HYDROGEN BUBBLE CHAMBER USED FOR LOW-ENERGY MESON SCATTERING *

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(presented by R. H. Hildebrand)

Summary

A 2.5 × 2.5 × 10 cm. hydrogen bubble chamber has been developed for experiments on the scattering of particles from the 450 Mev synchrocyclotron. Seventy-five thousand pictures have been taken at the rate of one every two seconds and are being scanned at the rate of two thousand per day. The average track length per picture is about one gram per square centimeter. The characteristics of the bubble chamber are described and examples of the pictures are shown.

1. *Introduction*

In this paper we describe a Glaser bubble chamber [1]), operating with liquid hydrogen [2,3,4]), which has been used to study low energy pion-proton scattering. It is valuable to study these events at such low energies that counter techniques are difficult because of the short range of the pions, while cloud chamber and emulsion studies are difficult because of the low cross sections. A bubble chamber for this type of study must allow rapid scanning and accurate measurement of angles and ranges. Since it is used with the synchrocyclotron in a search for rare events, it should recycle rapidly and should operate reliably for hundreds of thousands of expansions.

The present 2.5 × 2.5 × 10 cm. chamber is designed to meet these specifications. Its cycling time is two seconds. With it, we have taken seventy-five thousand pictures of low-energy meson tracks. Fifty thousand of these pictures have been scanned and preliminary results will soon be published.

2. *General features of the apparatus*

The central feature of this apparatus is the all-glass, square-cross-section bubble chamber. The four flat transparent walls allow 90° stereo-photography, which in turn assures maximum accuracy, rapid scanning of pictures, and maximum use of the chamber volume. The completely smooth inner surface minimizes spontaneous boiling at the walls.

The principal parts of the bubble chamber apparatus are shown schematically in fig. 1. There are three distinct hydrogen systems: The first is the reservoir which contains liquid hydrogen boiling continuously at one atmosphere. It serves as a source of cooling for the others. The second, consisting of the jacket and its attached condenser, serves as a temperature controlling bath for the bubble chamber. The bubble chamber itself and the metal bellows connected to it comprise the third circuit. All are enclosed by an aluminium shield kept at liquid nitrogen temperature in order to reduce the flux of thermal radiation. The whole apparatus is vacuum jacketed and continuously pumped.

The temperature of the chamber is maintained by the bath of liquid hydrogen in the jacket which surrounds it. The bath temperature is determined by the balance between heat lost through the heat leak to the reservoir and heat gained from the surroundings and from the heater. Good thermal contact with the end of the heat leak is achieved by means of a reflux condenser of large surface area. The heater is used for temperature control, and also provides a simple method for momentarily stopping the boiling in the jacket at the instant the picture is taken (see Sec. 4.).

The pressure in the bubble chamber is controlled by a metal bellows pushing directly on the liquid hydrogen. The bellows unit is coupled by a push rod to a second bellows unit at room temperature which is driven by compressed air.

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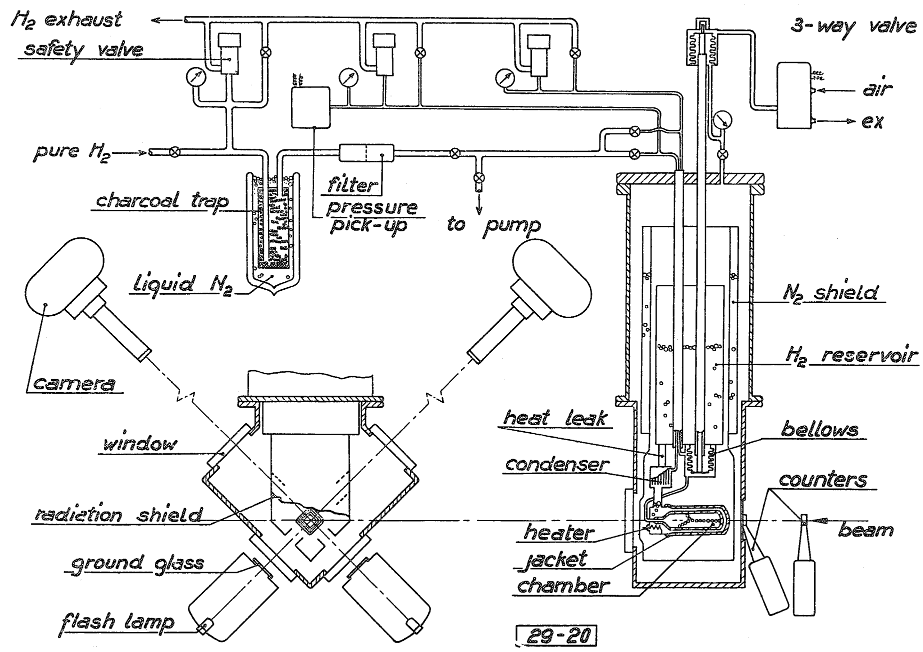

