LIQUID HYDROGEN BUBBLE CHAMBERS *

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(presented by E. M. McMillan)

After the first hydrocarbon bubble chambers were built by Donald Glaser in 1952, work was started at Chicago and Berkeley to find if liquid hydrogen could be used as the working fluid in a bubble chamber. In the fall of 1953, it was found by the Chicago group that superheated liquid hydrogen could be made to boil under the influence of ionizing radiation, but no tracks were observed. The observation of tracks at Berkeley a few months later completed the proof that hydrogen was a usable bubble chamber liquid. (Irradiated liquid nitrogen boils when superheated, but as of spring 1956 no one has seen tracks in liquid nitrogen.) In the past two years, the Chicago group has built several all-glass hydrogen chambers, the most recent of which is approximately 5.5 by 5.5 by 20 cm. inside dimensions. Their chambers have been of the so-called clean variety (like Glaser's early ones), in which no boiling takes place unless ionizing particles are present. They have used their latest chamber in an extensive study of the scattering of low-energy pions by protons.

The Berkeley group started its work with the intention of using its chambers at the Bevatron. It was at once obvious that if such chambers were to be useful, they would have to be much larger than any of the clean chambers originally built by Glaser. It seemed at the outset quite out of the question to expect that a very large volume of liquid hydrogen could be kept from boiling spontaneously as soon as it was superheated. No attempts were made, therefore, to operate a clean hydrogen chamber, and it was soon found that the liquid maintained track sensitivity throughout its volume, even though it was boiling vigorously at the walls. This demonstration of the feasibility of unclean chambers made it possible to consider the construction of large chambers with machined metal walls and gasketed glass windows. Another important early observation was that the rate of bubble growth was more than a hundredfold slower in hydrogen than it was in Glaser's early ether chambers. The almost explosive growth rate in ether, with its microsecond time scale, would, if duplicated in hydrogen, have desensitized a large chamber before the completion of a Bevatron pulse. It would also have given Bevatron tracks with bubbles varying in size from a fraction of a millimeter to more than a centimeter, a in a single picture. It is exceedingly fortunate that in hydrogen, the bubble radius is approximately

$$r(\text{mm}) = 10^{-1}\, t^{1/2} \text{ (t in milliseconds).}$$

The first metal and glass chamber was operated at Berkeley in the summer of 1954. It was 6.3 cm. in diameter, and 3.8 cm. long. Its temperature was maintained at approximately 27°K by immersing it in a bath of liquid hydrogen boiling at 4.5 atmospheres, the corresponding vapor pressure. The bath required an additional pair of windows for illumination and observation. Pure lead gaskets were found to work satisfactorily at hydrogen temperature. The chamber was superheated by letting the hydrogen expand as a gas, forcing a piston back in a cylinder. In later work a free expansion of the gas into an evacuated cylinder has been used. Good tracks were obtained with this chamber, and it was shown that the bubble density was a monotonic function of the energy loss. In addition, it was shown that for particles of a given energy loss the bubble density increased with increasing temperature. If the chamber was irradiated by a Po-Be source, which gives both neutrons and gamma rays, the sensitivity could be varied by changing the temperature, so that at high temperatures both Compton electrons and recoil protons could be seen, but at low temperatures the electrons were not visible, while the recoil protons persisted. In emulsion terms, this is like changing from Ilford type G.5 to C.2.

As soon as the operation of the 6.3 cm. chamber was understood, a 10 cm diameter 5 cm. deep chamber was constructed. This dispensed with the high pressure bath; the temperature of the chamber was maintained by a balance between the heat radiated to the chamber from the walls of the vacuum system, and the heat conducted from the chamber to a colder metal flask filled with hydrogen boiling at atmospheric pressure. For fine adjustments of the chamber temperature, an electric heater was imbedded in the copper conductor between flask and chamber. The wall of the chamber was copper, and it was fitted with a thermocouple (referred to the 20°K hydrogen in the flask) and a fast-acting condenser-microphone-type pressure gauge. With this instrumentation, the operation of the chamber became more of a science and less of the

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art it had formerly been. It now became possible to adjust the temperature, the pressure drop on expansion, and the timing of the stroboscopic light relative to the pressure pulse so that good tracks could be assured on the first picture.

