged particle, the less curved its trajectory in a magnetic field. (For very fast particles the mass is not constant but increases with velocity, according to the theory of relativity.) Also, the greater the velocity, the less curved the trajectory (or the larger the radius of curvature). In fact, the radius of curvature of a charged particle's path in a magnetic field is proportional to its momentum (the product of mass and velocity); therefore, if the radius of curvature is measured, the momentum can be calculated. If the velocity can be established from bubble density measurements, then from velocity and momentum the mass of the particle may be determined. The magnetic field also shows whether a particle has positive charge, like a proton, or negative charge, like an electron, because the direction in which the trajectory of the path is curved depends on the sign of the charge.

To help further in the identification of particles in an event, two laws of physics can be applied. One is the law of conservation of energy: the total energy of all particles produced in a collision must be equal to the total energy before the collision of all the particles involved. Like momentum, the energy of a particle is also a function of its velocity and mass. (Even the struck particle, which was at rest – zero velocity – before the collision, possesses energy due to its mass, which is also a form of energy.) An algebraic equation can be set up involving the parameters of the whole event, which certainly will allow determination of one of the unknown quantities. The other law is the law of conservation of momentum: the sum of all the momenta before the collision must be equal to the sum of all the momenta afterwards. Unlike energy, momentum has direction as well as magnitude; to be fully defined, it requires statement of its magnitude in three mutually perpendicular directions. Since momentum is determined by three quantities, three additional algebraic equations can be set up, again involving all the parameters of the event, from which three more of the unknown quantities in the event can be determined. Very often this further information is sufficient to identify the event completely.



The output of a digital computer, showing all the parameters of an event as well as the quality of the fits to the various hypotheses, is often very large. All these results must be analyzed, their correctness verified, and their meaning pondered.

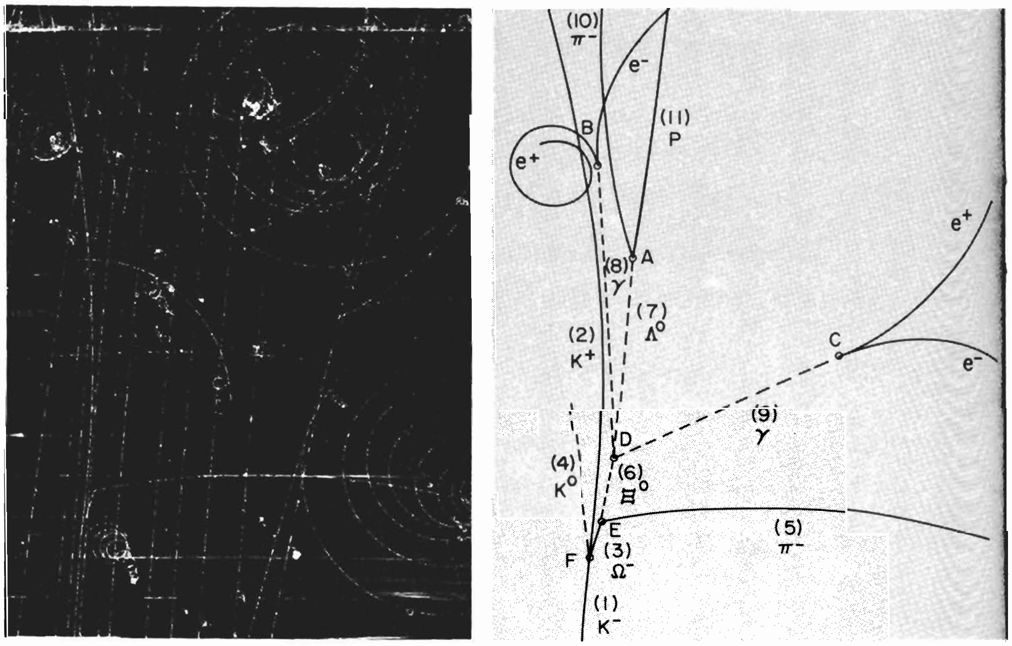
If all particles were electrically charged, the above methods would present relatively few problems. But many uncharged (or neutral) particles also exist, such as neutrons, neutral pi mesons, gamma rays, etc. Since these do not produce any tracks, nothing about them can be measured directly; their presence and properties must be inferred from quantities measured from other tracks. For instance, the algebraic equations mentioned above, resulting from energy and momentum conservation, can be used to calculate their parameters. Also, neutral particles can collide with nuclei in the liquid and produce visible secondary events. The mounting of heavy metal plates in the liquid increases the production of such secondary events and thus facilitates neutral particle analysis.

Besides mass, velocity, electric charge, and mean life, particles are characterized by other quantities: spin, a relativistic quantum number, sometimes pictured as a rotation; isotopic spin, which is related to the different electric charges a family of particles can have; parity, a subtle property concerning the symmetry of elementary processes; and some other quantum numbers whose definition requires more detailed understanding of quantum mechanics. Some of these properties can be determined only when many events of a particular type have been detected and their collective or statistical behavior has been studied. A new particle may be discovered as the result of one single event, but all its properties can be found only after measurements have been made on many examples of its production or decay pattern.

Summary and A Look Into the Future

The 80-inch bubble chamber is part of a long chain of apparatus. The AGS produces primary protons, and these are caused to produce secondary particles by hitting a target. From among the latter, an array of magnets and beam separators selects the particles that are to enter the 80-inch bubble chamber. Here they produce their own tracks and also tracks originating from collisions in the liquid. The tracks are recorded on photographic film. The film is scanned for events of interest, and then measurements and computations are made on the tracks of these events. The results are fitted to assumed reactions or hypotheses. Information from events that fit is collected, and finally an interpretation is given of the particular physical phenomena observed in these events. Usually the results are compared with the predictions of theoretical calculations and either confirm or contradict them. In either case progress is made, and the interplay between scientific thought and the gathering of experimental data continues; answers are found to the questions at hand, and new questions are raised.

