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Characteristics of Bubble Chambers*

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The bubble chamber is a new radiation detector in which ionizing events produce tracks consisting of strings of tiny bubbles in a superheated liquid. By means of fast flash photography, practically distortionless bubble tracks can be recorded for the study of high-energy nuclear events. A chamber six inches long has been constructed and chambers several feet long seem feasible, so the bubble chamber can have both high stopping power and large size. Liquids containing only elements of low atomic number can be used to minimize Coulomb scattering so that accurate magnetic curvature measurements can be made. Tracks of minimum ionizing particles contain up to 100 bubbles per centimeter, and the bubble density varies with ionization density, thus making bubble counting a possible method for measuring ionization. The short sensitive and resetting times of bubble chambers tend to reduce background radiation problems and increase data collection rates for experiments with pulsed accelerators. Unfortunately the lifetime of the bubble nuclei seems to be too short to permit counter-controlled expansion after the passage of the particle to produce tracks. Therefore it is unlikely that the types of bubble chambers described here will be useful for cosmic-ray experiments.

INTRODUCTION

A BUBBLE chamber is a vessel filled with a transparent liquid which is so highly superheated that an ionizing particle moving through it starts violent boiling by initiating the growth of a string of bubbles along its path. For the chambers to be described below, these bubble tracks provide an accurate record of the paths of ionizing particles when the bubbles are photographed a few microseconds after the ionizing events. Although still in its infancy, the bubble chamber technique shows considerable promise of being useful for experiments in high-energy nuclear physics because it combines many of the advantages of cloud chambers and nuclear emulsions with several new unique characteristics.

Bubble chambers used in the early studies contained only a few cubic centimeters of liquid,[1] but recently a chamber with a sensitive volume of over 600 cubic centimeters has been operated successfully, and chambers up to a few feet long seem feasible. Thus liquid-filled bubble chambers combine the high stopping power of nuclear emulsions with the large volume of cloud chambers. The density of typical operating liquids is about 0.5 g/cc, which is 300 times the density of the gas in the usual argon-filled cloud chamber. When the operating liquid is sufficiently superheated to form tracks of minimum ionizing particles, the bubbles grow so rapidly that a photograph can be taken before there is time for motions in the liquid to distort the tracks. This fact, coupled with the possibility of using liquids containing only elements of low atomic number to minimize Coulomb scattering, should permit very accurate measurements of magnetic curvature. On the other hand, liquids containing various atomic nuclei can be used as the sensitive media for special experiments. For example, beautiful bubble tracks have been obtained in a chamber filled with liquid hydrogen,[2] a pure proton target.

Since the sensitive time of these chambers is usually less than 10 milliseconds, and they can be reset in less than 5 seconds, they are ideally suited for experiments with pulsed accelerators in which the interesting events occur in short bursts in a sea of rather intense background radiation.

Bubble tracks made by many kinds of particles have been photographed, including minimum ionizing electrons and muons, and slow nuclear fragments. The density of bubbles along a track is found to increase with ionization density, but no careful calibration has been made. Particles originating in radioactive materials, pulsed accelerator beams, and cosmic rays have been photographed in bubble chambers, but counter-controlled expansions after the passage of a particle have not produced visible tracks.

GENERAL PRINCIPLES OF BUBBLE CHAMBER OPERATION

Track formation in a bubble chamber can be understood in terms of two fundamental facts; first, a clean liquid can be superheated considerably by rapidly reducing the pressure on it, and second, an ionizing event can initiate boiling in a liquid if it is sufficiently superheated. The discovery of this last effect[3] was motivated by the desire to produce a detector with properties like those of the bubble chamber, and was guided by a detailed physical model of the mechanism by which ionization could nucleate bubble formation.[4] Since the first experiments with diethyl ether, other liquids including iso-pentane, benzene, sulfur dioxide, and ethyl alcohol have been found to be similarly radiation-sensitive, in close agreement with the pre-

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[1] D. A. Glaser, Phys. Rev. 91, 762 (1953).

[2] J. G. Wood, Phys. Rev. 94, 731 (1954).

[3] D. A. Glaser, Phys. Rev. 87, 665 (1952).