The 10 cm. chamber was exposed to low-energy positive pions from the 184-inch cyclotron, and to high-energy negative pions from the Bevatron. It was soon apparent that if the device were to have real utility, it should be traversed by a magnetic field. Therefore a pair of close-fitting Helmholtz coils were constructed to produce a pulsed field of 7000 gauss. The coils were molded in plastic, cooled by liquid nitrogen, and energized by the discharge of a large capacitor bank. To avoid the heating effects of eddy currents in the copper walls, a thin stainless steel cylinder was used in place of the copper. The retaining rings that pressed the glass windows against the cylinder were cut radially to avoid " short circuited turns ". Calculations made at this time showed that it was impractical to use pulsed magnetic fields with large hydrogen bubble chambers, because of eddy-current heating. This is the only disadvantage of bubble chambers in comparison with cloud chambers that has so far become evident. It increases the cost of the generators and the cooling circuits required for bubble chamber magnets.

The 10 cm. magnetic chamber has been used in a study of the scattering of 700-Mev π^- mesons by protons. In some preliminary experiments in the higher-energy π^- beams from the Bevatron, a number of neutral V particles were seen. The chamber was on one occasion filled with liquid deuterium, and minimum-ionizing particles were observed. The temperature and pressure for deuterium operation are both higher than for the usual hydrogen operation, and our new chambers are designed to take the higher pressure with a larger safety factor than was available in the 10 cm. chamber.

In the past year our main effort has been on the chamber 25 cm. in diameter and 16.5 cm. deep. This was built to fit into an existing cloud-chamber magnet, and was therefore oriented with horizontal windows. The steady magnetic field is about 8000 gauss. The general operating conditions are quite similar to those for the 10 cm. chamber. Since the magnet had one unremovable pole piece, it was necessary to use a new illumination scheme. (On the 10 cm. chamber, dark-field illumination is used, with a point light source focusing a beam through the chamber to a point midway between the two lenses of the stereo-camera. The bubbles appear bright against a dark background.) The 25 cm. chamber, like the 10 cm., uses dark-field illumination, but the light source for the 25 cm. chamber is a frosted plastic plate, edge-lighted by a circular discharge tube. The plate is covered by a metallic " Venetian blind assembly ", which keeps direct light from the camera lenses, but allows light scattered through a small angle by the bubbles to reach the lenses. (The polar diagram of the light scattered from bubbles in liquid hydrogen is peaked strongly forward, with a half angle of about 6°, so that conventional cloud-chamber illumination schemes are not usable.) The light source, diffusing screen, and Venetian blind system are all mounted in the vacuum system, just below the bottom window of the chamber.

Tracks were found in the 25 cm. chamber as soon as it was filled, but it was quickly noted that they appeared only in the top few centimeters. The temperature gradient in the liquid, which was responsible for this trouble, was traced to the heat given off at the top window when the large bubble was recompressed. Heat of vaporization is liberated in this process, and since both the window and the liquid are poor conductors, the heat remains where liberated. (In the 10 cm. chamber, with its vertical windows, the heat is liberated at the top of the metal cylinder, which is in turn connected to the hydrogen flask by a copper bar. For this reason, no such problem arose in the operation of the 10 cm. chamber.)