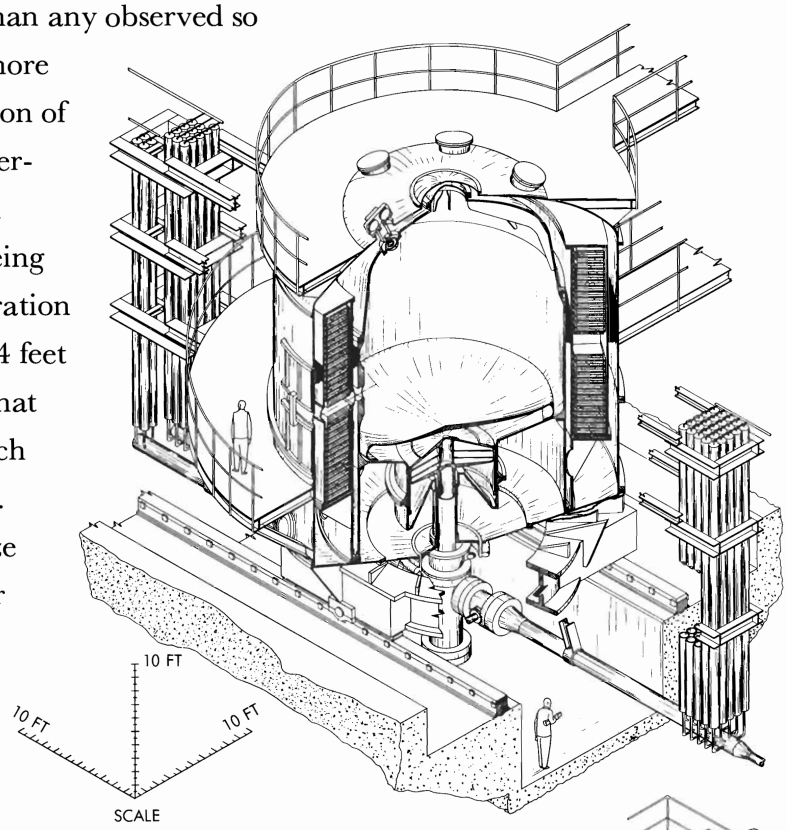
The 80-inch chamber has already provided many significant results. In February 1964 a new particle called omega-minus (Ω^-) was discovered by exposing the chamber to a 5-BeV K^- beam. The existence of this particle had been postulated by a new theory based on mathematical groups. This discovery was especially significant, providing experimental evidence for the first theory to suggest an arrangement of the many subnuclear particles so far found into a pattern of some regularity, reminiscent of the periodic system of the elements or of optical line spectra. Discovery of the Ω^- has given very strong support to this theory, referred to as $SU(3)$ symmetry or the eightfold way. The first event producing an Ω^- revealed itself by a pattern of 10 bubble tracks which, when correlated to each other, fitted some of the properties required for the new particle.

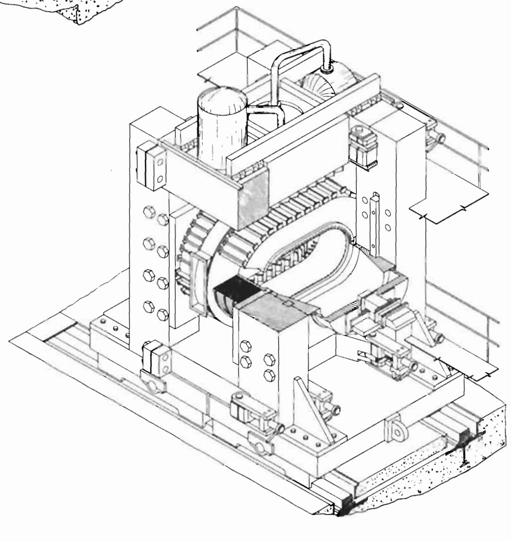


This bubble chamber photograph was the first to show the existence of the omega-minus particle. The sequence of events in the production of the particle is given in the sketch at the right. The track of a *K*-minus meson (K^-) is seen at the bottom of the photograph. The K^- collides with a proton at vertex *F* to yield a *K*-zero meson (K^0), a *K*-plus meson (K^+), and an omega-minus particle (Ω^-). The K^+ makes an identifiable track. The Ω^- disintegrates at vertex *E* to a pi-minus meson (π^-) and a xi-zero particle (Ξ^0). The Ξ^0 is identified by its decay products, emerging from decay vertex *D* – two gamma rays that give rise to positron-electron pairs (e^+ and e^-) at *C* and *B*, and a lambda-zero hyperon (Λ^0) that yields a π^- and a proton (p) at vertex *A*. Knowledge of the masses and momenta of charged decay products of neutral particles that leave no tracks (broken lines) enables physicists to identify them. Thus the third particle branching from vertex *F* is known to be a K^0.

It is doubtful that an event of this complexity would have been detected by any other method. The large size of the 80-inch chamber was also essential in the discovery and identification of the Ω^-. The chance of production was good because of the many target nuclei present. The chance to observe subsequent decays, after a long flight path, was good because of the length of the chamber. The momenta of the tracks could be measured very accurately because they were long and therefore showed marked deviations from straight lines.

As separated particle beams of even higher energies become available at the AGS and at much more powerful accelerators still to be built, events will be seen which will be more complex than any observed so far and will require not only more information but also information of greater accuracy for their understanding. For this reason, even larger bubble chambers are being contemplated. Under consideration at Brookhaven is a chamber 14 feet in diameter and 15 feet high that would contain 50 times as much liquid as the 80-inch chamber. Even after chambers of this size are built, the 80-inch chamber will almost certainly remain in use for many years as a valuable research tool.





A diagram of the 80-inch bubble chamber (lower right) and the design for a 14-foot-diameter chamber (upper left). Such a large chamber, containing 46,000 liters of liquid hydrogen visible to the cameras, has been proposed for use at the Alternating Gradient Synchrotron. (The 80-inch chamber contains 900 liters visible to the cameras). Such very large chambers will be useful in extending the research now going on. They will produce more events to be studied and will permit the observed events to be measured with much greater accuracy. A superconducting magnet is a unique feature. The hydraulically controlled expansion mechanism below the chamber is designed to conserve the energy released during the expansion process and thus minimize the power requirements for compression. Wide-angle-lens photography will be used, and most of the inside of the chamber will be "wallpapered" with Scotchlite.®

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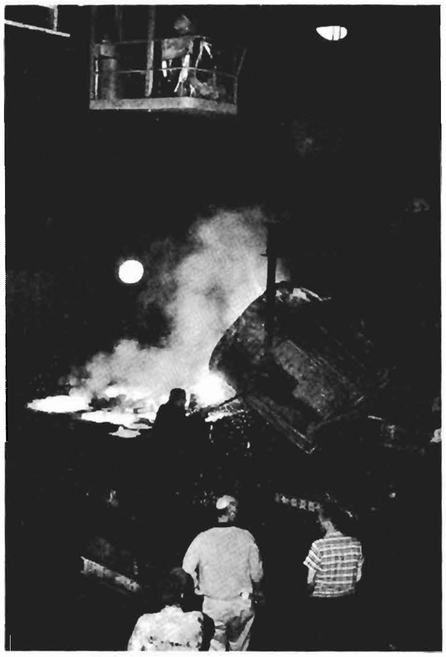
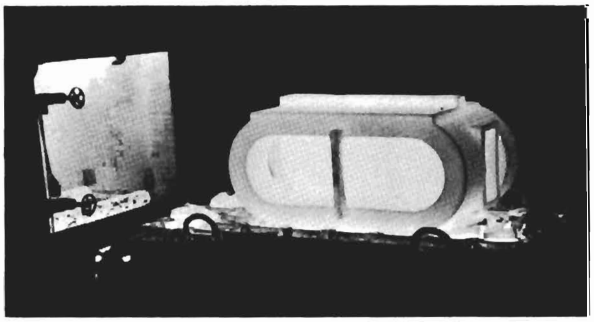
FABRICATION OF THE 80-INCH CHAMBER BODY CASTING



Stainless steel (Kromarc-55) being cast in a form.

The raw casting.