Fig. 1. Schematic diagram of apparatus.

3. *Bubble chamber and jacket*

The bubble chamber is a hollow glass prism of inside dimensions 2.5 × 2.5 × 10 cm. and wall thickness 4.5 mm. It is oriented so that the mesons travel parallel to its long axis. It is made from square pyrex tubing whose inner surfaces are accurately plane and whose outer surfaces have been ground flat and polished. The tubing is sealed off at one end and a Kovar-to-Pyrex graded seal is attached at the other end. Lines are etched on the outside surfaces to provide a reference system for scanning.

The jacket is also made of pyrex tubing of the same type, but of inside dimension 4 cm. square, and length about 15 cm. This is also ground and polished, sealed at one end, and attached to a 5.7 cm. diameter Kovar cup at the other end.

The bottom of the Kovar cup is removable to allow the bubble chamber to be assembled inside the jacket. The two portions of the Kovar cup are soft soldered together.

The assembled chamber and jacket are shown in fig. 2.

4. *Jacket temperature control and measurement*

The jacket surrounding the bubble chamber specifies the temperature of the bubble chamber walls, and hence the average temperature of the bubble chamber. The jacket temperature control depends on the following mechanism: during operation, the liquid hydrogen in the jacket is maintained at a level somewhat above the highest point of the bubble chamber. The liquid in the jacket normally boils because of heat from thermal radiation, and from the jacket heater. The resulting vapor liquifies in the condenser and drops back into the jacket, a process of heat transfer so efficient that the condenser temperature and the jacket temperature are closely the same.

Control of the temperature is achieved by empirically choosing the heat leak (a copper bar 2 inches long with a $1^1/_4$ square inch cross section) to have approximately the correct thermal conductance, and then adjusting the heater power to produce the desired temperature. The heater is turned on and off by the pressure "pick-up" in the jacket system which is shown in fig. 1. Thus a drop in temperature reduces the pressure causing the switch to turn on the heater. The pressure pick-up is simply a diaphragm between the jacket system and a reference system. A difference of 0.01 atmospheres between the jacket and reference pressures is sufficient to cause the diaphragm to deflect, thus making or breaking the heater control circuit.

During the time the chamber is waiting for a meson, the jacket must be free of bubbles which would obscure the track. This is done by momentarily disarming the pressure switch and keeping the heater on, at a high current, for about 250 milliseconds before the picture is to be taken. The boiling around the heater, which is hidden from the camera, is then too rapid for the condenser to cope with, so the pressure rises rapidly, and the bubbles disappear in the portion of the jacket around the bubble chamber. After the picture is taken, the pressure switch is given control again, the heater is turned off, and the pressure falls. The use of the heater to stop jacket boiling does not materially increase the average heater power delivered to the whole system. The power dissipated by the heater accounts for about 20 per cent of the total evaporation of liquid hydrogen.

The jacket pressure is read on a bourdon gauge, and the temperature of the jacket estimated from the known vapor pressure data for hydrogen [5].

Typical operating values are given in Table I.

TABLE I.

Operating conditions for bubble chamber

Heater power (average)	6 watts
Heater power (during pulse to stop jacket boiling)	50 watts
Jacket pressure (average)	75 psi
Pressure rise due to heater pulse	10 psi
Bubble chamber temperature	27 °K

The condenser surface is a spiral of 0.005-inch copper sheet. The turns of the spiral are separated by a 0.015-inch spacer strip. The whole assembly makes a roll $1^1/_4$-inches long and 2 inches in diameter. This spiral is soldered into a copper can to form the condenser.

