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ABSTRACT

Following the proposal of Donald Glaser for the use of superheated liquids as radiation sensitive track forming nuclear detectors, bubble chambers operating with liquid hydrogen have been made. Three chambers of increasing size have been operated, the largest being four inches in diameter. The operating principles of these chambers have been investigated. A chamber ten inches in diameter is under construction and a much larger instrument is now planned. It is believed that the bubble chamber will materially speed the accumulation of data regarding high energy nuclear reactions.

HYDROGEN BUBBLE CHAMBERS FOR NUCLEAR RESEARCH

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INTRODUCTION

A new instrument, recently invented and currently under development, gives promise of becoming a very valuable tool for high energy nuclear research. This instrument is termed a bubble chamber.[1]

The instruments of nuclear research can be divided into two functional groups: the accelerators, which provide high energy particles, and the nuclear detectors, used to study the interactions of high energy particles with matter. Accelerators are usually thought of as the important instruments of nuclear physics. However, progress in the field has been strongly controlled by the progress of particle detecting instrumentation. A large body of excellent nuclear research has been done using only ingenious detection methods for the study of interactions of cosmic rays with nuclei.

Cosmic rays provide a low intensity source of subatomic particles of almost limitless energy and great variety. The principle advantage in the use of accelerators is the enormously greater particle flux an accelerator can provide. As accelerator development provides increased particle energies and intensities, it is necessary to develop new detection techniques that can efficiently use the power of the accelerators.

Prior to the invention of the bubble chamber there were three basic techniques of particle detection extensively used in high energy nuclear investigations. The use of particle counters is one of these.[2] Another technique involves an instrument known as the Wilson cloud chamber.[3] The third makes use of specially compounded photographic emulsions.[4] The counting method has advantages in the rate at which data can be accumulated. It is difficult, however, to distinguish between different radiations with counters. About all a counter can do is to signal the passage of a particle through its sensitive volume. The second two techniques mentioned do something quite different. They record a detailed trajectory of any particle that passes through their sensitive volume. They also record the trajectories of secondary particles that result from nuclear interactions

within them.

The track forming detectors are most useful for finding previously unknown kinds of nuclear interactions or for investigating reactions where new particles are created. Once these instruments have shown the basic properties of a new nuclear process, counter experiments can be designed to accumulate more detailed data rapidly. The bubble chamber is the newest member of the track forming detector family, and has important advantages over older methods.

DETECTION OF NUCLEAR REACTIONS

The advantages of the bubble chamber can perhaps be best illustrated by examining a very generalized nuclear reaction and considering what information regarding a reaction is needed. Let us choose a type of reaction that actually occurs in high energy experiments. Assume that a particle X, possessing a high energy, suffers a collision with a nucleon Y. A possible reaction might be written,

$$X + Y + Q \longrightarrow X' + Y' + Z + Q'.$$
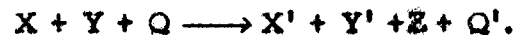
X' might be identified with the primary high energy particle, or might not. Y and Y' also may or may not retain the same identity. Z represents a particle created in the reaction. The term Q represents the energy of the incoming particle. Q' will be different from Q and their difference represents the energy required to create the particle Z. All resultant particles leave the center of reaction with the energy Q' shared among them.

The most important data needed for interpretation of the reaction are the following. 1. The nature and energy of the primary particle. This may be known from the properties of the particle source, or may have to be measured separately. 2. The type of particle struck. 3. The mass and charge of each particle leaving the reaction and their respective energies. 4. The direction in which each particle approaches or leaves the scene of the event. 5. The relative probability of the reaction's happening.

When a nuclear reaction, such as is shown in Fig 1, is examined, it can be imagined that the determination of these quantities is not simple. Determination of the type of particle struck can be eliminated if the detector can operate with only one kind of nucleus present. This is almost possible in the case

of the cloud chamber, where the filling gas may be hydrogen mixed with a small amount of condensible vapor. It is quite impossible in the case of a photographic emulsion, which is a very complicated chemical mixture.

One can learn the charges on the particles by bending them in a magnetic field. The paths of particles with positive and negative charges curve in opposite directions. The particle energies, or more properly their momenta, can also be determined in the cloud chamber with the aid of a magnetic field. The radius of curvature of the trajectory of a charged particle moving in a magnetic field is directly proportional to the particle momentum.[5] The magnetic bending technique does not work with emulsion detectors because random scattering, due to the highly charged silver and bromine nuclei, causes random curvature larger than that which can be produced with practical magnets.

In emulsions one can sometimes have a long enough track for the particle to come to rest. This total range is a function of particle energy and mass.[6] One can also make use of the scattering, which destroys the possibility of magnetic analysis,[6] to get an approximate value for the momentum of a track forming particle. This process is a tedious one, but emulsion workers produce magnificent results with it.

The probability that a given nuclear reaction will occur is controlled by many factors. The first is that enough energy be available to make the reaction "go." A second factor is how many nuclei the particle passes near before falling below the threshold energy. If the particle has a very high energy, compared with the threshold energy of the reaction sought, one can say that the probability of reaction per unit length of path is proportional to the density of target nuclei. It is desirable that the nuclear density be large within a track forming detector in order that the size of the detector remains reasonable and that the probability of observing interesting reactions. The emulsion detector has a high density of nuclei per unit volume. It has proven impractical to have high densities in cloud chambers. Cloud chambers are gas-phase devices, and high densities mean high pressures and attendant operational difficulties.

To sum up, the emulsion has high density and gives excellent spatial definition of the tracks of particles, but momentum and energy measurement is a difficult task. The cloud chamber can also give an excellent spatial display of particle trajectories, and can give a simple momentum measurement, but has low density. Counters can have good density,[2] but it is impractical to use enough

of them to define the tracks of many particles accurately in space. With the
appearance of new accelerators in the multibillion electron volt range,[7,8] the
shortcomings of these older detectors became increasingly evident.