[4] D. A. Glaser, Nuovo cimento 11, Suppl 2, 361 (1954).

dictions of the theory. Even liquid hydrogen and liquid nitrogen have been found to be radiation-sensitive[5] in the expected range, although temperatures and pressures were not measured accurately in these tests. To find out whether the proposed explanation of the effect is correct, a number of liquids are being exposed to various radiations in an extended series of experiments now in progress. The results thus far are in good agreement with the theory, though other plausible models cannot yet be excluded by the experiments. One striking result is that diethyl ether can be superheated only slightly when exposed to fast neutrons. A higher degree of superheat is attainable in the presence of a gamma-ray flux, the results being independent of the gamma-ray energy in the range 0.6 Mev to 5 Mev. Finally an ultimate limit is reached at which a liquid will not remain superheated even in the absence of external sources or radiation. This limit, which we have called the absolute superheat limit, is analogous to the "cloud limit" in a cloud chamber, and probably corresponds to the condition under which bubbles are produced copiously by spontaneous density fluctuations. The results of this series of experiments should be ready for publication soon.

RESUME OF EARLY EXPERIMENTS

1. Experimental Technique

Until recently all of our bubble chambers have been made entirely of pyrex glass. Various sizes of heavy-walled tubing were used to make the chamber body which was joined to heavy-walled capillary tubing. The capillary was in turn sealed with O-rings to pressure-controlling apparatus operated at room temperature. After fabrication the glass parts were cleaned with hot chromic acid, flushed with distilled water, evacuated, flamed under hard vacuum, and sealed off. Just before use the seal was broken while immersed in the filling liquid. In the first experiments the pressure was controlled by a $\frac{1}{2}$-inch steel piston sealed by an O-ring into a brass cylinder and adjusted by a screw and hand crank. For automatic operation the control apparatus contained a small teflon diaphragm backed with neoprene and actuated by compressed air as in a cloud chamber. Temperatures in the range 135°C to 143°C were maintained by an oven or liquid bath for experiments with diethyl ether.

2. The First Particle Tracks

In the first attempts to observe tracks the chamber was superheated by reducing the pressure rapidly from twenty atmospheres to one atmosphere while the chamber temperature was 135°C. An ether-filled chamber with a sensitive volume of few cubic centimeters often remains quietly superheated for several seconds under these conditions. High-speed movies show that the eruption which finally occurs sometimes begins with a line of bubbles passing through the liquid.[4] The track develops very rapidly so that after twenty milliseconds it is hardly recognizable.

3. Counter-Controlled Pictures

Cosmic-ray tracks[1] were next obtained in automatic operation by means of a vertical counter telescope which was permitted to trigger flashlamps during the few seconds of sensitive time if a particle passed through the chamber. Variation of the temperature in these experiments showed that the bubble density along a minimum-ionizing track increases rapidly with temperature.

4. Vibration-Controlled Pictures

In order to see events more interesting than muons passing straight through the chamber, we took advantage of the violence of the eruption which produces an audible "plink" at each event. A General Electric variable-reluctance phonograph pickup was mounted with its stylus pressing against the wall of the chamber. Vibration signals occurring during the quiescent period after the expansion were allowed to trigger the lights and take pictures. In this way we saw tracks of particles passing through the chamber in various directions, being scattered, and so on, but the method is limited intrinsically by the speed of sound in the liquid. Vibration signals require about 100 microseconds to go a distance of 10 cm in the liquid, but in 10 microseconds the bubbles are already too big for precision measurements.

5. Scattered-Light-Controlled Pictures

Another method of triggering the flashlamps for random events in a nonselective way made use of light scattered by the bubbles. A weak steady light beam passing through the chamber was monitored by a photomultiplier which flashed the lights whenever it saw any change in optical density. This method gave rather poor quality tracks but could probably be refined.

CONSTRUCTION AND OPERATION OF LARGE BUBBLE CHAMBERS

Fabrication of large all-glass chambers with flat viewing windows is a formidable technical problem because the chambers are required to withstand rapid pressure changes of 300 pounds per square inch. On the other hand chambers built with metal parts, cements, and gaskets would not remain quiescently superheated under conditions required for the detection of minimum-ionizing particles. Boiling always started at some wall surface in such a chamber before the required degree of superheat could be attached.

For operation with diethyl ether, a solution of the problem was to expand the chamber very rapidly.

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[5] R. H. Hildebrand and D. E. Nagle, Phys. Rev. 92, 517 (1953).