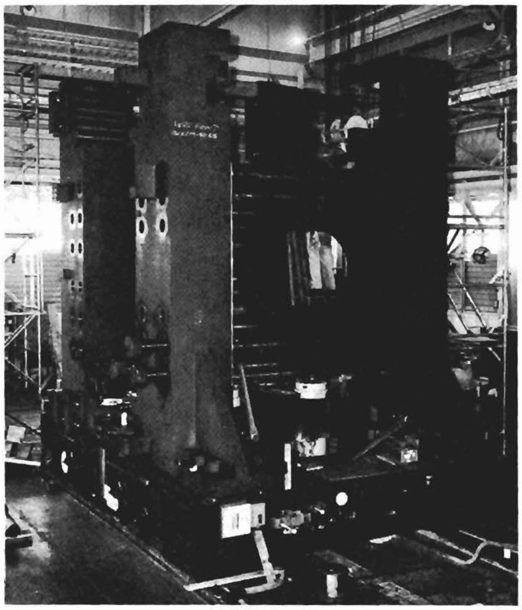


The cleaned-up casting after heat treatment.

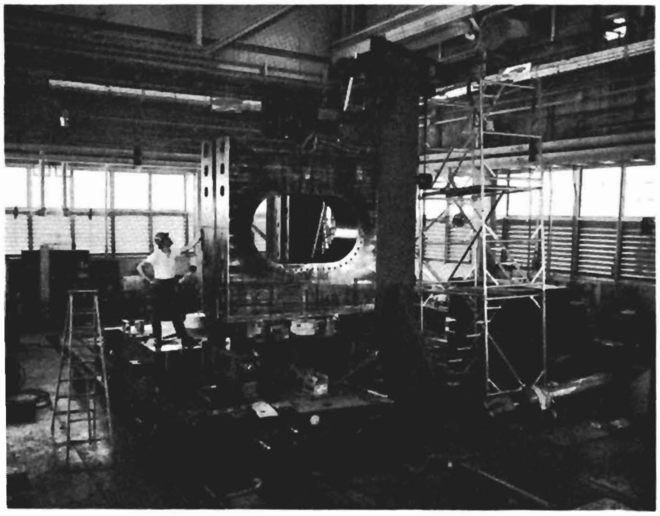
The concrete pit and steel rails (here covered with wood for protection).

The undercarriage and bottom plate of the magnet. The bottom plate can be raised and lowered by four hydraulically synchronized lifting jacks. The whole carriage can slide on the rails which are lubricated by special material called Lubrite.

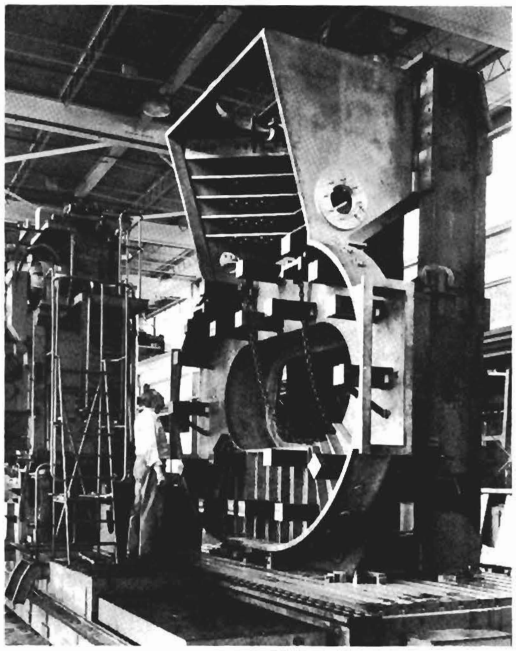
PHASES OF ASSEMBLY OF THE 80-INCH CHAMBER MAGNET YOKE



The yoke almost complete.

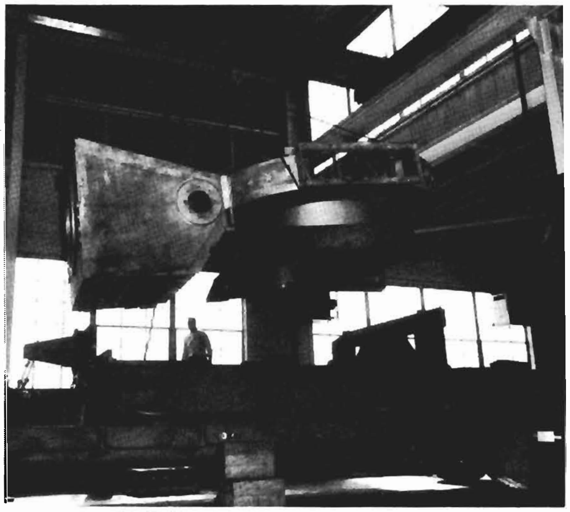


Installation of the front part of the magnet yoke through which illumination and photography are performed.

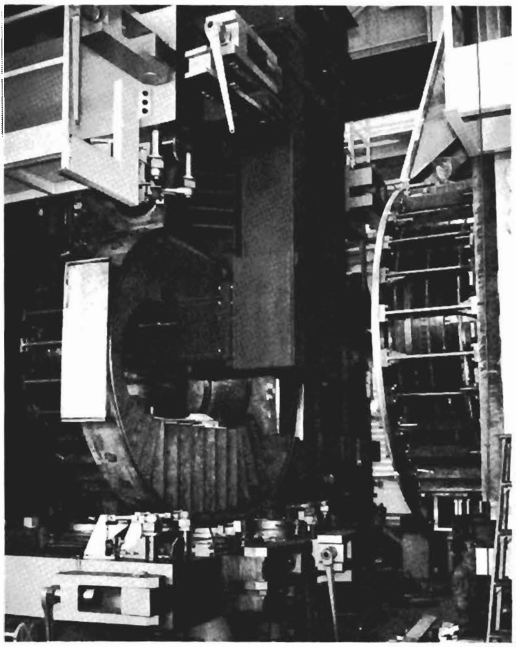


Machining in Kellering machine.

PHASES OF FABRICATION AND ASSEMBLY OF THE VACUUM CHAMBER (REAR HALF)

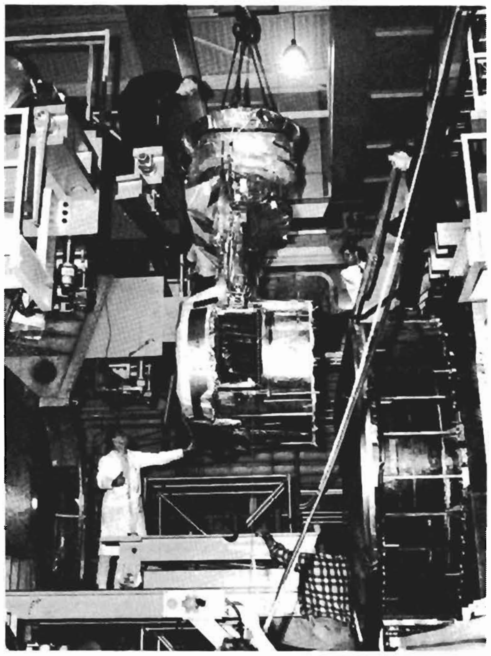


Hanging on crane.