GLASER'S IDEA

It was against this background that Donald Glaser, of the Univer-
sity of Michigan, began a search for a new method of particle detection. His
hope was to find a detector more nearly matching the power of the new accel-
erators. His success is evident in that almost all high energy physics labora-
tories are now building devices along the line he proposed.

Glaser presented the details of this new detector at the 1953 meeting
of the American Physical Society, in Washington, D.C.[9,10] He showed the first
photographs of the tracks of nuclear particles traversing a superheated liquid.
In his search for a better detector he had noticed that the phenomenon of the
growth of vapor bubbles in a superheated liquid is similar to that of the formation
of liquid droplets in a cloud chamber. These two phenomena are treated in texts
by very similar methods. Glaser recognized the possibility that bubble growth
in a superheated liquid might start from the ions formed along the path of a fast
nuclear particle, and that such bubbles, if formed, could be photographed to give
a record of a trajectory. One obvious advantage of a liquid detecting medium
would be its high nuclear density at reasonable pressure. Glaser developed a
theory, based on the balance between surface tension forces in the liquid and
the electrostatic forces caused by ions, that predicted success with certain
liquids and degrees of superheat.

He also investigated the properties of bubble chambers experi-
mentally. Early in his program he assembled a pyrex chamber 0.5 inch in
diameter and 1 inch long. With diethyl ether as a working fluid, the chamber
was heated to a temperature of 140°C while pressurized to about 20 atmospheres
to prevent boiling. By reducing the pressure, the liquid could be put into a super-
heated condition. Glaser found that when the pressure was released, the liquid
would remain quiescent for periods up to 100 seconds. He also found that the
superheated liquid would erupt into violent boiling if a source of nuclear radiation
was brought near. Glaser arranged a counting circuit such that any cosmic ray
passing through the chamber would flash a stroboscopic lamp, which illuminated
the chamber. A camera was provided, and photographs of the tracks of mesons

were recorded.

The report of this work caused considerable interest among the physicists present. The immediate question arose whether the effect could be produced in liquid hydrogen. Hydrogen occupies a unique place as a target material in high energy physics, because it contains only the simplest nuclei, protons. A reaction taking place in a mass of hydrogen has the struck particle automatically identified. Further, if more than two positively charged particles are observed to leave an interaction, it is immediately evident that particles have been created. This is not true when one bombards more complex nuclei.

HYDROGEN FILLED CHAMBERS

Several members of the staff of the University of California Radiation Laboratory heard Donald Glaser's paper. They returned to Berkeley determined to find out whether hydrogen could be used in the device he proposed. It was apparent that operation with hydrogen would involve complex problems in cryogenics. At normal atmospheric pressure, hydrogen boils at 20°K. Its critical temperature is 33°K, above which no liquid phase is possible. If a hydrogen filled bubble chamber was to operate at all, the operating temperature must lie between these two values. After a short series of experiments to verify Glaser's result with ether, the investigation of hydrogen chambers was begun.

Before describing the chambers made at the Radiation Laboratory, let us examine the properties of hydrogen at low temperatures. Like all real gasses, hydrogen ceases to obey the simple relation

$$PV = NRT$$

at a sufficiently low temperature. Figure 2 is a plot of the pressure-volume relationship observed for a real gas in the region of interest. Several isotherms are plotted. Those with temperatures above the critical temperature are unimportant to bubble chamber operation. Let us examine the one marked $T \ll T_k$. Starting along this curve, to the right of point E, the working substance will be a gas. If we reduce the volume, the pressure will increase until the curve intersects the vapor saturation curve at point E. If we continue compression, generally we will find that the pressure now remains constant. The PV relation follows the line ECA, intersecting the liquid saturation curve at point A. The region of constant pressure is one in which two phases, liquid and gas, are in

stable equilibrium.   A change in volume merely changes the relative proportion
of these two components.   Compression beyond point A will result in a rapid
rise in pressure, since to the left of point A only liquid can exist.

If a pure gas is compressed in a clean and smooth walled vessel,
one frequently finds that the PV relationship will not follow along ECA.   The
pressure may instead rise to point D.   Under this condition the material remains
gaseous even though inside the vapor saturation region.   If some disturbance
occurs, part of the gas may suddenly condense to liquid.   Similarly, if we start
with a mass of liquid to the left of point A, and lower the pressure, it may trace
out the curve AB.   If expansion is stopped at B, the liquid is in an unstable
condition.   A small disturbance can result in boiling, which restores the vapor
liquid equilibrium normally existing along the line ACE.   It is this latter process
which provides the unstable condition necessary for bubble chamber operation.

Using Glaser's theory and experimental data on the properties of
hydrogen at low temperatures, it was predicted that satisfactory operating condi-
tions might be: a liquid temperature between 25 and 29°K, with a corresponding
vapor pressure of 3.2 to 6.6 atmospheres.   In the compressed phase, a pressure
above the saturation vapor pressure would be applied.   The chambers could be
conveniently expanded to a pressure of one atmosphere and this was chosen for
the reduced pressure.

Bubble Growth

The problem of bubble growth in a superheated liquid had received
theoretical attention prior to the invention of the bubble chamber.[11,12] If a small
bubble appears in a superheated medium it may either grow or collapse.   Its fate
will be determined by the forces acting on it.   The static pressure and the surface
tension of the liquid tend to collapse the bubble.   The pressure of vapor inside the
bubble tends to expand it.   It can be shown that the pressure due to surface tension
is given by

$$P_\sigma = 2\sigma/r,$$

where σ is the surface tension constant of the liquid and r is the radius of the
bubble.   Owing to the $1/r$ relation, a bubble cannot grow from a very small
radius in the absence of other forces.   Glaser demonstrated that the presence
of electrostatic charge within a bubble will also contribute a force.   He proved

that the presence of a single electric charge within will lead to collapse, and
also that if more than one charge is contained, the electrostatic force tends to
cause the bubble to grow.*

       Once a bubble has reached a certain size, it continues to grow.
The rate of growth is then determined by the supply of heat of vaporization to the
liquid-gas interface.[12] This has been investigated in other connections. The
results predict that the radius will increase according to

$$r = kt^{1/2},$$

where k depends on properties of the liquid. The term t is the time after
reaching a radius where surface tension is no longer an important factor. For
hydrogen at 28°K and one atmosphere, we have found that this relation becomes

$$r = 0.2\, t^{1/2},$$

with t measured in milliseconds and r measured in millimeters.

