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Argonne National Laboratory

BUBBLE CHAMBERS 1964-1966

by

M. Derrick

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BUBBLE CHAMBERS 1964-1966

by

M. Derrick

High Energy Physics Division

(Rapporteur Talk given at
International Conference on
Instrumentation for High Energy Physics,
Stanford, September 10, 1966)

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BUBBLE CHAMBERS 1964-1966

by

M. Derrick

I. INTRODUCTION

My traditional job at a meeting such as this is to bring you up to date on the developments in the technology that have occurred since the last conference, to stress what I feel are the important and significant aspects, and to make some prognostications for the future.^{1,2} I was perturbed because the second volume of the 1964 conference (containing the instrumentation sections) had not appeared, and had nightmares about having to cover the last four years, which have seen the technique grow to maturity, but then a few weeks ago I was saved by the appearance of the Dubna reports.

On reading them, I was less sure that it would have been so bad! People say about the physics conferences traditionally held at about the same time as our plumbing conventions that things never seem to change much. Experiments just take a long time to plan, execute, and analyze. We have a similar disease but in a more acute form. Bubble chambers take several conference intervals to build and sometimes as much as one conference interval to bring into satisfactory operation. Nevertheless, important advances are being made in a span of two years.

A very significant pointer to the maturity of the technique is the obituary list. I don't know what sex bubble chambers have, but in religion they seem to be Buddhist. The Saclay 50-cm chamber has been reincarnated as an 82-cm chamber, the BNL 20-in. chamber as a 31-in., the CERN heavy-liquid chamber suddenly was reborn with twice the volume, and the venerable 72-in. chamber promises to appear here in this laboratory with an 82-in. length. On the other hand, the Berkeley 30-in. propane chamber really seems to have retired, and the Saclay 1-m propane chamber--so successfully used at CERN--has returned to Paris.

II. NEW CONVENTIONAL CHAMBERS

Now for the births column. Table I shows the new chambers in operation at accelerators for physics. This is not the same as the experimental chambers that will be discussed later. The two weak-focusing proton accelerators, NIMROD at the Rutherford Laboratory and the Argonne ZGS, have been fully equipped. Both have heavy-liquid chambers just in operation in a beam. Both have medium-sized, conventional hydrogen

chambers in separated K beams, and, to complete the similarity, both have helium bubble chambers. At the British laboratory, the large (80-cm) helium bubble chamber will shortly be having an engineering test and therefore is not included in the list.

TABLE I. New Chambers in Operation at High-energy Accelerators for Physics since September 1964

Chamber	Size, cm	Field, kG	Accelerator
82-cm Saclay	82 x 50 x 40	22	NIMROD
1.5-m heavy liquid	150 x 50 x 50	20	NIMROD
2-m CERN	200 x 60 x 50	20	CERN PS
1-m heavy liquid	100 ϕ x 66	46	ANL ZGS
25-cm helium ANL-CIT	25 ϕ x 35	40 SC Magnet	ANL ZGS
50-cm helium Northwestern	50 x 25 x 30	30	ANL ZGS
80-cm	80 x 40 x 40	22	DESY

In the midwest, two helium bubble chambers have been cohabiting in the same experimental area. The in-house chamber was exposed to a stopping K beam, while somewhat later the visitor chamber from Northwestern was exposed to a 3-BeV/c π^- beam, which we all hope has satiated its appetite--at least temporarily. Previously it had a successful physics run with low-energy pions (150 MeV/c) at The University of Chicago synchrocyclotron. Figure 1 shows the Northwestern chamber.³ It is a conventional design with a bellows expander above the magnet coils. The system has been elegantly thought out and makes a very compact, portable device.

At CERN, the 2-m chamber shown in Fig. 2 has come on in an impressive manner and promises to be the most productive single physics instrument in Europe. It is piston-expanded, similar to the BNL 80-in. chamber, but uses through illumination, which means the pictures are prettier. Following the interesting work of the CEA group, using the old Columbia 12-in. chamber, a large exposure of an 80-cm chamber to a photon beam has been made at DESY.

Two very similar heavy-liquid chambers have come into use. CERN has long had a vigorous heavy-liquid chamber program, using first the Saclay 1-m chamber and then the CERN chamber. This latter has been enlarged to a volume of 1,100 liters and so, in a sense, is a new chamber. Most of the work has been in weak interactions with some notable exceptions. At Argonne a similar chamber, built by a Michigan-Argonne group⁴ (1-m diam, 0.66 m deep, 46 kG), is just starting a program

137-1782

Fig. 1. Northwestern Helium Chamber; Section Perpendicular to Beam Direction. The lights are on the left and the 3 cameras look through the vacuum window on the right. The chamber extends upwards in a narrow neck to the circular expansion bellows.

of work in a separated beam of momentum up to 900 MeV/c. Particle orbits of 800 MeV/c K^- in the fringe field and the large central field are shown in Fig. 3 to illustrate the beam-entry problem. With the very high magnetic field, the multiple-scattering error on the tracks for a propane filling of this chamber is about 2%, which is equal to that in a hydrogen chamber with a field of 14 kG. We have then a new device, a chamber with the precision of the hydrogen bubble chamber, but yet a 30 to 50% probability of converting a gamma ray. This chamber is well suited to experiments requiring production reactions on free protons, resulting in a final state having a modest number of gamma rays. Things like branching ratios of decays of resonant states and studies of reactions such as $K^- p \rightarrow \Sigma^0 \pi^0$ spring immediately to mind. Separation of the events occurring on hydrogen does not seem to be a problem.⁵ I personally feel that in addition to a continuing usefulness in weak interaction studies, the next few years will see important results on strong interactions coming from the heavy-liquid chambers.