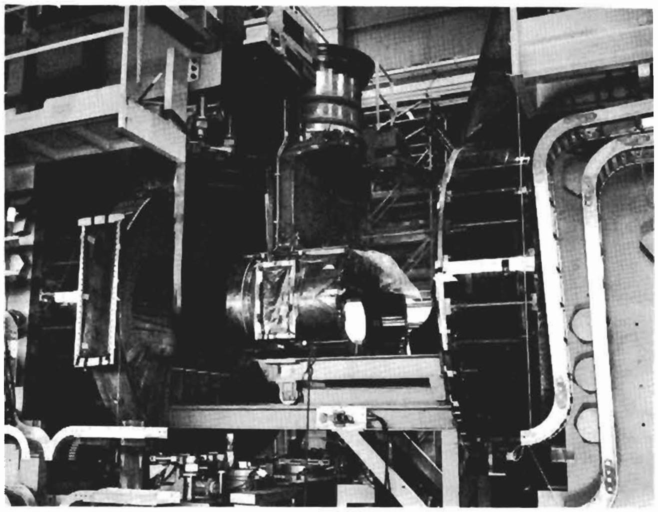


Insertion into magnet yoke.

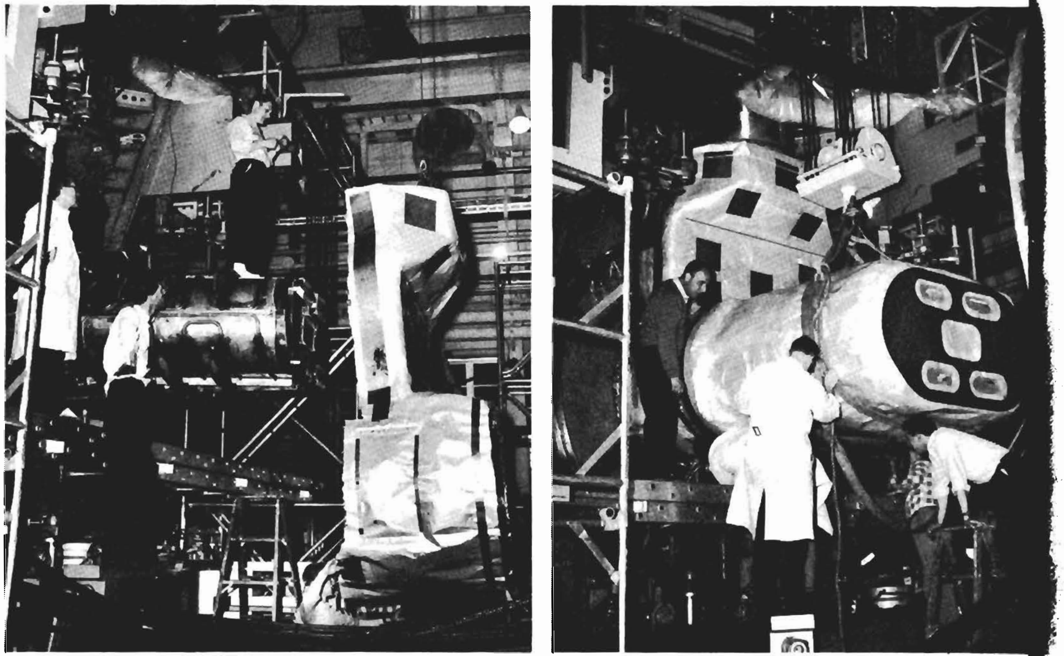
INSULATION OF CHAMBER IN VACUUM TANK



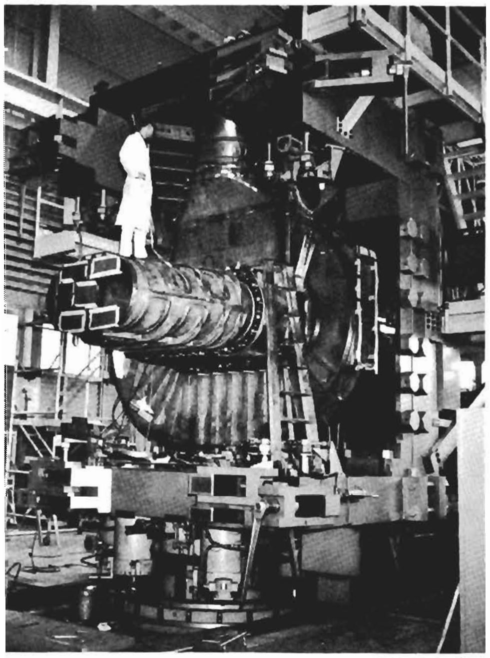
Chamber partially insulated.



Uninsulated chamber, positioned between magnet sections.

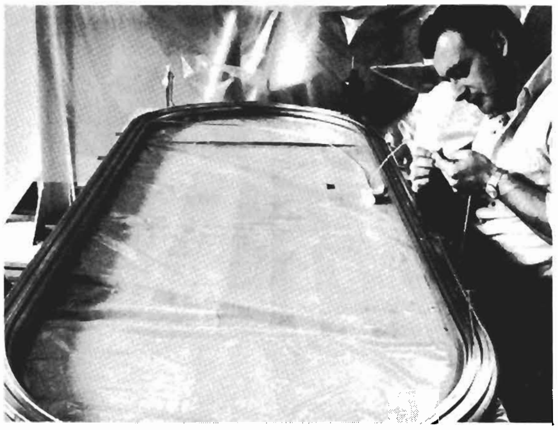


Insulation being completed.

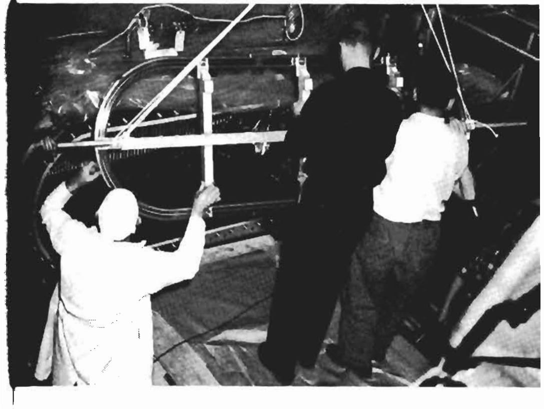


Chamber with safety chamber.

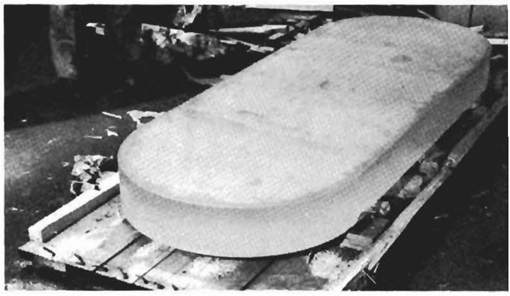
The inflatable seal assembly being "charged" with indium wire, which flattens out under pressure and thus provides a seal. There are two such wires between which any hydrogen leaking through the first seal can be pumped out so that the high vacuum around the outside of the chamber will not be disturbed by small leakages. The assembly is pressurized with hydrogen up to pressures of 1200 psi.



ASSEMBLY OF GLASS-TO-METAL SEAL AND FABRICATION AND MOUNTING OF MAIN WINDOW IN CHAMBER

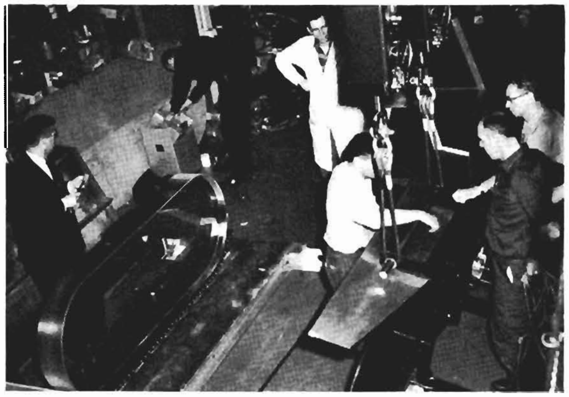


Mounting of the inflatable seal assembly.