CONSTRUCTION OF HYDROGEN CHAMBERS

       The first hydrogen filled bubble chamber to operate at the Univer-
sity of California was constructed by John Wood.[13] This chamber was made
entirely of glass. Its temperature was controlled by surrounding it with a bath
of liquid hydrogen, the bath being pressurized to 6.5 atmospheres. This bath
then boiled at a temperature of 29.3°K. Hydrogen was introduced inside the
chamber under sufficient pressure to produce liquefaction. A valve that could
suddenly lower the chamber pressure was provided. When the pressure was
released there was appreciable delay before boiling began. A stroboscopic
light was arranged to flash shortly after depressurizing the liquid, and photo-
graphs showed that tracks of nuclear particles could be produced. It was found
that the time during which the chamber could be kept superheated was about one
second in the absence of nuclear radiation. It was also found that the chamber

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* There is at present some dispute regarding the electrostatic theory of bubble
   growth. It has been argued that local heating along a particle trajectory could
   result in small regions of the liquid being far above the critical temperature.
   In that event, arguments based on the properties of superheated liquids would
   be inapplicable.

walls had to be very smooth or boiling would start on rough places immediately after pressure release.

Since a chamber of interest for physics research had to be large, it was necessary that the all glass construction be abandoned. The problem of maintaining smoothness was ignored, and a chamber was constructed from a metal cylinder using glass ends for viewing. This chamber was 2.5 inches in diameter. It was constructed by Peter Schwemin and Douglas Parmentier.[14] The same method of temperature control was used for this chamber as for the all glass chamber. It was indeed found that boiling occurred at the metal-glass joint upon expansion. However, the important discovery was made that this boiling increased the pressure relatively slowly. The bulk of the liquid would remain radiation sensitive for a time of at least 20 milliseconds.

The accelerators to be used with these chambers are pulsed machines;[7,8] their output can be delivered into a time span of a few milliseconds repeated every few seconds. There is adequate time to photograph tracks before metal-glass chambers lose sensitivity. With this information it became clear that hydrogen bubble chambers could be made in any desired size.

THE FOUR-INCH CHAMBER

A four-inch chamber,[14] two inches in depth was begun immediately. This chamber was intended for nuclear research and involved several departures from previous technique. The four-inch chamber construction is illustrated schematically in Fig. 3. The apparatus is contained in a vessel that is evacuated to provide thermal insulation. A hollow cylindrical shield, suspended in the vacuum, contains liquid nitrogen. This serves as a thermal radiation shield for a flask of liquid hydrogen, which is suspended from the vacuum tank top, concentric with the nitrogen shield. The hydrogen flask contains liquid hydrogen boiling at 20°K. The bottom of the flask is in thermal contact with the bubble chamber. Thermal contact is provided by a brass member which contains a small electric heater. The dimensions of the brass piece are chosen so that it will provide the desired thermal conductivity between the chamber and the flask. By proper choice of conductivity, the bubble chamber temperature is maintained in the neighborhood of 27°K. The brass conducts enough heat to balance thermal radiation and certain other heat sources which act on the chamber during operation. Since it is impossible to maintain constant heat input to the chamber, the heat leak

is made slightly too conductive. The chamber temperature is trimmed to final operating value by adjusting the power supplied to the heater.

The vacuum system is provided with glass windows to permit photography, and with thin aluminum windows to permit entry of particles to be studied.

An expansion line of stainless steel tubing connects the interior of the chamber with the expansion system. This latter mechanism is located outside the insulating vacuum and operates at room temperature. Several expansion systems were tried in the course of development. The present one consists of a fast opening solenoid valve connected between the expansion line and a cylinder and piston. Just prior to expansion, the solenoid valve is closed and the chamber pressure is 6 atmospheres. The piston is retracted to create a partial vacuum in the cylinder. To sensitize the chamber, the valve is opened and gas from the expansion line enters the cylinder. Opening of the valve lowers the chamber pressure in a time of 5 milliseconds. The chamber is found to remain radiation sensitive for 50 milliseconds. After this, the piston is driven forward to re-compress the hydrogen. The solenoid valve automatically closes at the peak of the compression stroke, completing the cycle.

The expansion line is filled with a series of tufts of copper wool. This material is called a heat regenerator.[15] It is the function of this material to maintain a constant thermal gradient along the expansion line. It does this by taking up heat as room temperature gas is displaced from the cylinder into the expansion line, later releasing this heat to the gas on the expansion part of the cycle. If the regenerator were absent, cold gas would enter the cylinder during each expansion. This gas would be warmed by the walls of the cylinder, and upon recompression would carry a large amount of heat to the chamber.

Even with a regenerator, considerable heating of the hydrogen occurs on each cycle of operation. The diagram of Fig. 4 illustrates the pressure volume cycle. Initially, the pressure is at P_1 and the volume at V_1. Upon opening the expansion valve, the volume increases to V_2 and the pressure drops to P_2. With a rate controlled by the bubble growth law, the pressure rises to P_3 at constant volume. P_3 is the saturated vapor pressure for hydrogen at the chamber temperature. As the system is recompressed the pressure and volume return to the original conditions. The area enclosed on this diagram represents work done on the system by the expansion mechanism. The exact path of a chamber cycle

on the PV diagram is partially indeterminate. One can assume a triangular trace as shown and calculate the minimum possible heat input. In practice such a calculation is found to give a reliable answer.