The temperature gradient was eliminated by two changes in the 25 cm. chamber. It was tilted, so that bubbles rising to the top flowed to the highest point under the glass, where they could be compressed against a copper plate that was placed under a small area of the glass and soldered to the wall. This measure is not now considered of sufficient importance to be worth including in future designs. But more importantly, a fast recompression system was installed on the chamber. In all previous work, we had allowed the bubbles to grow until the chamber pressure reached its vapor pressure at the operating temperature of 27 °K ($P = 4.5$ atmospheres). Hydrogen was then forced into the chamber until the large bubble was reliquefied. The mechanical work done on the system (and thus the heat of vaporization liberated) reaches its maximum value under such conditions. It had long been realized that the consumption of liquid hydrogen could be drastically reduced if one repressurized the system quickly, before the bubbles had grown to their saturation volume. Accordingly, a solenoid valve was opened about 30 milliseconds after the expansion valve had opened, and a source of high-pressure hydrogen at liquid nitrogen temperature was connected to the chamber. The bubbles from all tracks are reliquefied before they have risen 1 cm. under gravity. Some bubbles from rough places in the chamber still reach the top, but they are for the most part reliquefied under the copper plate. Under these new conditions, the chamber has nearly uniform sensitivity throughout its entire height, and the consumption of liquid hydrogen has been cut by almost a factor of ten. At a pulse rate of one in 40 seconds, the static heat load (radiation, etc.) is 1.5 liters per hour, and the dynamic heat load ($\int P dV$) is 1.2 liters per hour. With slow recompression, the total load was about 20 liters per hour.

The safety aspects of hydrogen bubble chambers have been studied in great detail. The cracking of a window, or the loss of vacuum in the chamber system, would result in a sudden pressure rise in the system. All chambers are equipped with pressure-sensitive relief valves, which

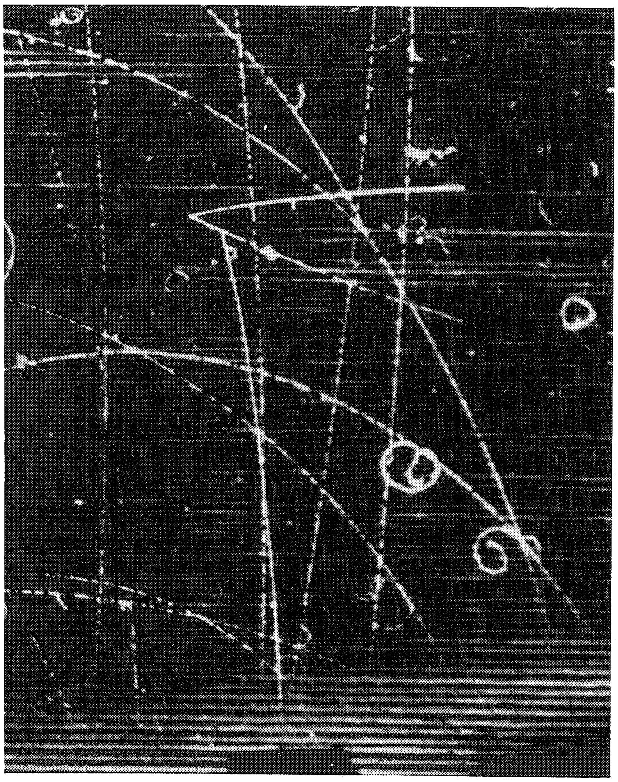

Fig. 1. Capture of a K^- by a proton. The reaction is $K^- + P \rightarrow \pi^- + \Sigma^+$. The Σ^+ always according to the reaction $\Sigma^+ \rightarrow \pi^+ + N$.