5. *Pressure control system*

The pressure in the bubble chamber is controlled by the motion of the lower metal bellows. The lower and upper metal bellows are mechanically coupled by a hollow push rod, sliding inside of a guide tube. Compressed air is admitted to the upper bellows by a solenoid valve *, forcing the push rod down and compressing the liquid hydrogen in the lower bellows.

On the "expand" part of the operating cycle, the solenoid valve closes off the compressed air line and releases the air in the upper bellows to the atmosphere. As the push rod moves up, the pressure in the bubble chamber falls rapidly, and the chamber becomes sensitive to ionizing particles.

The bellows ** are $1^3/_4$-inch inside diameter two-ply stainless steel units with an effective area of 3.45 square inches. They are assembled so as to allow a maximum stroke of one-half inch. The actual motion during operation is $^3/_{16}$ inch. The displacement is, thus, about 0.74 cubic inches. The volume of the chamber system is 9.4 in^3 of which there is 5.3 in^3 at 27 °K, 3.7 in^3 near 20 °K, and 0.4 in^3 filled with vapor. Most of the vapor is at room temperature.

The design of the bellows system is such as to minimize the hazard due to bellows failure. As shown in fig. 1, the compressed air and the liquid hydrogen are in contact with the *outside* of the upper and lower bellows respectively, while the push rod runs through the *inside*. The inside system composed of the guide tube and the two bellows is evacuated at the beginning of a run by opening a valve leading to the main vacuum system. The valve is then closed leaving the bellows system isolated. A failure of either bellows is registered by the vacuum gauge mounted below the upper bellows (see fig. 1). No danger results from such a failure since the main vacuum system remains undamaged.

A rod attached to the upper bellows extends into a lucite tube at the top of the assembly so that the position and motion of the bellows can be easily seen.

6. *External plumbing*

The external plumbing, which is shown in fig. 1, must insure the purity of the hydrogen gas entering the system and must provide for pressure control and limitation.

All the hydrogen gas entering the system is purified by passing through a charcoal trap immersed in liquid nitrogen. A sintered glass filter beyond the charcoal trap removes any dust which may be present.

Before a run, while the bubble chamber is still warm, hydrogen is admitted to the chamber and jacket and then pumped out again. This process is repeated several times to flush out all other gases. The system is then left full of hydrogen under pressure while the nitrogen shield and hydrogen reservoir are filled.

The bubble chamber and jacket cool slowly by conduction and radiation to the reservoir. After about one hour liquid hydrogen begins to condense. When the bubble chamber and jacket are full of liquid hydrogen, the valves are closed isolating them from the filling line and from each other. The heaters are then turned on and the apparatus is ready for operation.

Each of the three isolated pressurized systems, namely, the charcoal trap, the jacket, and the chamber is protected by a safety valve, since accidental heating of any of these systems could cause a large pressure rise. Valves bypassing the safety valves are used for normal release of gas at the end of a run.

The volume of the external (room temperature) chamber and jacket system is kept to a minimum so as to reduce heat loss due to the flow of gas in and out of the internal (cold) apparatus.

7. *Operation of the bubble chamber*

After the apparatus has been aligned with the desired beam of the cyclotron and the chamber has been filled with liquid hydrogen at the proper temperature, a clock pulse starts the following cycle of operation, summarized in Table II.

First, the heater is pulsed for a period of 250 milliseconds. By the end of this period, all boiling stops in the region around the bubble chamber (see Sec. 4.).

About 50 milliseconds after the jacket heater is turned off, the chamber is expanded by releasing the pressure in

* Obtained from the Bellows Manufacturing Company, Chicago, Ill.
** Obtained from the Flexonics Corporation, Elgin, Ill.