For the four-inch chamber the expansion volume is equal to the chamber volume. The effective volume of the expansion line is 10% of the chamber volume. The initial pressure is 6-atmospheres and the final pressure is 1-atmosphere. The saturation vapor pressure (P_3) is typically 5.5-atmospheres. From these values the P-V work amounts to 20 Joules per pulse. If a cyclic rate of 12 operations per minute is used, 4 watts will be delivered to the chamber. This heat must be removed by evaporating hydrogen from the flask.

Two means could be used to reduce this heat input. One would be to expand and repressurize quickly, before the pressure could rise owing to boiling within the chamber. The rate of rise of pressure from P_2 to P_3 is an inverse function of the size of the chamber. For the 4-inch chamber, the time constant associated with this pressure rise is 0.1 second. With larger chambers, the self-repressurizing time will be longer, and it may be possible to follow the dotted curve of Fig. 4 on the compression cycle. This would materially reduce the heat input.

Another and better method would be to eliminate altogether the vapor part of the expansion system. The reason that the volume of the expansion cylinder must be so large is that the gas in the expansion line is warmed from an average temperature of 160°K up to 300°K in passing into the cylinder. In addition, the pressure falls by a factor of six. Therefore, the volume change in the system needs to be about ten times the expansion-line volume for proper expansion. The compressibility of liquid hydrogen over this pressure range is quite small. Most of the volume change is associated with gas expansion. If a cold piston were to act directly on the chamber liquid, the change of system volume required for the desired change in pressure would be only that due to the compressibility of the liquid; about three percent. This would drastically reduce the area swept out on the PV diagram.

It is not practical to reduce the expansion line volume in a vapor expansion system sufficiently to gain much. Because of the finite compressibility of the liquid hydrogen, some space must be allowed for liquid to rise in the tube.

It is also necessary to provide sufficient space to allow a regonerator to be installed, and to have a large line so that the chamber pressure can be reduced quickly.

Photography and Illumination

When bubbles form along the track of a particle, they are very short-lived and must be photographed to provide a permanent record of the event. The problem of successful hydrogen bubble photography is somewhat different from that encountered in the photography of cloud chamber droplets. The difference in index of refraction between the bubble and the surrounding liquid is less than 0.09. Also the object to be photographed has a lower index of refraction than the medium surrounding it. A theoretical and experimental determination of the distribution of scattered light from a bubble in liquid hydrogen showed the scattering to be predominantly forward, i.e., in the direction of the original light. An approximate distribution of the scattering is shown in Fig. 5. Very little light is scattered through angles larger than 5° from the original direction. In order that such objects may be best photographed, light must be passed through the liquid in such a way that it does not strike the camera lens. The direction is chosen so that rays refracted by small angles do enter the camera lens, producing a photographic image. The method of illumination is shown in Fig. 6. Since for accurate analysis it is necessary to reconstruct the direction of a track in space, stereo photography is used.

Windows

One of the most difficult problems encountered in the design of hydrogen bubble chambers is the design of a suitable window seal. Since it is necessary that the chamber operate in vacuum, permissible leak rates are exceedingly small. The large difference in thermal expansion between transparent materials and metals complicates the problem. There are no known materials that retain sufficient flexibility at 20° K to permit a flexible gasket design. At present, the window seal uses lead gaskets with heavy spring loading to compensate for differential expansion and flow of the lead. Other approaches to this problem are under development. One that appears promising is a solder seal between a flexible metal section and the glass.

Bending Magnets

The scattering of nuclear particles by hydrogen nuclei is a very small effect. Consequently, magnetic momentum and charge analysis is possible. The four-inch chamber has been equipped with Helmholtz coils which produce a pulsed magnetic field of 15,000 gauss throughout the chamber volume. By means of this field, the curvature of particles with energies as large as ten billion electron volts can be measured. The use of a pulsed magnet complicates the chamber design somewhat because of the eddy current heating which is produced in the chamber walls. It was found necessary to make the chamber of thin stainless steel and to split the window flanges to reduce this source of heat.

Operation

Figures 7 and 8 show the 4-inch chamber as completed. With it, numerous photographs have been made of interesting nuclear events. Experiments have been performed using both the 300-Mev synchrotron and the 6-Bev Bevatron as particle sources. A typical interesting event is shown in Fig. 9. This has been tentatively identified as pion pair production through the reaction

$$\pi^- + P \longrightarrow \pi^- + P + \pi^- + \pi^+$$

FUTURE PLANS

Early in 1955 plans were begun for two larger chambers. The design of the first of these is very similar to the four-inch chamber design, but it is to be 10 inches in diameter. Some modification of the four-inch arrangement of refrigerating dewars and illumination system was made to permit the new chamber to fit into an existing magnet. The ten-inch chamber is intended to serve two functions. First, it is to be a useful tool for nuclear research, and complete equipment for precision track analysis is being provided. Second, it will serve as an engineering tool and check point along the way to a chamber optimized for research at the energy of the Bevatron, 6 Bev. The ten-inch chamber is nearly complete as of this writing and will be placed in operation this Fall.

In choosing the dimensions of an optimum chamber for high energy research, [16] one must balance the desire to make it as large as possible against

eaoe of operation. By considering the dynamics of some known reactions, some broad guides as to the best size can be obtained. One of the moot interesting kinds of events that is observed in very high energy processes is the disappearance and reappearance of charged particles. This can happen in reactions where the incoming charged particle interacts with one of opposite charge. In such a reaction, the reaction products may be electrically neutral and leave no tracks. It happens that some of these reaction products have very short lifetimes, and decay into pairo of charged particles. If the apparatus is large enough, this decay may occur within the detector. Because the pair of decay products are charged they will produce tracks. A typical reaction of this sort is

$$\pi^- + P^+ \longrightarrow \theta^0 + \lambda^0$$

$$\theta^0 \longrightarrow \pi^+ + \pi^- \qquad \lambda^0 \longrightarrow P^+ + \pi^-$$
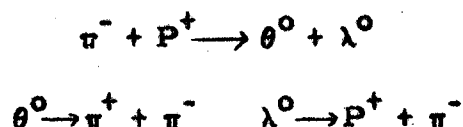
The dynamics of this reaction are illustrated by Fig. 10. The ellipses shown in Fig. 9 are contours one uncharged particle mean life away from the point of reaction. Relativisitic effects cauoe a particle emitted in along the direction of the primary particle to travel further before decay.