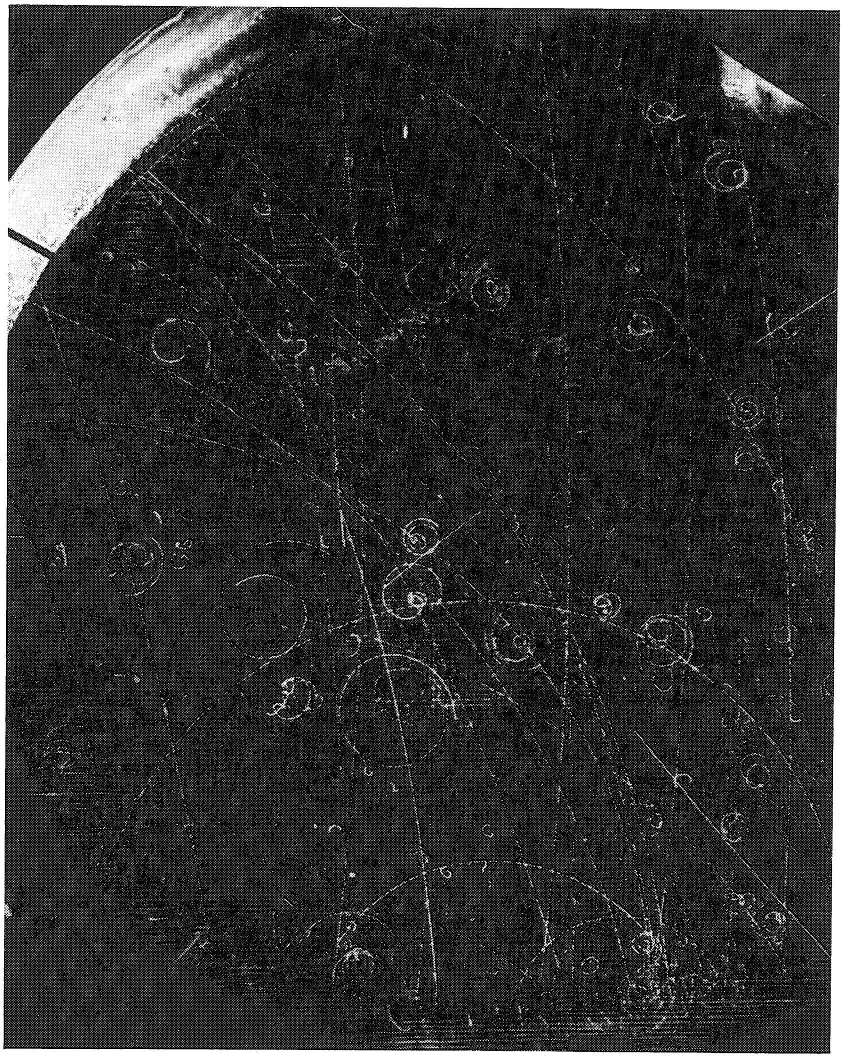

Fig. 2. Capture of a K^- by a proton. The reaction is $K^- + P \rightarrow \pi^+ + \Sigma^-$.

allow the hydrogen to escape through pipes to elevated burners, where the gas is safely ignited. Field tests have simulated such accidents, and have shown that burning is a good solution to the problem.

The 25 cm. chamber has been used in a continuation of the 700-Mev π^- proton scattering experiment, and is at this time placed in a beam of K^- mesons to look for reactions that take place when K^- mesons at rest interact with protons. Many examples of the associated production of strange particles have been observed, and a systematic study of such reactions is planned for the near future. The " no field " tracks appear to be at least as straight as those in the highpressure hydrogen diffusion chamber with which they have been compared. Spurious radius of curvature throughout most of the chamber is 30 to 50 meters. It therefore appears that turbulence is relatively negligible in measuring magnetic curvatures. The limiting factor will probably be the multiple Coulomb scattering of particles as they pass through liquid hydrogen.

Plans are well along for the construction of a large liquid hydrogen chamber in a strong magnetic field. The chamber will have inside dimensions of 183 by 50 by 38 cm., and the magnetic field will be 15,000 gauss. A reliquefaction system will be installed to avoid the loss of liquid hydrogen from the 20° system. Until recently, it appeared that a liquid-expansion system would have to replace the vapor-expansion system used on all our previous chambers. But the success of the fast vapor-recompression system has so increased the thermodynamic efficiency that it will be used on the large chamber. To reduce the cost of the magnet, and to simplify the construction of the chamber, it is planned to illuminate the chamber through its single glass window. This presents some optical problems that seem very formidable but not insoluble.

The problem of reducing the large quantity of data from the photographs is a very serious problem. To illustrate, it is convenient to remember that a reaction with a cross section of 1 barn has a mean free path of 25 cm. in liquid hydrogen. If one has 28 parallel tracks in a chamber 183 cm. long, the path length is 50 m. Therefore an event with a cross section of 5 millibarns will show on an average of once each photograph. An associated production of strange particles will appear every five pictures, or at the rate of approximately 20 per hour. Extensive planning has been done on the problem of data reduction by semiautomatic scanners coupled to high-speed digital computors.