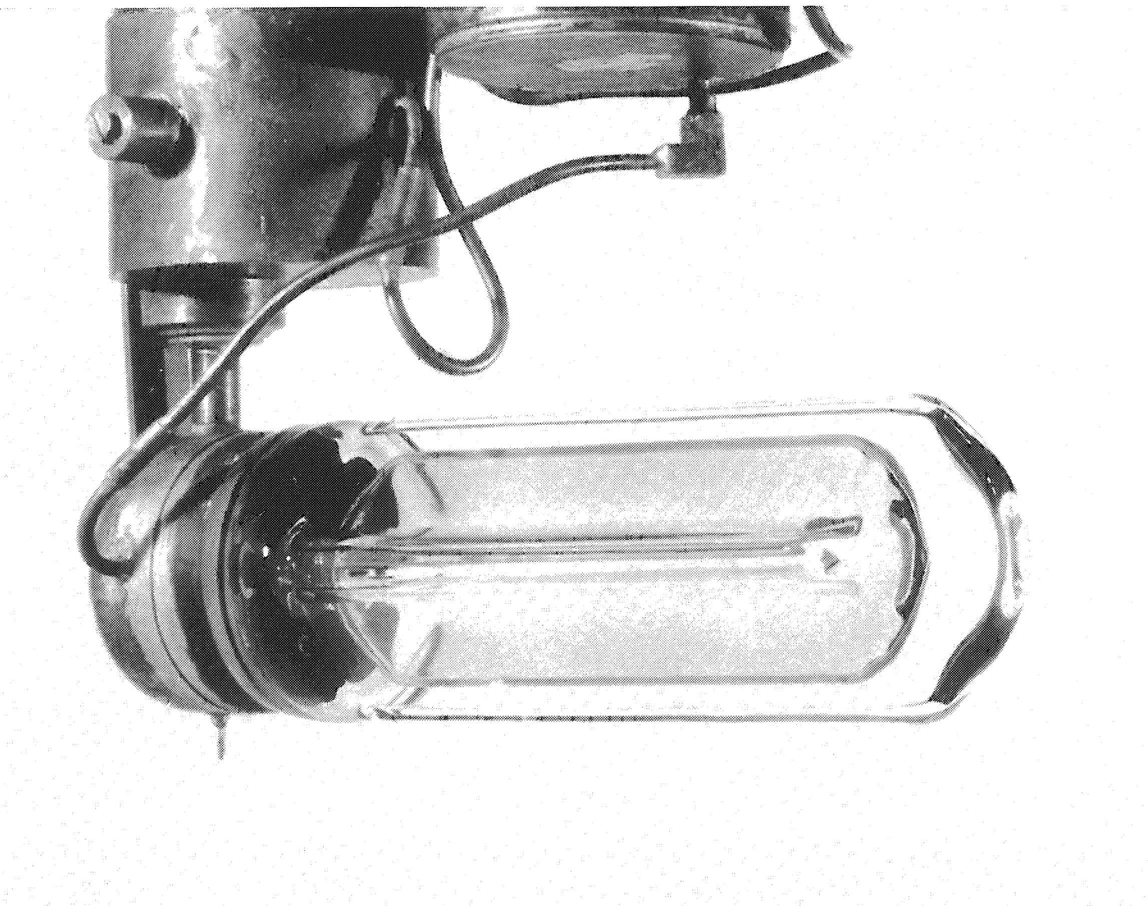

Fig. 2. Assembled bubble chamber and jacket.