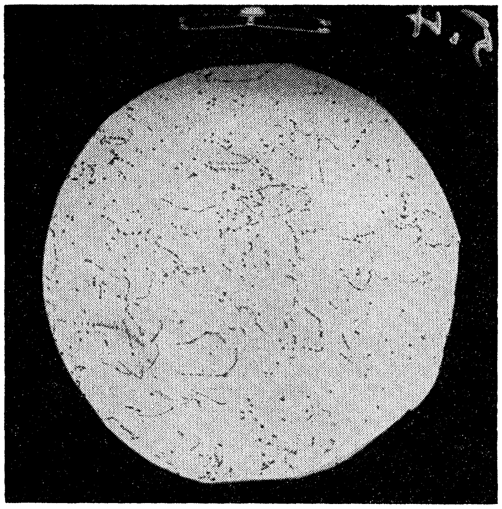

FIG. 1. Electron tracks produced in an ether-filled bubble chamber by gamma rays from a 25-mC radium source held about three inches from the center of the chamber in the plane of the photograph. The chamber has an inside diameter of two inches, a depth of one inch, and was operated at a temperature of 155°C and a pre-expansion pressure of 320 pounds per square inch (gauge). This picture was taken 5.4 milliseconds after the beginning of the rapid expansion.

Boiling then begins on the walls, but fortunately there is an interval of time during which the pressure is low enough to permit the formation of tracks of minimum-ionizing particles. The same effect has been observed with liquid hydrogen chambers.[2] The explanation for this behavior is probably to be found in the fact that the growth of a bubble in the boiling process is severely retarded after the earliest stages by heat conduction in the liquid, a relatively slow process. A recently developed mathematical theory of bubble growth incorporating the heat conduction effect has given dramatic agreement with measured bubble growth rates.[6,7]

A chamber based on these principles has been constructed with plate glass windows sealed to a duraluminum body with teflon gaskets. The sensitive volume, which is two inches in diameter and one inch thick, communicates with an expansion chamber outside the oven through a $\frac{3}{8}$-inch brass tube eight inches long. Nitrogen at a pressure of 300 pounds per square inch compresses the chamber by pushing on a flexible teflon diaphragm backed with neoprene in the expansion chamber. Rapid expansions are carried out by releasing the nitrogen with a magnetic pop valve of the type commonly used for cloud chambers. With this arrangement minimum-ionization tracks due to a radium source standing nearby can first be seen about five milliseconds after the expansion starts. Figure 1 is a photograph taken 5.4 milliseconds after the beginning of the expansion. Tracks of various ages appear in a later photograph taken at 6.7 milliseconds (Fig. 2). A krypton-filled flashlamp with a flash duration of about 5 microseconds illuminated a diffusing screen just behind the chamber for these bright field pictures. Linagraph panchromatic recording negative was used in a 35-mm camera operated at $f/16$. Photographs taken as late as 12.0 milliseconds from the beginning of the expansion still show new tracks, so the sensitive time of this chamber is about 7.0 milliseconds.

For experiments at the Brookhaven Cosmotron a bubble chamber with a sensitive volume of six by three by two inches has been built. Made of one piece of dural, the body of the chamber has walls one inch thick polished on the inside. Tracks are photographed through tempered plate glass windows of free area six by three inches bolted to the chamber body and sealed with teflon gaskets. At one end of the chamber the two by three inch inside cross section is flared out to a circular cross section with a gasket ring five inches in diameter. A diaphragm of 30-mil teflon backed by a sheet of $\frac{1}{8}$-inch silicone rubber is clamped to this ring, effectively forming a movable wall of the chamber. The position of this diaphragm is controlled by compressed nitrogen. When released by a magnetic pop valve, the nitrogen escapes and permits the diaphragm to be pushed by the hot liquid against a fixed supporting plate. The controlling magnet for the expansion valve is outside the oven, but the valve and its teflon seat are in the oven. Heat is provided by conducting glass plates clamped to the flat metal chamber walls with thin mica separators. A thermistor inserted in a well