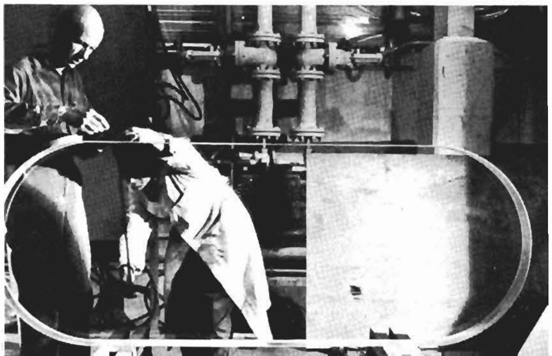
Unpolished glass plate
on arrival from glass manufacturer.

Grinding and polishing of glass.

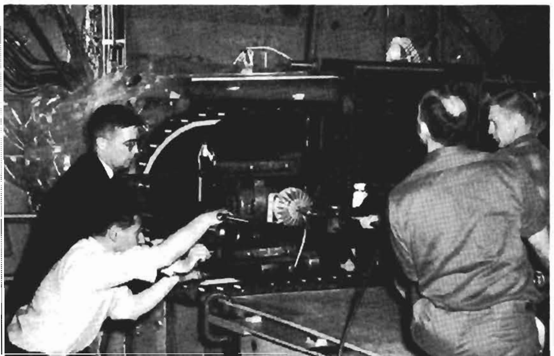


Main window insertion fixture being readied.

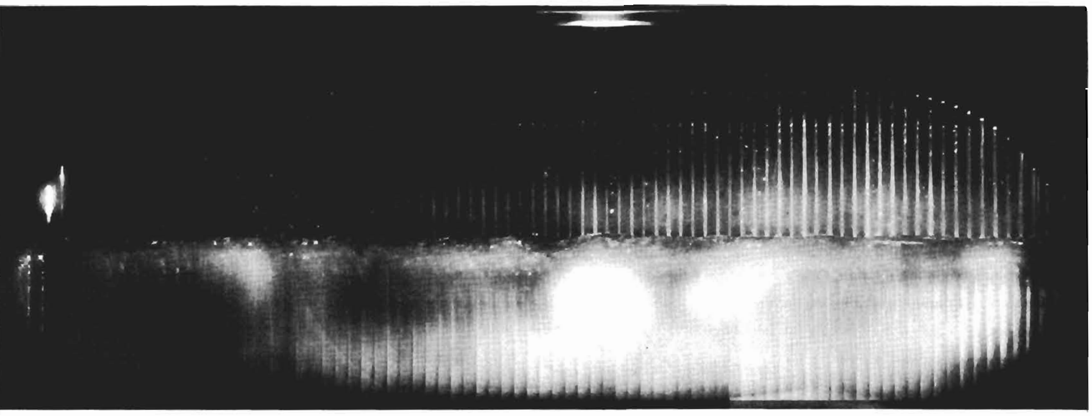
Main window undergoing last inspection.

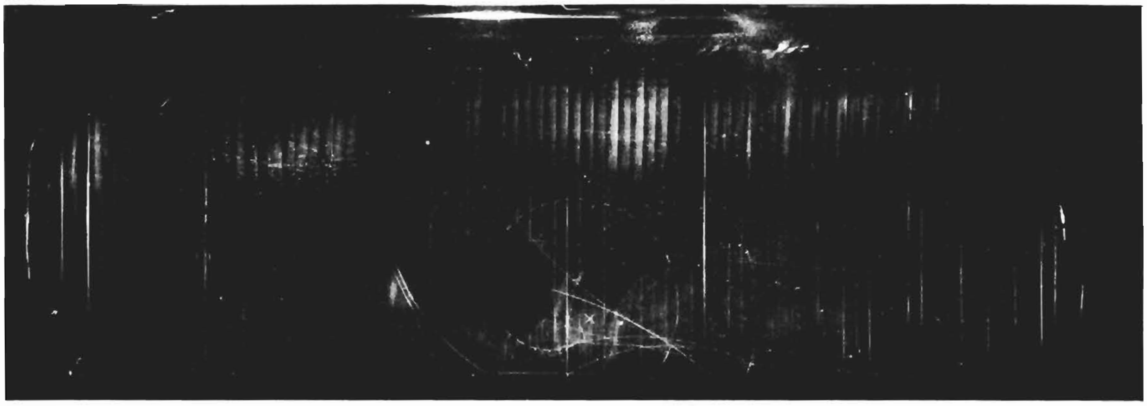


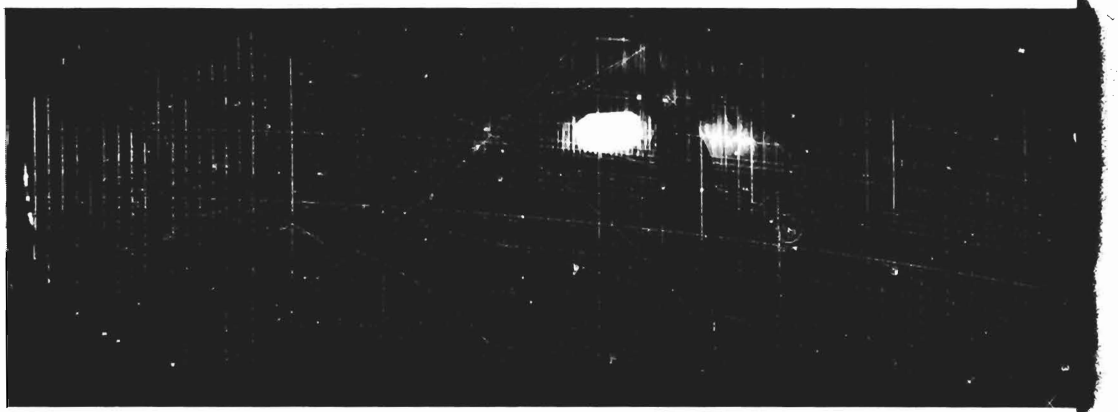
Main window being transported in exact orientation toward chamber.



FIRST COOL-DOWN

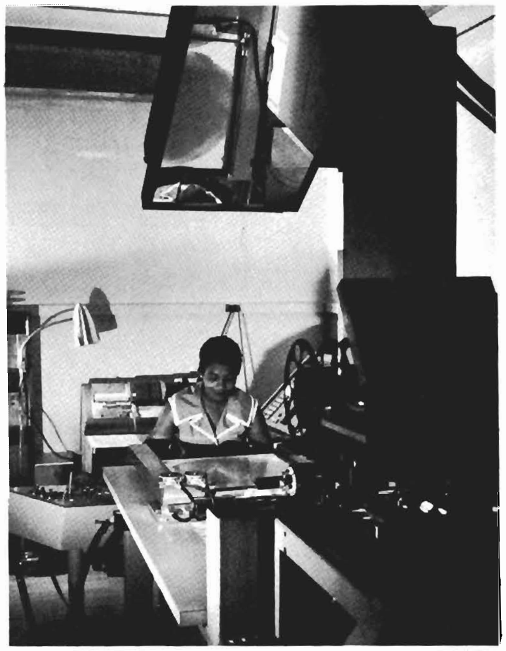

Chamber half full of liquid hydrogen.