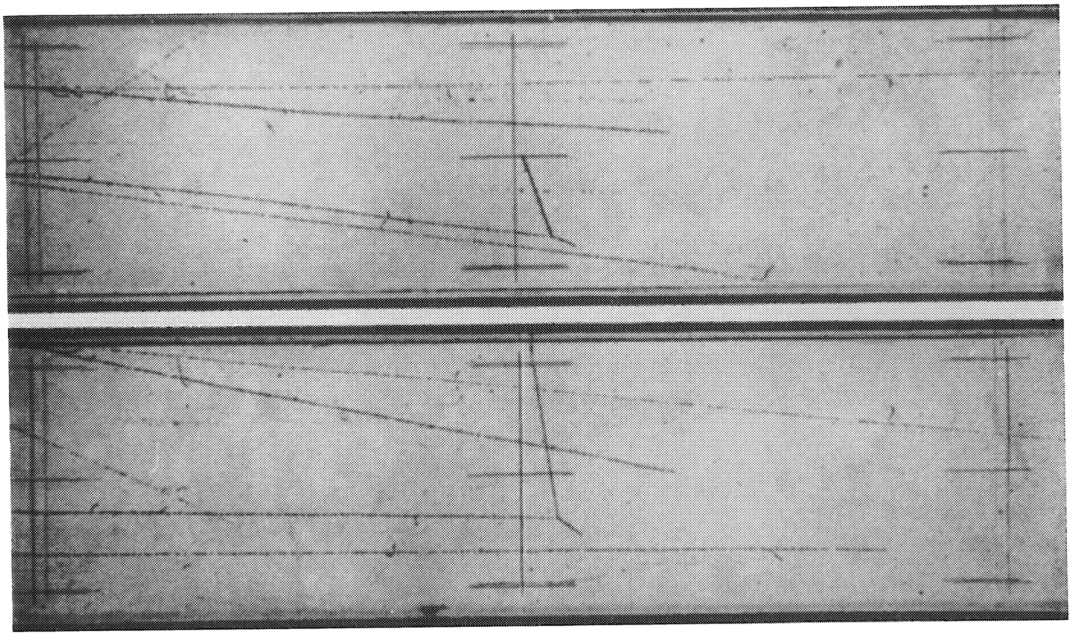

Fig. 3. Two views of a π - p scattering event. The pion scattering angle is $102° \ 0' \pm 1° \ 30'$. The short horizontal lines are spaced 1 cm. apart.

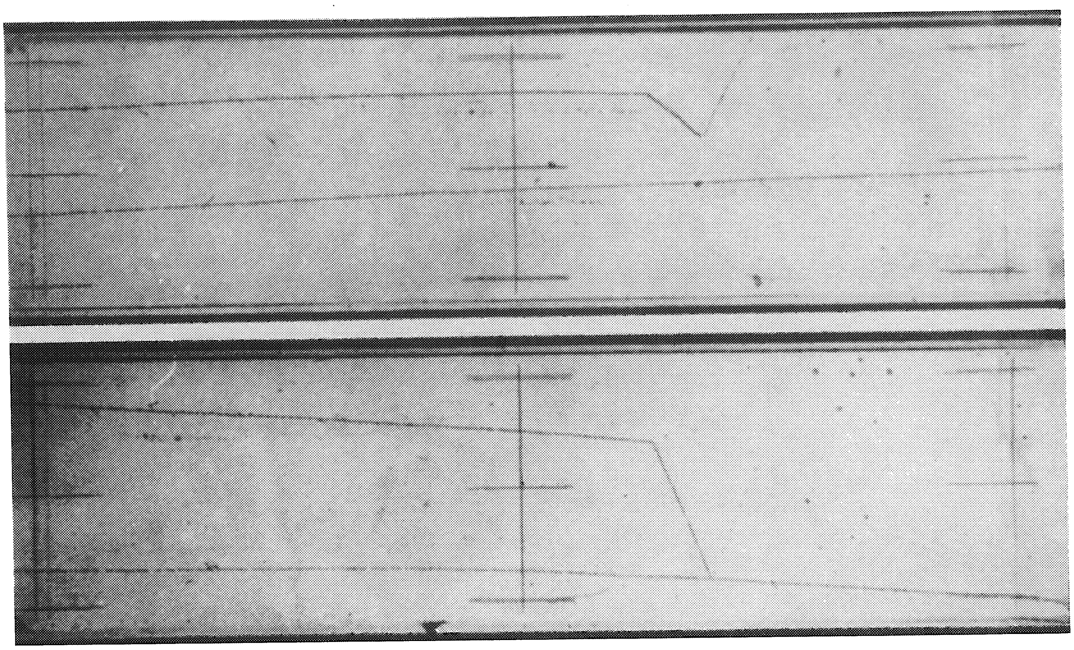

Fig. 4. Two views of a π - μ - e decay.

the upper bellows. When this pressure has dropped to 1.5 atmospheres (after about 70 milliseconds) the cyclotron rf (normally off) is operated for one frequency modulation cycle.

TABLE II

Time sequence of operations

Operation	Starting Time Millisec [a]	Duration Millisec [b]
Clock pulse	0	short
Heater pulse to stop Jacket boiling	0	250
Compressed air release [c]	300	70
Pulse to cyclotron	385	short
Meson pulse	400 ± 10	.001
Flash	$(400 \pm 10) + 3.5$	$\ll 1$
Next clock pulse	2000	short

[a] Column two refers to the delay time between the operation in that row and the initial clock pulse.

[b] Column three refers to the duration of the operation.

[c] There is a delay of about 50 milliseconds between the operation of the compressed air valve and the change of bubble chamber pressure. At the end of the release operation, the compressed air is reapplied, but the same delay leaves the bubble chamber sensitive until after the picture is taken.