Through consideration of this and similar reactions, the dimensions of a "best" chamber have been chosen. It will have a length of 72 inches, a width of 20 inches and a depth of 15 inches. It will contain 350 liters of liquid hydrogen. A large magnet will be provided for momentum analysis. With such a chamber there will be sufficient track length to permit observation of exceedingly rare events. It io estimated that a day of operation in conjunction with the Bevatron can yield ao many as 10,000 interesting events.

This power produces a severe data-analyois problem.[16] A man working with a deok calculator could properly analyze not more than about 10 events per day. To eliminate this bottleneck, a program for transferring track coordinates into punched card data storage is being developed. For each interesting event, a set of cards will be prepared for an automatic computer. The computer will then make a calculation of the momenta of the particles, and from certain other information it can also make various trial identifications of the particles. If the computer is suitably programmed, corrections for nonuniform magnetic field and optical distortions can also be made.

ACKNOWLEDGMENTS

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CAPTIONS

Fig. 1. A nuclear reaction in hydrogen. A six prong star can be seen near the top of the picture. Photo made by Dr. Wilson Powell's cloud chamber group at UCRL.

Fig. 2. A Pressure-volume plot of isothermal curves for a real gas.

Fig. 3. A schematic diagram of the physical arrangment of four-inch hydrogen bubble chamber.

Fig. 4. Pressure volume relationship during a cycle of chamber operation.

Fig. 5. Distribution of light scattered from a bubble in liquid hydrogen. The graph is illustrative, not a plot of measured values.

Fig. 6. Dark field illumination scheme used for photography of events in four-inch chamber.

Fig. 7. Four-inch liquid hydrogen bubble chamber removed from vacuum vessel. The liquid nitrogen shield, the top of the hydrogen flask, the chamber and one magnetic field coil can be seen.

Fig. 8. The four-inch chamber is shown ready for operation near an accelerator.

Fig. 9. Stereoscopic views of possible π-meson pair production in four-inch chamber.

Fig. 10. Decay contours for θ° and λ° for $\pi^{-} + P \longrightarrow \theta^{\circ} + \lambda^{\circ}$ from 2 to 6 Bev.