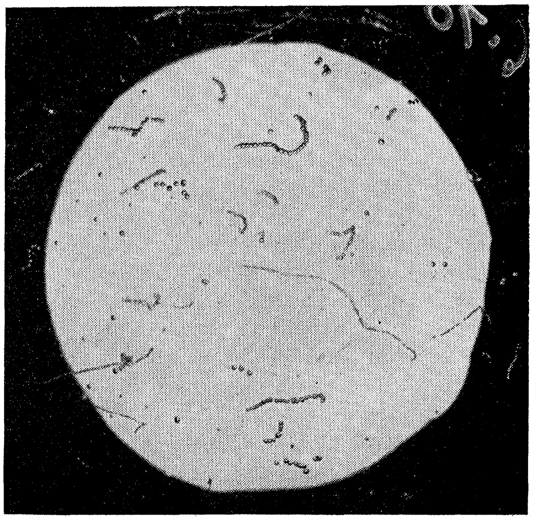

FIG. 2. Photograph of the two-inch ether chamber taken 6.7 milliseconds after the expansion began. The operating conditions were the same as in Fig. 1 except that the radium source was eight inches from the chamber center in the plane of the photograph. Since the chamber had been sensitive for 1.7 milliseconds when this picture was taken, there are a number of "old" electron tracks characterized by larger bubbles than mark the "recent" tracks.

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[6] H. K. Forster and N. Zuber, J. Appl. Phys. **25**, 474 (1954).

[7] M. S. Plesset and S. A. Zwick, J. Appl. Phys. **25**, 493 (1954).

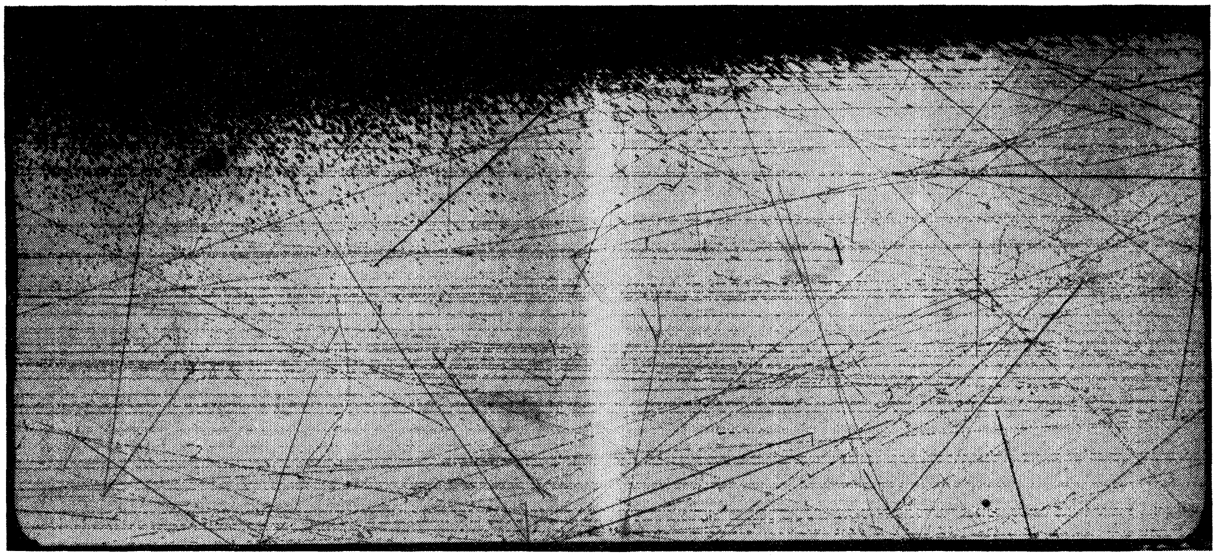


FIG. 3. A beam of 2-Bev protons from the Brookhaven Cosmotron enters an iso-pentane chamber six inches long from the left in this picture and produce a number of nuclear interactions in the liquid. Tracks of various bubble densities are produced in this chamber, operated at 157°C, even though violent boiling has already started at the top.

in the dural chamber wall controls the power delivered to these heaters by means of a conventional 60-cycle ac bridge circuit and a 5632 thyratron. Finally the whole assembly is insulated with a blanket of glass wool in a thin-walled plywood box provided with double "storm windows" to reduce heat losses from the windows of the bubble chamber. This construction, in which the moving diaphragm is in the oven, is a return to the typical expansion cloud chamber type of design which permits more rapid expansion than the earlier designs in which the liquid was expanded through a tube running to an expansion device outside the oven. When operated at 157°C with a pre-expansion pressure of 350 pounds per square inch (gauge) using iso-pentane, the six-inch chamber is fully sensitive to minimum ionizing particles 3.5 milliseconds after the expansion is initiated. The chamber seems to remain sensitive for about 10 milliseconds.