Tracks! June 2, 1963.

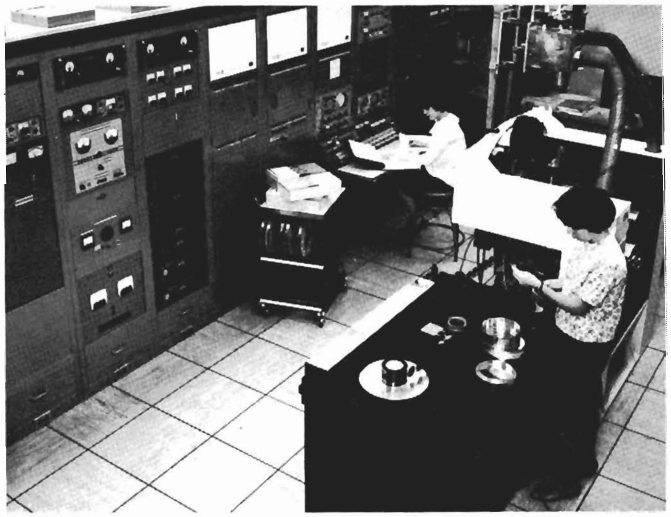

Better tracks.

Scanning machines which project the picture by means of a lens and mirror onto a scanning table are used to find events of interest.

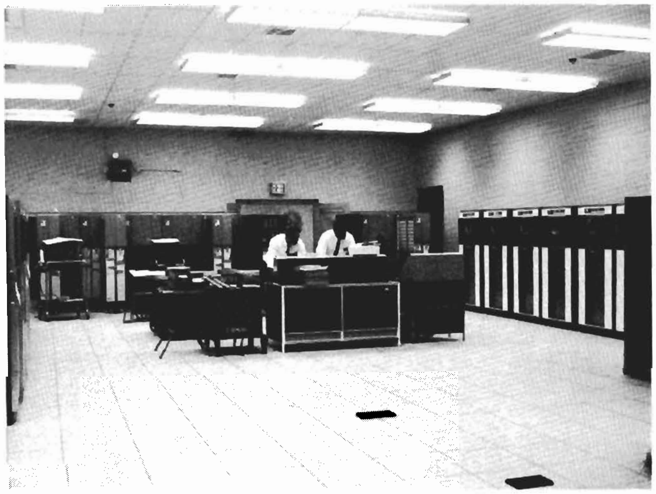
DATA PROCESSING EQUIPMENT



Events being projected and measured by a trained data processing technician.



The 70-mm Flying-Spot Digitizer (Hough-Powell device) and associated electronic equipment which is connected directly to a large digital computer.



The IBM 7094 digital computer at Brookhaven.

Glossary

(A few of the definitions used here are from "Glossary of Terms Frequently Used in High Energy Physics" published by the American Institute of Physics)

Accelerator	A machine for accelerating charged particles (usually protons or electrons) to high energies.
AGS	Abbreviation for the Alternating Gradient Synchrotron, the world's largest accelerator, located at Brookhaven. This proton synchrotron operates at energies up to 33 BeV, using vertical and horizontal strong focusing to keep the protons in the proper orbit. (See Synchrotron.)
Antiparticle	The equations describing the quantum theory indicate that for each particle there must exist a corresponding antiparticle with the same mass, spin, and mean life, but with opposite charge (for charged particles) and opposite magnetic moment. When a particle and its antiparticle interact, they may be annihilated with a release of energy. (See also footnote b, Table 1.)
Beam	See Separated beam.
BeV	A unit of energy equal to one billion (10^9) electron volts (sometimes called GeV outside the United States).
Bubble chamber	A device that detects charged particles by producing bubbles along the particles' path through a superheated liquid.
Cloud chamber	A device that detects charged particles by producing a droplet trail along the particles' path through a supercooled vapor.
Cosmotron	A proton synchrotron machine, located at Brookhaven, which accelerates protons up to energies of 3 BeV. (See Synchrotron.)
Counter	A charged particle produces light when it passes through certain materials. In modern counters photomultiplier tubes are used to convert this light into an electrical signal by which the passage of a charged particle can be detected. Scintillation counters and Cerenkov counters are examples of such devices.
Decay	Most of the elementary particles are unstable and decay by way of weak, strong, or electromagnetic interactions. The decay properties of various elementary particles are listed in Tables 1 and 2.
Decay products	The particles resulting from the decay of an unstable particle.

Detector	Any device used for detecting particles, e.g., a bubble chamber, cloud chamber, or spark chamber, emulsion, or electronic counter.
Deuterium	Heavy hydrogen. The nucleus of the deuterium atom consisting of a neutron and a proton is called the deuteron. It is an isotope of the proton, having the same charge but a different mass.
Elastic scattering	An interaction in which the outgoing particles are of the same type as the incoming ones, and in which no kinetic energy has been lost.
Electric charge	A property ascribed to certain particles to explain electrical attractive and repulsive forces. By definition, protons have positive charge while electrons have equal but opposite negative charge.
Electric field	A region in which a force is experienced by a charged particle or body; the direction of the field at a given point is the direction of the force on a positive test charge placed at that point.
Electron	An elementary particle with a unit negative electrical charge and a mass $1/1836$ that of the proton. Electrons surround the atom's positively charged nucleus and determine the atom's chemical properties.
Electron volt	The amount of kinetic energy gained by an electron when it is accelerated through a voltage difference of one volt. The electron volt is thus a unit of energy equal to 1.6×10^{-12} erg.
Elementary particle	A particle that cannot be described as a composite of two or more other particles.
Energy	A conserved quantity that can be neither created nor destroyed. It may, however, be exchanged from one body to another or converted from one form to another. According to the special theory of relativity, energy and mass are equivalent, being connected by the Einstein equation $E = mc^2$, where c is the speed of light. (See Electron volt; Rest mass.)
Event	See Nuclear interaction.
Gamma rays	High energy, short wavelength electromagnetic radiation emitted by a nucleus. Gamma rays are very penetrating and are best attenuated by dense materials.
Gauss	A unit of magnetic field strength defined as one line of force (or one maxwell) per square centimeter. The total number of lines of force passing through a surface is called the magnetic flux.