Fig. 1

Fig. 2

Fig. 3

VOLUME OF SYSTEM

Fig. 4

DIRECTION OF ILLUMINATION

~12°

VAPOR BUBBLE IN
LIQUID HYDROGEN

Fig. 5

DIFFUSER

CHAMBER

PATH OF
CRITICAL
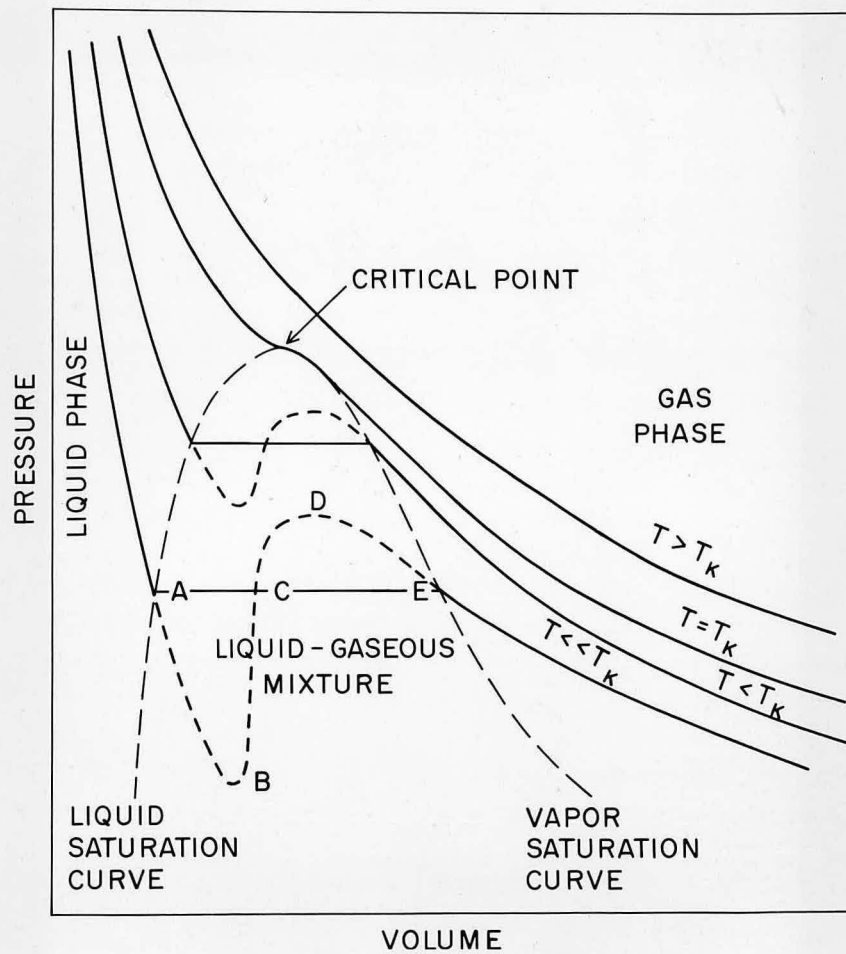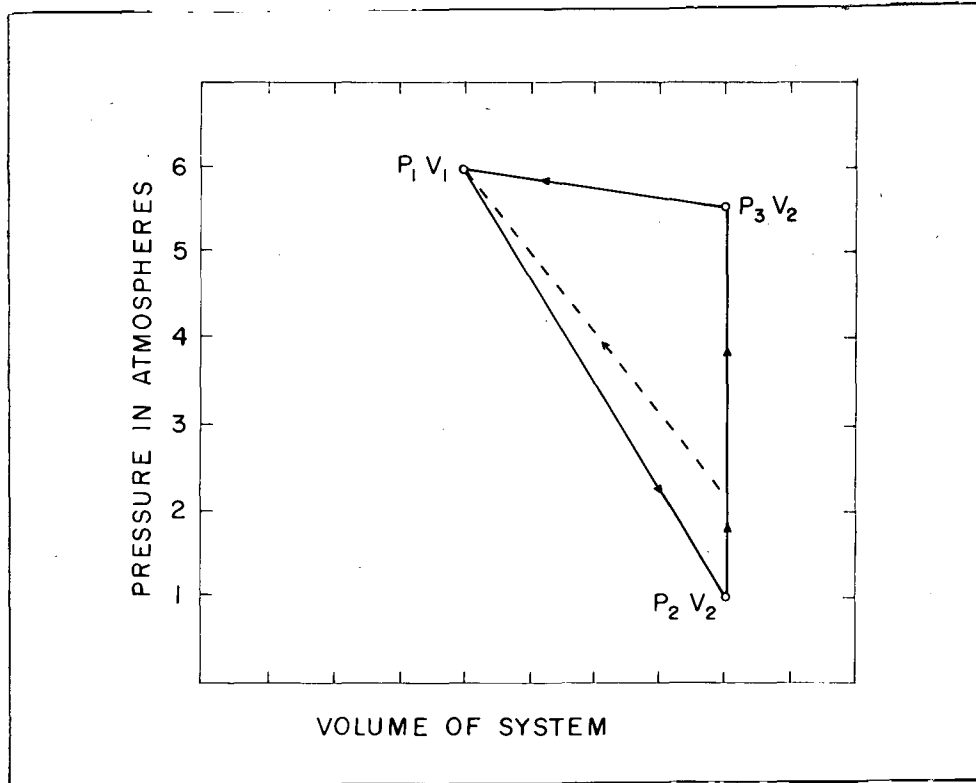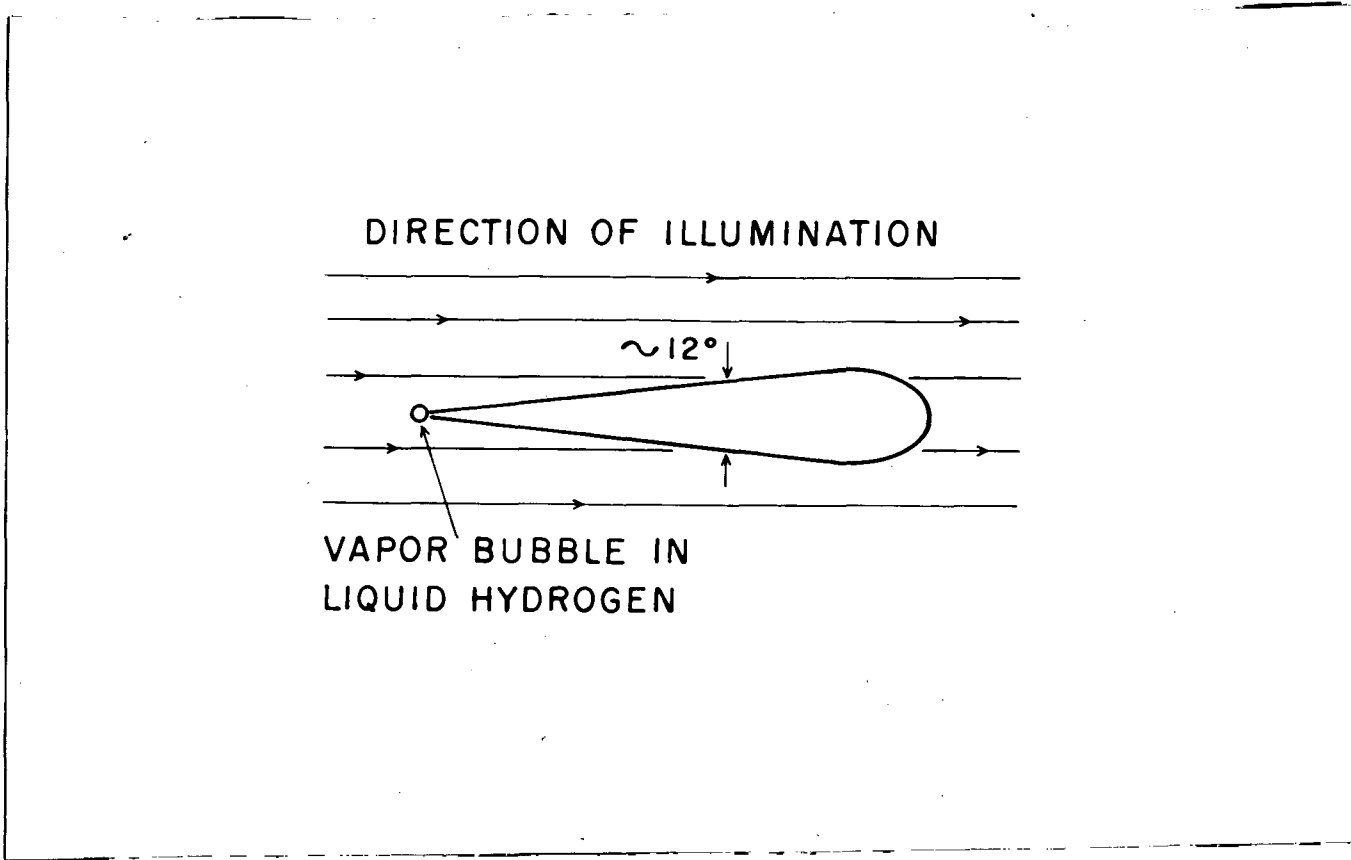LIGHT RAY