Figure 3 is a picture taken in an external beam of 2-Bev protons at the Brookhaven Cosmotron. The iso-pentane-filled chamber was expanded four milliseconds before the beam arrival and the lights were flashed 90 microseconds after a four-fold scintillation counter telescope recorded the arrival of the first hundred protons of the pulsed beam on a fast scaler. In this picture the 2-Bev protons entering at the left make tracks containing about 24 bubbles per centimeter in isopentane at 157°C while at 155°C the bubble density is closer to 8 bubbles per centimeter along such tracks. A number of nuclear interactions in the liquid can be seen to emit both lightly and heavily ionizing particles. Violent boiling began first at the top of the chamber partly because more heat was inadvertently delivered to the top wall. Figure 4 is a picture taken earlier with respect to the proton pulse, but the conditions are otherwise the same as for Fig. 3. One of the three visible particles apparently originating in an interaction in the wall of the chamber exhibits what seems to be a characteristic successive π-μ-electron decay. Eight similar π-μ-electron events were found in a rapid scanning of the first 22 pictures taken in this test at the Cosmotron. Pictures were taken every 30 seconds in this run, but more rapid operation is possible.

These pictures were taken on 70 mm linagraph orthofilm with a stereoscopic camera operated at $f/45$ using bright field illumination.

There seems to be no fundamental limitation on the possible size of bubble chambers constructed and operated in this way. A considerably larger chamber is being planned for use at the Cosmotron.

SENSITIVE TIME OF BUBBLE CHAMBERS: COUNTER-CONTROLLED EXPANSIONS

More precise information about the sensitive time of the two-inch chamber was obtained by exposing it to intense bursts of x-rays generated by the pulsed 420-kilovolt electron injector of the University of Michigan synchrotron. X-ray pulses several microseconds long were introduced at various times during the expansion process to see how the chamber sensitivity varied as the pressure was dropping. Because of limitations of photographic contrast and grain size, the lower limit of size of bubbles observed in this particular experiment was 0.1 mm, though that is not an ultimate limit for either photographic recording or bubble chambers. By counting the bubbles in sample volumes of the bubble chamber, the total number of bubbles in the chamber was estimated to be zero for

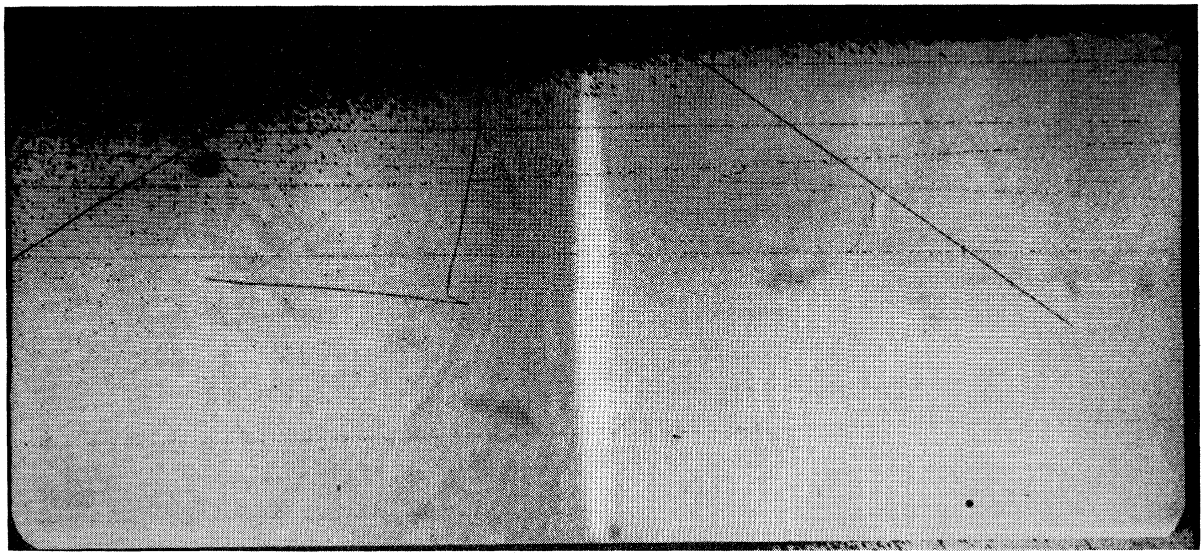


FIG. 4. A nuclear interaction in the top wall of the six-inch chamber operated in the 2-Bev proton beam from the Cosmotron produces a particle which stops in the liquid and produces an event which is probably a π-μ-e decay. The first 22 pictures of this run contained 8 examples of this type of event.