The beam arrives at the apparatus about 15 milliseconds after the cyclotron is pulsed. Its arrival is detected by a pair of scintillation counters in coincidence. The second counter is placed as close to the bubble chamber as possible, so that even for low energy beams, very few particles are lost by scattering before entering the chamber.

The coincidence pulse is delayed about 3 milliseconds to allow time for the bubbles to grow. At the end of this delay, the pulse fires the flash lamps and the picture is taken.

The coincidence pulse also starts the "reset" operations of advancing the film and the registers which number each picture. The chamber remains under compression until the next clock pulse starts another cycle. The period is determined by the time required to clear the chamber of old bubbles.

In test runs, it has been found that the chamber will remain sensitive for intervals of about $^1/_4$ second after being expanded because of its clean, all-glass construction. This feature is valuable when working in very weak beams. If no particle emerges in the first rf pulse, the cyclotron may be pulsed again and again until one does emerge and fires the coincidence counters.

8. *Photography and reprojection*

The photographic system is shown schematically in fig. 1. The ground glass screens provide bright backgrounds against which the bubbles appear as dark spots. Lines etched on the outside walls of the bubble chamber are visible in the pictures, thus establishing a coordinate system to which the bubble tracks may be referred. These features are illustrated by the sample pictures shown in figs. 3 and 4.

The flash tubes are Amglo Type H-D-1 excited by the discharge of an 80-μF condenser charged to 250 volts. The duration of the flash is about 20 microseconds.

The pictures are taken by a pair of Bell and Howell Eyemo-K 35 mm. motion picture cameras, converted to single frame operation. The lenses are 21 cm. Zeiss Tessars, stopped down to f-30. The object distance was 105 cm. The film was Kodak Linograph Ortho.

In order to scan the pictures, they are reprojected three and a half times life size on a flat table. The two views appear side by side and are measured independently. Angles and lengths are measured with a Bruning Drafting Machine. The angles are read to 5 minutes of arc and the magnified lengths to 0.2 mm. These are recorded as the initial data.

From these measurements, the true angles and lengths in the plane of the event are rapidly and accurately determined with an analyzing instrument which uses the familiar properties of stereo-graphic projection. This instrument is described by Pless and Plano[6]).

Pictures containing more than five tracks are difficult to scan. The beam is therefore limited to give an average of two tracks per picture.

9. *Bubble tracks*

The scanning speed and the accuracy of the measurements are influenced by the size and the number of bubbles along the tracks.

The size of the bubbles, as they are photographed, is controlled by adjusting the delay between the time the particle traverses the chamber (as detected by the counters) and the time the light is flashed. The bubble diameter used in most of our work is about 0.2 mm., which is larger than the resolution of the photographic equipment (about 0.1 mm.) but smaller than the average distance between bubbles (about 0.4 mm.).

The number of bubbles per unit track length depends on the operating conditions and on the rate of energy loss of the particle. Under our conditions, a 20 Mev pi-meson track has about 30 bubbles per centimeter, while a high-energy electron track has about 15 bubbles per centimeter. This difference is usually sufficient to distinguish electrons from mesons, even though the mesons have energies extending all the way from 10 to 30 Mev. Thus, fig. 5 is a histogram showing the bubble densities of 20 pion and 20 electron tracks. In making this histogram, each pion was identified as a component of a π-p scattering event or π-μ-e decay, while each electron was identified as a component of a π-μ-e decay or Dalitz pair associated with π^- capture. Three centimeter lengths of track were counted to obtain the bubble densities. Statistical fluctuations in bubble-spacing along the 3 cm. lengths are sufficient to explain much of the spread in the two groups of points.

The π-μ-e decay in fig. 4 illustrates the difference in the appearance of electron and slow-meson tracks.

10. *Summary of bubble chamber characteristics*

One measure of the usefulness of the apparatus is the number of scattering events which can be found for a given expenditure of liquid hydrogen, cyclotron time, and scanning time. This information, which is summarized in Table III, may be interpreted as follows: For a process with a cross section of 10^{-26} cm^2, each event requires 0.6 liters of liquid hydrogen, 0.15 hours of cyclotron time, and three quarters of an hour of scanning time. Although we hope to reduce these figures by further improvement of the apparatus, it is apparent that processes with cross sections of this magnitude may already be studied.