STEREOSCOPIC
CAMERA

STROBOSCOPIC
LIGHT

VANES

PATH OF
CRITICAL
LIGHT RAY
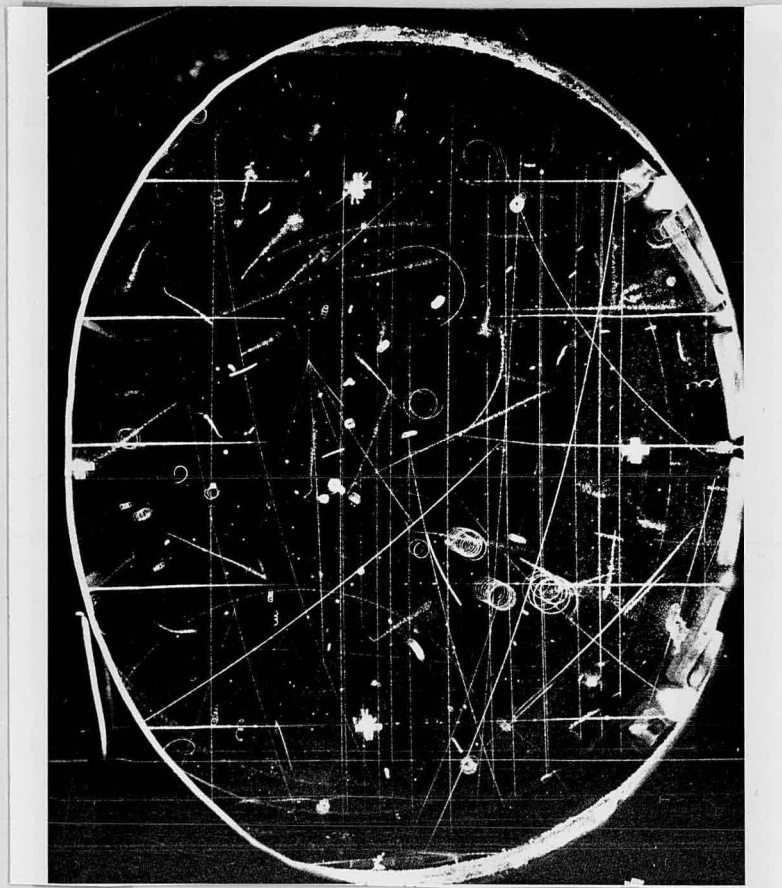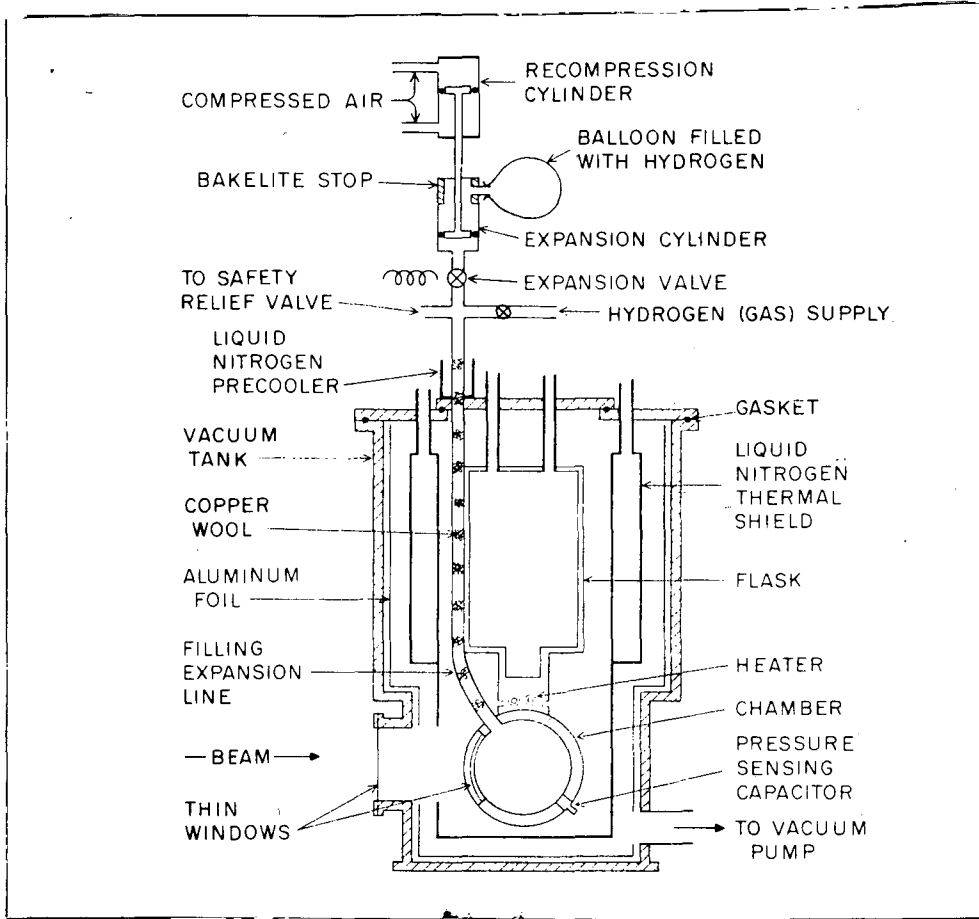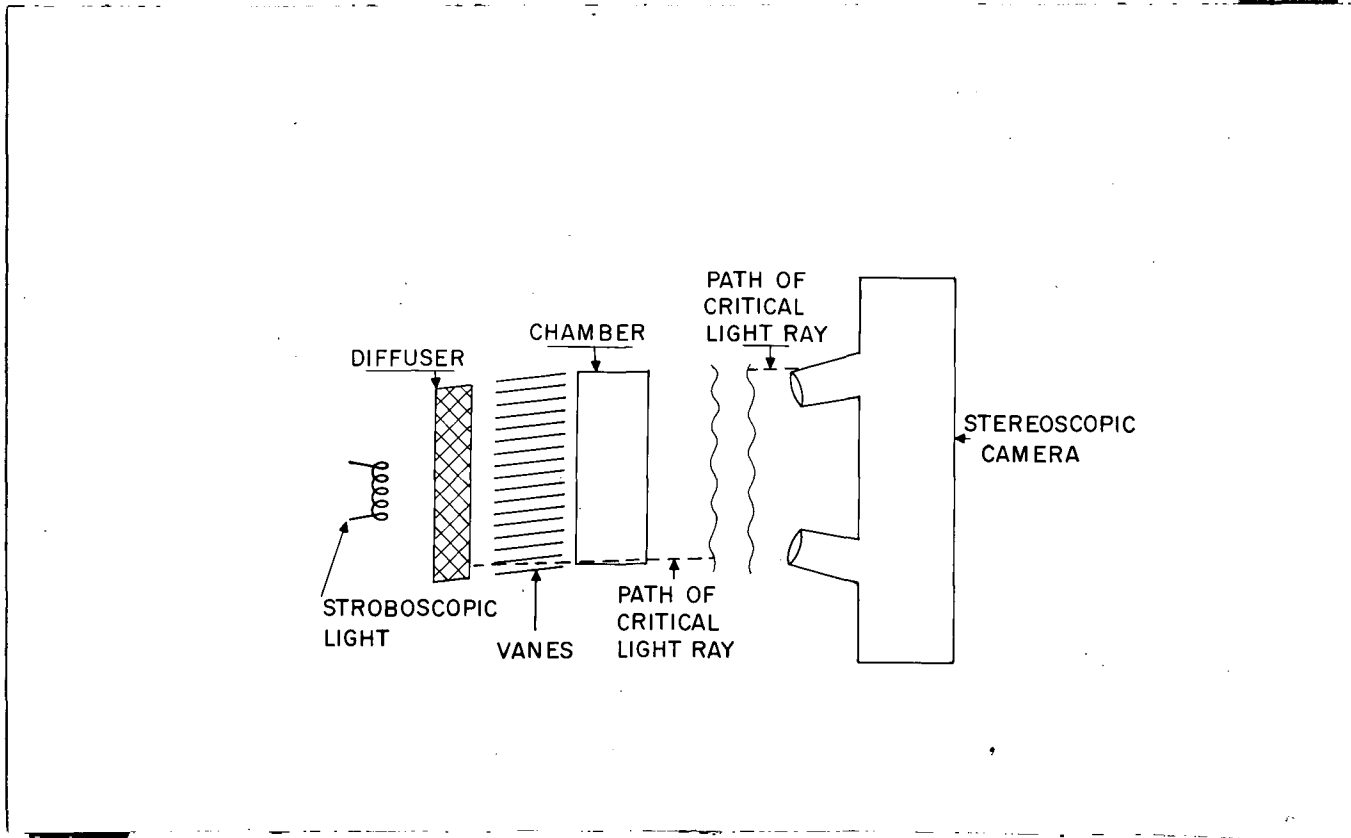
Fig. 6