radiation bursts earlier than 3.6 milliseconds after the expansion began, 20 for bursts at 3.7 milliseconds, 20 000 at 4.9 milliseconds, and 20 000 for bursts occurring until 12.0 milliseconds at which time the chamber bubble count drops very rapidly to zero. These results are independent of the time of the light flash so long as it comes at least a few microseconds after the radiation burst and not earlier than 4.5 milliseconds after the expansion begins. The rapid cutoff in bubble sensitivity is simultaneous with a pressure rise in the chamber which is accompanied by the appearance of a mushroom-shaped jet of vapor-liquid foam at the exhaust tube orifice.

We can understand the plateau and final cutoff in terms of the pressure curve. Apparently there is some time interval during the cycle in which wall boiling evolves vapor just fast enough to keep up with the expansion process, maintaining a sufficiently low pressure to provide the superheat condition necessary for minimum ionization track formation. With the small all-glass bubble chambers, this pressure is known to be one atmosphere, is maintained for several seconds, and requires a liquid temperature of about 143°C. For rapid operation of the large metal chambers the ambient pressure during the sensitive time must be higher, and is estimated to be about 10 atmospheres when the operating temperature is 155°C. At 160°C the whole chamber exceeds the absolute superheat limit sometime during the expansion before tracks can be seen and is filled with a dense fine-grained foam regardless of the intensity of ionization in the liquid.

It is important for cosmic-ray studies with bubble chambers to be able to take counter-controlled pictures of sizeable chambers. Since the large chamber described here has a sensitive time of only a few milliseconds, counter-controlled expansions after the event of interest seem necessary if this type of chamber is to be used. Whether this will be feasible depends crucially on the lifetime in the unexpanded state of the bubble nuclei produced by the ionizing event. Presumably the visible bubbles originate from microscopic nuclei that grow to visible size only after the pressure has been lowered sufficiently. Their lifetime is limited by ion recombination times or ion mobilities if the nucleating mechanism is electrical, or by thermal diffusivity if the nucleating mechanism is thermal. It is probable that an ionizing event creates bubble nuclei containing different amounts of energy, so that the more energetic ones require less severe superheat to produce visible bubbles. Using these ideas we can explain the results of the sensitivity experiment by supposing that at each instant during the expansion process the conditions are right for rapid growth to stable size of nuclei of a certain energy. Stronger ones grow to be surviving bubbles and weaker ones disappear. Then the observed bubble density *versus* time curve is a result of selecting from a population of nuclei of various energies those which are "strong enough" to grow at the pressure and temperature prevailing at the time of their "birth." If by lifetime we mean the length of time a nucleus remains capable of forming a bubble able to grow when given a chance, then the date are consistent with a lifetime of less than a few microseconds. On the other hand, this experiment proves definitely that the lifetime of the most energetic bubble nuclei is not more than 1 millisecond, and that some of the weaker nuclei that contribute bubbles to minimum-ionizing tracks have lifetimes less than 0.1 millisecond. These results obtained with the two-inch chamber depend somewhat on the geometry of the chamber and the hydrodynamics of the expansion process, but the general orders of magnitude are probably characteristic of this type of bubble chamber operation. Possibly working liquids with considerably different thermodynamic and mechanical properties will give different results.

The shortness of the lifetime of bubble nuclei happily tends to reduce the background of unwanted ionization events for work with high-intensity pulsed accelerators, but unhappily will probably make counter-controlled expansions for cosmic-ray experiments impossible with this technique. Before undertaking these detailed sensitive-time measurements we tried without success to photograph cosmic-ray tracks by means of counter-controlled expansions.