High energy physics	The branch of physics involving energies sufficiently high to cause particles emerging from an interaction to be different from those that entered. For example, for pi-mesons to be produced by a collision the incident particle must have an energy of at least 150 MeV. (Also called particle physics.)
Hydrogen	The element with the simplest atom found in nature. It consists of the nucleus (containing one proton) and an outer electron.
Hyperon	Any of a class of short-lived elementary nuclear particles with masses greater than that of the neutron. This term includes lambda, sigma, and cascade particles.
Inelastic process	A reaction in which the kinetic energy of the outgoing particles is not the same as that of the incoming particles. In such a reaction some energy may be converted into mass or may produce an excited state in a nucleus.
Interaction products	The particles created in a nuclear interaction (which see).
Interactions	There are four primary types of interaction in nature. 1. Strong interactions. These are manifested by the force that holds the nucleus together. They are characterized by their short range ($\approx 10^{-13}$ cm) and their great strength. 2. Electromagnetic Interactions. These are the interactions of charged particles with electromagnetic fields. 3. Weak Interactions. These short range interactions are many orders of magnitude weaker than either the strong or the electromagnetic ones. They occur in the decay of many particles. 4. Gravitational Interactions. These are the weakest of the four general types of interaction. They depend on the masses of the bodies involved and result in the mutual attraction of all bodies.
Isotopic spin	Isotopic spin is a nuclear quantum number obtained by considering a family of particles as different states of the same particle. For instance, an isotopic spin of ½ is assigned to the nucleon, with the components +½ for the proton and −½ for the neutron.
Linde cycle	A thermodynamic cycle in which refrigeration is produced by expansion of a high-pressure gas through an orifice.
Liquid hydrogen	Liquid hydrogen is commonly used as the detecting medium in bubble chambers. The boiling point of liquid hydrogen is −423°F at atmospheric pressure.

Magnetic field	A region in which a force is experienced by a magnetized body. A magnetic field also manifests itself by the force that it exerts upon electrically charged objects moving across it. (See Gauss.)
Mass	Mass is that property of an object by virtue of which it possesses inertia.
Mean life	Any unstable particle has a certain probability of "living" for some length of time. The average lifetime before decay for a large number of particles of the same kind is called the mean life.
Measuring machine	A machine used to measure curvature and angles of tracks from events found on a scanning machine. These measurements are then used to calculate other parameters, which enable a physicist to interpret the event.
MeV	A unit of energy equal to one million (10^6) electron volts.
Meson	Particles with mass greater than the electron mass and less than the mass of a nucleon are called mesons. Included in this group are the K meson, the mu meson (sometimes called muon), the pi meson (sometimes called pion), and many others (see Tables 1 and 2).
Momentum	The linear momentum of a particle due to translation is the product of its mass and velocity. The angular momentum of a particle is due to its rotation.
Neutrino	The neutrino is an uncharged particle with zero rest mass which was originally postulated to explain the beta decay of radioactive nuclei. The existence of the neutrino associated with electrons, ν_e, was confirmed at the Savannah River reactor in 1956. Another type of neutrino, associated with mu mesons, ν_μ, was discovered at Brookhaven in 1962.
Neutron	The neutron is a particle with no electric charge and a mass equal to 1838 electron masses. An isolated neutron is unstable and decays into an electron, proton, and neutrino in a period of about 15 minutes.
Nuclear force	The strong interaction force between nucleons and many other particles acting at short range.
Nuclear interaction	When two particles approach closely, there is a certain probability that they will interact with a resultant rearrangement of energy. In such nuclear interactions one or more new particles are created. (Also referred to as nuclear reaction, nuclear event, or nuclear collision.) (See Interactions.)

Nucleon	One of the particles of which the nucleus is composed, a neutron or a proton.
Nucleus	The small, central, positively charged portion of the atom in which almost all of its mass is concentrated. Nuclei have radii in the range from $\approx 10^{-13}$ to 10^{-12} cm.
Particle	A minute constituent of matter with a measurable mass.
Parity	According to the parity principle, a "mirror-image" of a physical process depicts a possible physical process obeying the same laws as the original one. It has been experimentally shown that this principle holds (namely, that parity is conserved) for the strong interactions, but not for the weak interactions. (See Interactions.)
Photon	A photon is a quantum of electromagnetic radiation; it may be described as a "bundle" or particle of radiation with a discrete quantity of energy.
Photosensitive tube	A device that converts light signals into electrical pulses.
Program	The set of detailed instructions by which an electronic computer carries out the computations required of it.
Proton	An elementary particle with a single positive electrical charge and a mass approximately equal to 1836 electron masses.
PSI	Pounds per square inch (unit of pressure).
Quantum theory	The theory on which all atomic and nuclear physics is based, whose primary postulate is that energy is not absorbed or radiated continuously, but discontinuously, in discrete units called quanta.
Rest mass	The mass of an object at rest. According to Einstein's special theory of relativity, the mass of an object increases with velocity, the effect becoming appreciable when the velocity of light is approached. Therefore, when speaking of the mass of a rapidly moving particle one must distinguish between its total mass and its rest mass.
Scanning machine	A machine designed to scan bubble chamber photographs for nuclear events of interest. The bubble chamber film is projected and inspected by trained scanners.

SEPARATED BEAM	A stream of particles having selected properties, separated and focused by electromagnetic means. A separated beam can be directed into a bubble chamber, where it causes interactions in the liquid.
SPIN	A quantum number characterizing a particle, which must be included when describing the total angular momentum of elementary particles or nuclei.
STEREOPHOTOGRAPHY	Photography of an object from two or more different directions to establish the precise position of the object in space. Stereoscopic views can be combined optically to show a three-dimensional effect; measurements from stereoscopic views are used to calculate positions in space.
STRANGE PARTICLES	A class of elementary particles whose lifetimes are extremely long on a nuclear time scale. Hyperons and K mesons are in this class. (See STRANGENESS.)
STRANGENESS	A quantum number such as $+1, 0, -1, -2$ or -3, which is assigned to particles in order to describe their production and decay processes. It is then possible to account for all observations by assuming that strangeness is conserved in strong and electromagnetic interactions, but not in weak interactions.
STRONG INTERACTIONS	See INTERACTIONS.
SYNCHROTRON	An accelerator in which particles are accelerated inside a magnet ring of essentially constant radius. The particles are guided in their orbits of fixed radius by magnets whose fields increase as the particles gain energy. The accelerating forces are produced by electromagnetic fields, oscillating at radio frequencies, and synchronized in time with the passage of the particles.
TRACK	The trail of bubbles produced by charged particles along their path through the bubble chamber.
VAPOR PRESSURE	The pressure exerted by the vapor (gas) given off by a liquid. The vapor pressure of a liquid depends strongly on its temperature. (Also called saturation pressure.)
WEAK INTERACTIONS	See INTERACTIONS.
YOKE	The metal frame that connects and supports the coils of an electromagnet. If made of magnet iron, the yoke intensifies the magnetic field produced by the coils alone.