Fig. 7
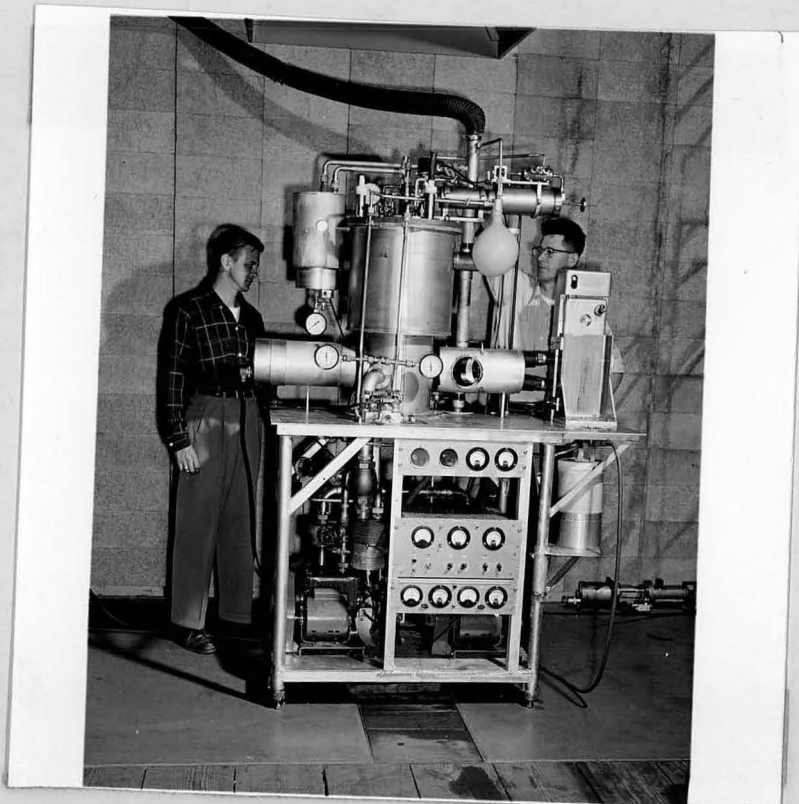
Fig. 8

Fig. 9

DECAY CONTOURS FOR Θ° & Λ°
FOR $\pi^- + p \rightarrow \Theta^\circ + \Lambda^\circ$ FROM 2 TO 6 Bev

APPROXIMATELY 1/4" SCALE

Fig. 10