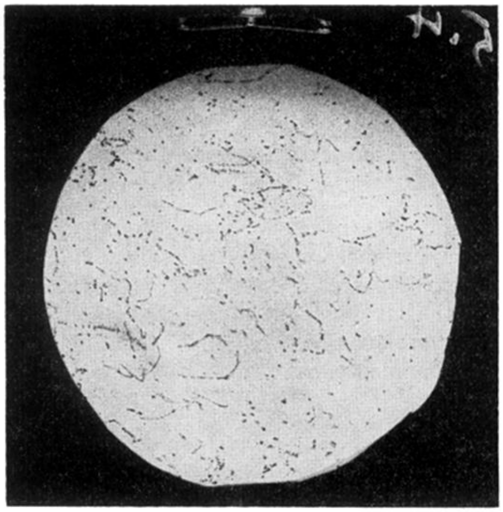
SUMMARY OF PROPERTIES OF BUBBLE CHAMBERS

As a result of these developments it is now fairly easy to construct a bubble chamber with a sensitive volume of several liters of diethyl ether, iso-pentane, or some similar liquid. For these liquids the density of the sensitive medium is about 0.5 g/cm^3 of which 0.1 g/cm^3 is hydrogen. Liquid hydrogen chambers of almost 100 cm^3 containing 0.05 g/cm^3 of hydrogen have also been operated successfully.[2] Chambers with a long dimension of several feet seem feasible with recent techniques. Other liquids of various densities and chemical compositions can be used. A very rough guide for estimating the operating conditions for a given liquid is that the operating pressure is about two-thirds of the critical pressure and the operating temperature lies about two-thirds of the way from the normal boiling temperature to the critical temperature. A more accurate estimate can be obtained with the published formula[1,4] if one takes $n=6$. For diethyl ether and iso-pentane the volume expansion ratio is found to be 1.03. These chambers can be expanded in less than five milliseconds and may have a sensitive time of the order of ten milliseconds. Because the lifetime of the bubble nuclei is so short and the sensitivity increases from zero to a maximum in about 1 millisecond, these chambers can be operated in a region of high radiation background without excessive bubble background. For operation with pulsed beams, the chamber can be expanded just before the beam arrival and pictures can be taken by counter-controlled flashlamps. Since the bubbles grow large enough to photograph in a few microseconds, there are virtually no distortions of the tracks due to motions in the liquid. Another advantage of the chambers is that their operation cycle can be as short as three or four seconds, even for chambers containing a liter of liquid. This makes it possible to accept particles from every pulse of a large accelerator such as the Brookhaven Cosmotron, which delivers a pulse once every five seconds.

For bubble chambers operated with liquids of low atomic number, Coulomb scattering will not interfere seriously with measurements of magnetic curvature in magnetic fields of convenient size. At maximum sensitivity a minimum-ionizing particle in diethyl ether or iso-pentane makes a track containing about 100 bubbles per cm, making possible precision measurements of ranges of particles up to a range of tens of g/cm^2. Improved photography should make possible the detection of bubbles as small as 0.01 mm in diameter. Then magnetic curvature measurements will be limited principally by optical problems, and it may become possible to measure scattering along a track.

Finally it has been found that the bubble density along a track varies with the ionization of the particle, making the measurement of ionization possible by counting bubbles along a track. Minimum-ionizing particles can produce 100 bubbles per centimeter down to less than 1 bubble per centimeter depending on the temperature of the liquid and the pressure. This fact leads to the interesting possibility that the bubble chamber sensitivity can be adjusted for different experiments, but may give rise to great experimental difficulties in the attempt to calibrate bubble density *versus* ionization density.

We are grateful to the Cosmotron staff at the Brookhaven National Laboratory for making possible our tests of the six-inch bubble chamber, and especially to the cloud chamber group at the Laboratory for their considerable help in carrying out the experiments.



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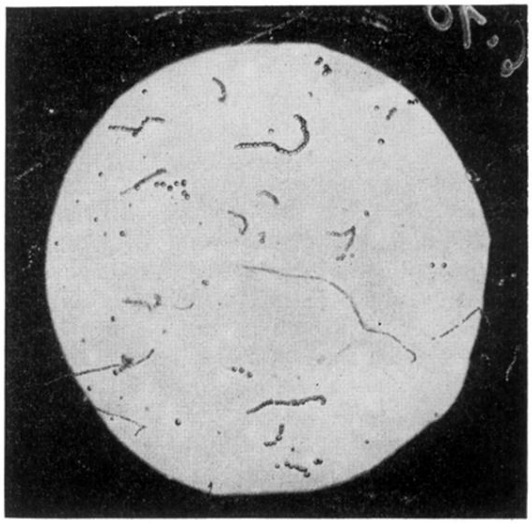