Table 1

Nuclear Particles, Stable and Quasi-Stable

		Rest mass (BeV)	Mean life (sec)	Spin	Parity	Isotopic spin	Strangeness	Examples of decay modes
Photon	γ	0	Stable	1	—		0	Stable
Neutrino	ν_e, ν_μ *	0	Stable	½			0	Stable
Antineutrino	$\bar{\nu}_e, \bar{\nu}_\mu$							
Electron	e^+, e^-	0.00051	Stable	½			0	Stable
Mu meson	μ^+, μ^-	0.1057	2.2×10^{-6}	½			0	$e^+ + \nu_e + \bar{\nu}_\mu$, $e^- + \bar{\nu}_e + \nu_\mu$
Charged pi meson	π^+, π^-	0.1396	2.6×10^{-8}	0	—	1	0	$\mu^+ + \nu_\mu$, $\mu^- + \bar{\nu}_\mu$
Neutral pi meson	π^0	0.1350	2×10^{-16}					$\gamma + \gamma$
Eta meson	η^0	0.549	$< 1 \times 10^{-14}$	0	—	0	0	$\pi^+ + \pi^- + \pi^0$, $\gamma + \gamma$, $\pi^0 + \pi^0 + \pi^0$
Charged *K* meson	K^+, K^-	0.4938	1.2×10^{-8}	0	—	½	+1, −1	$\mu^+ + \nu_\mu$, $\mu^- + \bar{\nu}_\mu$, $\pi^+ + \pi^0$, $\pi^- + \pi^0$, 3 π's, etc.
Neutral *K* meson	$K^0, \overline{K^0}$	0.4980	½ of 0.9×10^{-10}					
			½ of 5.6×10^{-8}					$\pi^+ + \pi^-$, $\pi^0 + \pi^0$, 3 π's, etc.
Proton	p	0.9383	Stable	½	+	½	0	Stable
Neutron	n	0.9396	1.0×10^3					$p + e^- + \bar{\nu}_e$
Antiproton**	$\bar{p}$	0.9383	Stable	½	+	½	0	Stable
Antineutron	$\bar{n}$	0.9396	1.0×10^3					$\bar{p} + e^+ + \nu_e$
Lambda hyperon	Λ^0	1.1154	2.6×10^{-10}†	½	+	½	−1	$p + \pi^-$, $n + \pi^0$
Sigma-plus hyperon	Σ^+	1.1894	0.8×10^{-10}	½	+	½	−1	$p + \pi^0$, $n + \pi^+$
Sigma-minus hyperon	Σ^-	1.1971	1.6×10^{-10}					$n + \pi^-$
Neutral sigma hyperon	Σ^0	1.1924	$< 1 \times 10^{-14}$					$\Lambda^0 + \gamma$
Xi-minus hyperon	Ξ^-	1.3208	1.7×10^{-10}	½	+	½	−2	$\Lambda^0 + \pi^-$
Neutral xi hyperon	Ξ^0	1.3143	3.1×10^{-10}					$\Lambda^0 + \pi^0$
Omega-minus hyperon	Ω^-	1.675	$\approx 10^{-10}$	3/2?	+?	0	−3	$\Xi^- + \pi^0$, $\Xi^0 + \pi^-$, $\Lambda^0 + K^-$

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*Neutrinos are denoted by "ν_e" or "ν_μ" according to whether they are associated with electrons or with muons during decays of particles.

**Only the antiproton and antineutron are listed here as antiparticles to the proton and neutron. The antiparticles of all the further listed particles are also expected to exist. Most have been found.

†On a nuclear scale a mean life of 10^{-10} sec can be considered about 10^{13} times "too long" to signify an instability. Therefore the decaying particles listed here are considered quasi-stable. Because of this behavior they have also been called "strange."

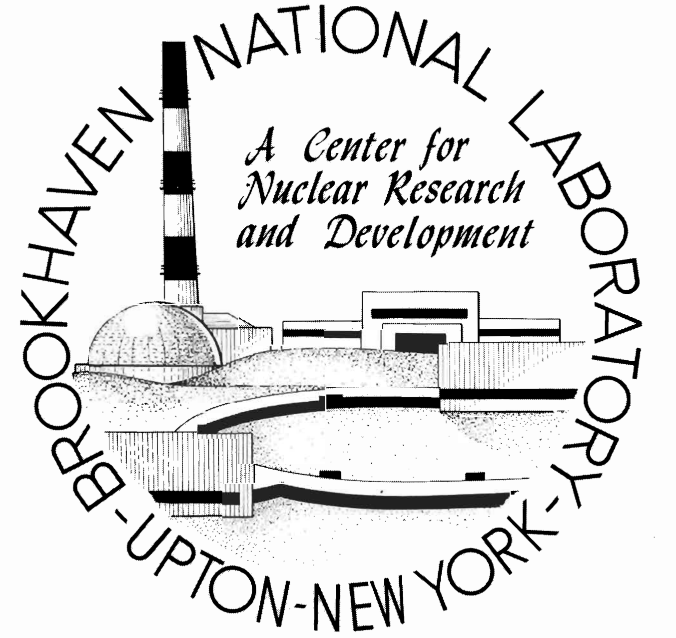
Table 2

Some Unstable Particles (with mean lives of $\approx 10^{-23}$ sec)

	Rest mass (BeV)	Spin	Parity	Isotopic spin	Strangeness	Examples of decay modes
ρ^+, ρ^-, ρ^0	0.763	1	$-$	1	0	$\pi^+ + \pi^0, \pi^- + \pi^0, \pi^+ + \pi^-$
ω^0	0.783	1	$-$	0	0	$\pi^+ + \pi^- + \pi^0$
ϕ^0	1.020	1	$-$	0	0	$K^+ + K^-, K^0 + \overline{K^0}$
f^0	1.253	2	$+$	0	0	$\pi^+ + \pi^-, \pi^0 + \pi^0$
K^{*+}, K^{*-}, K^{*0}	0.891	1	$-$	½	$+1, -1$	$K^+ + \pi^0, K^- + \pi^0, K^0 + \pi^+, K^0 + \pi^0$
$N^{*++}, N^{*+}, N^{*0}, N^{*-}$	1.238	3/2	$+$	3/2	0	$p + \pi^+, n + \pi^+, n + \pi^-, p + \pi^-$
Y_0^*	1.405	½	$-$	0	-1	$\Sigma^+ + \pi^-, \Sigma^- + \pi^+$
$Y_1^{*+}, Y_1^{*-}, Y_1^{*0}$	1.382	3/2	$+$	1	-1	$\Lambda + \pi^+, \Lambda + \pi^-, \Lambda + \pi^0$
Ξ^{*-}, Ξ^{*0}	1.529	3/2	$+$	½	-2	$\Xi^- + \pi^0, \Xi^0 + \pi^-, \Xi^0 + \pi^0$

Parameters for the Brookhaven 80-Inch Liquid Hydrogen Bubble Chamber

Dimensions	Liquid hydrogen as seen by cameras: 80 × 27 × 26 inches.
Volume	Total liquid hydrogen: 1500 liters (400 gallons). Liquid hydrogen as seen by cameras: 900 liters (240 gallons).
Total weight	Chamber, magnet complex, undercarriage, vacuum tank: 480 tons.
Operating pressure	Hydrogen: ≈80 pounds per square inch.
Expansion	Piston dimensions: 36 inches in diameter by 32 inches high. Piston weight: 250 pounds. Normal expansion ratio: ½ percent (piston motion ½ inch in ≈13 milliseconds). Compressor power: 150 horsepower.
Cycling rate	Maximum: one expansion cycle per second.
Illumination	Darkfield: retrodirective (coat hangers).
Window	Glass, optical quality, partially tempered: 81 × 30 × 6½ inches thick.
Cameras	Three or four cameras used, ≈14° minimum stereo angle.
Film	1000-foot rolls, perforated, 70-mm width.
Refrigerator	Hydrogen capacity: 2500 watts. Hydrogen and nitrogen compressor power: 500 horsepower.
Insulation	Aluminized Mylar,® 200 to 300 layers inside high vacuum (10^{-6} mm of Hg).
Magnet	Field: 20,400 gauss. Power: 4 megawatts. Voltage: 250 volts. Current: 16,000 amperes. Cooling water: 570 gallons per minute. Copper weight: 31 tons.
Magnet carriage	Translation, sliding. Rotation: 360°. Elevation: 24 inches.



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