A second factor affecting the usefulness of the device is the accuracy of the measurements. In the event shown in fig. 3, the meson scattering angle is measured as $102° 0' \pm 1° 30'$. The accuracy of this measurement is limited by multiple scattering and by the short range of the proton, and these in turn, depend on the energy of the incoming meson and on the scattering angle. The proton range in the same event is 2.08 ± 0.15 mm. from which we obtain the incident pion energy of 14.3 ± 1.0 Mev. In this case, the error depends primarily on the bubble size and density.

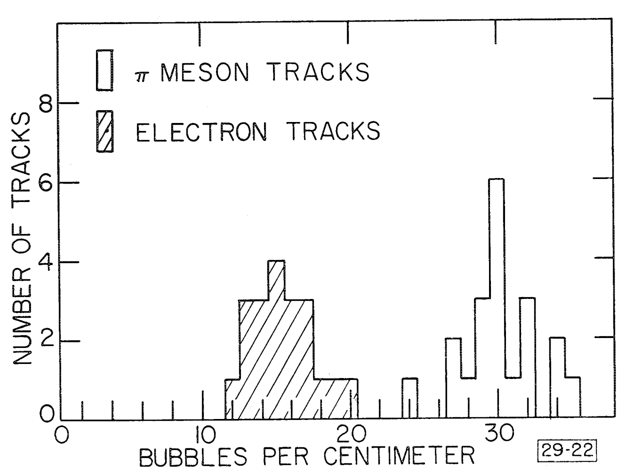

Fig. 5. Histogram showing bubble densities of twenty π meson and twenty electron tracks. Three centimeter track lengths were counted.

Finally, we must examine the efficiency for detecting events. In the present experiment, we consider only those events for which the recoil proton has a measurable range so that we can determine the energy of the pion, and so that we can distinguish scattering events from the more frequent π-μ decays. Under the conditions of this experiment, this means that the scattering angle must be greater than 50°. In one strip of film containing 2000 pictures, we found a total of 17 tracks with deflections greater than 30°. These events included π-μ decays and π scatterings above and below the minimum angle. When these pictures were rescanned by a different scanner, the same 17 deflections were found. On the basis of this test, we feel that the efficiency for seeing the relatively conspicuous scattering events beyond 50° must be greater than 90 per cent and may approach 100 per cent.

TABLE III.

Data on most recent operation of chamber

Cyclotron time used [a]	45 hours
Total liquid hydrogen consumption	200 liters
Number of (pairs of) pictures taken	56,000
Average number of (10 cm.) tracks per picture [b]	1.5
Hydrogen traversed by each track	0.6 g/cm^2
Time to scan 1000 pictures [c]	4 hours

[a] This figure includes only time during which there was liquid hydrogen in the apparatus. It does not include setup time, repair time, or time to measure the properties of the beam.

[b] This figure includes only tracks which traverse the entire length of the chamber and which remain far enough from the walls so that the events will be measurable.

[c] This figure includes the time to find, measure, analyze, and record all events in which a track is deflected more than five degrees. In this experiment, about one such event was recorded for every fifty pictures.

11. *Acknowledgments*

We are indebted to Professor Earl Long and Professor Lothar Meyer for many helpful suggestions about the design of the apparatus. We also wish to thank Dr. Irwin Pless for help during the construction and operation of the equipment and Mr. Konrad Benford for assistance in the design and construction of the electronic circuits. Finally, we must thank Mr. Christian van Hespin for the construction of the jacket and chamber in his glass shop.

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DISCUSSION

A. Roberts: The use of the hydrogen bubble chamber for meson-proton scattering is justified only for preliminary survey work. For the accuracy of cross-sections now required in pion-nucleon scattering, the amount of work required to obtain this information with a bubble chamber is prohibitively large. This is especially true at low energies.

R. H. Hildebrand answered that Roberts was right that whenever you can use counters you should do so. This is easy for energy greater than 50 Mev. With great ingenuity you can even go as low as 30 Mev with counters. Since p-wave scattering goes as the cube of momentum, to study s-waves it is very interesting to go to still lower energies. With bubble chambers it is possible to go down as far as 6 Mev.