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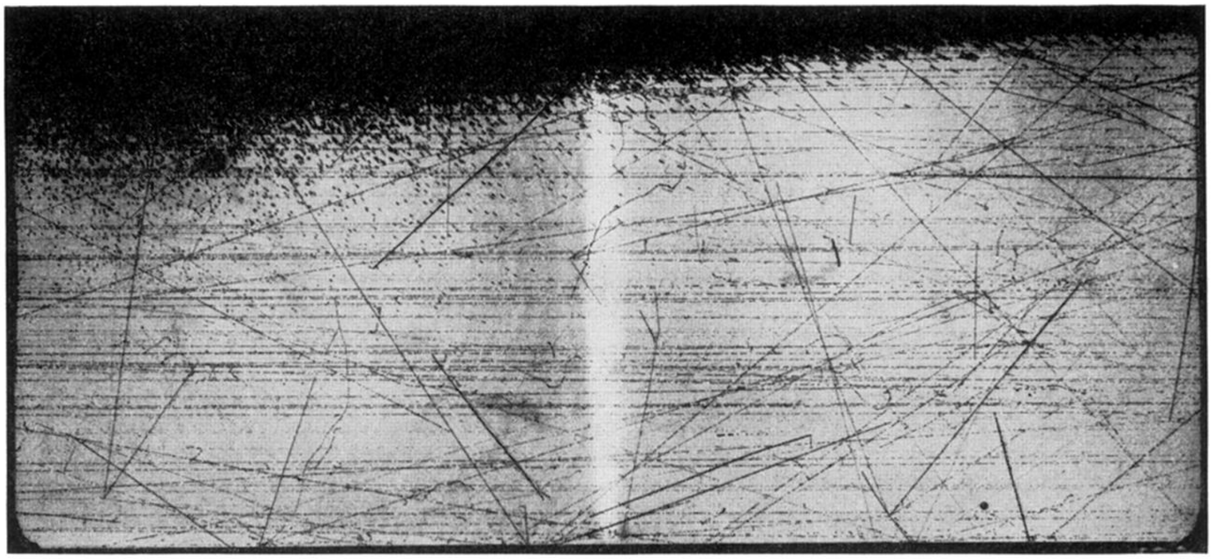

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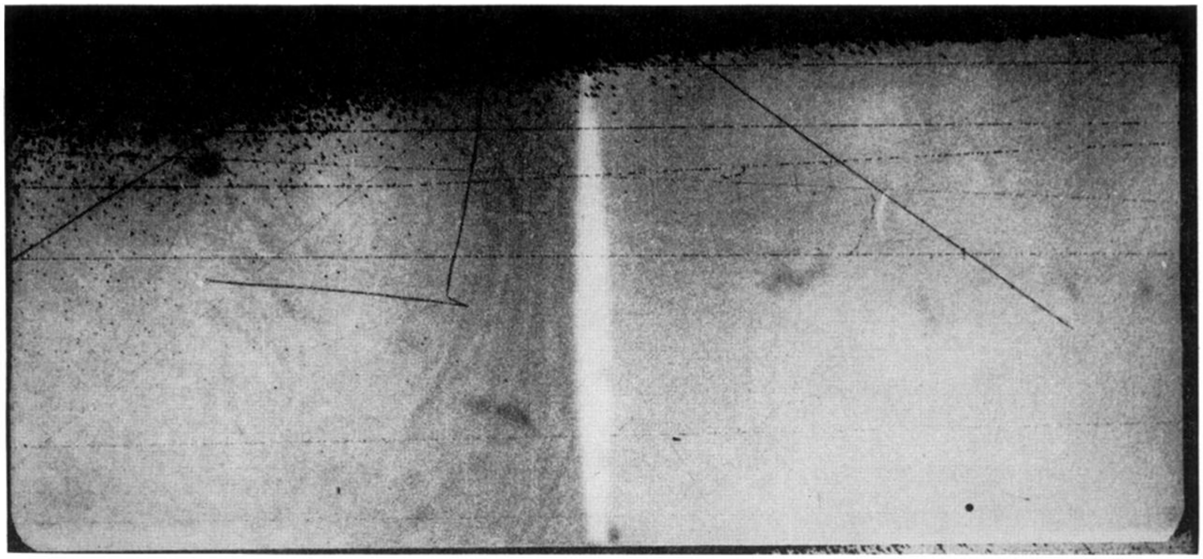

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