Fig. 3. Beam Orbits of 900-MeV/c Particles in the Michigan-Argonne Heavy-liquid Chamber. The small circles represent some of the axial flash tubes round the edge of the chamber. The outline of the coils and magnet iron can also be seen.

A number of conventional chambers are still under construction, and the next conference should see the MIT 40-in. hydrogen chamber installed at the Argonne ZGS, and the first operation of the SLAC 40-in. hydrogen chamber.⁶ A section drawing of the SLAC chamber is given in Fig. 4. We might call this the last of the old chambers, and it has several nice features resulting from a long slow development in many laboratories. The expansion system uses a toroidal bellows, as used in the ANL-CIT helium chamber⁷ and the Berkeley 25-in. hydrogen chamber.⁸ This elegant

Fig. 4. SLAC 40-in. Hydrogen Chamber. Notable features are the hydraulically actuated, moving back-wall expander and the single window. Electrons created by the gamma-ray beam in the aluminum vacuum window are swept out by a magnet.

system maximizes the useful volume of the chamber and provides a low turbulent, efficient expander. The actuator is hydraulic, making for long life and easy rapid cycling. A single window, 3 cameras, and a Scotchlite retrodirector are used for illumination and photography. A conventional 22-kG copper and iron magnet is provided.

III. PICTURE PRODUCTION

The bubble-chamber pictures actually taken in the five large proton-accelerator laboratories are listed in Table II. The periods covered are somewhat different. CERN works on calendar years, BNL and LRL on fiscal years (June to June). For the two new proton accelerators (NIMROD and ZGS) that are just starting into mass production of film, I have given the total pictures taken. In both cases, most of these were taken in the last year, indicating that the new accelerators are in high gear, if not yet in overdrive.

TABLE II. Bubble-chamber Pictures Taken in High-energy Proton-accelerator Laboratories

Laboratory	Chamber	Pictures Taken (K)	Period Covered
CERN	1.5-m British National Hydrogen	596	Jan to Dec '65 ↓ up to Aug '66 ↓ June '65 to June '66 ↓
	81-cm Saclay Hydrogen	2,016	
	2-m CERN Hydrogen	1,045	
	1.2-m CERN Heavy Liquid	1,193 + 367 for neutrino experiments	
	CERN Total	<u>5,217</u>	
Rutherford	82-cm Saclay Hydrogen	1,800	up to Aug '66 ↓ June '65 to June '66 ↓
	1.5-m Heavy Liquid	600	
	Rutherford Total	<u>2,400</u>	
ANL	30-in. MURA Hydrogen	1,282	up to Aug '66 ↓ June '65 to June '66 ↓
	10-in. Helium ANL-CIT SC Magnet	408	
	40-in. Heavy Liquid Michigan-ANL	30	
	20-in. Helium Northwestern	130	
	ANL Total	<u>1,850</u>	
BNL	30-in. Hydrogen	2,550	June '65 to June '66 ↓
	80-in. Hydrogen	1,544	
	BNL Total	<u>4,094</u>	
LRL	25-in. Hydrogen	1,079	June '65 to June '66 ↓
	72-in. Hydrogen	1,877	
	LRL Total	<u>2,956</u>	
Grand Total		<u>16,517</u>	

A number of points are immediately obvious. The first is that no single chamber has taken more than 3 million pictures, although some are close. Since a year has something over 30 million sec, there is still a considerable slack to take up. It should be possible in the near future to increase the number of pictures taken by a chamber in a stable beam arrangement to 5 million pictures in a year. Considering the repetition rate disadvantage of the Bevatron, the Berkeley total of 3 million pictures stands up very well. CERN has the best record--in line with the fine operation of the whole CPS complex. I am not equating the physics output of any laboratory with the number of bubble-chamber pictures taken, although in the long term there will obviously be a correlation.

To increase the output much further will be more difficult, although skillful scheduling of the entire accelerator program can produce significant improvements. The only obvious unexploited area is that of rapid cycling. The first use of this for physics pictures was with the 25-in. LRL chamber about two years ago.* The largest hydrogen chamber that has operated this way in a test is the BNL 80-in. chamber. It was possible to operate twice with only 75 msec between each expansion.⁹ The large heavy-liquid chamber at ANL has performed a similar test, but in this case 300 msec was necessary between expansions to avoid reappearance of the first tracks on the second pulse. More recently the Saclay 82-cm chamber and the ANL 30-in. chamber have also taken physics pictures in this double-pulse mode. Provided the plumes can be kept under control, the second picture in any chamber seems to suffer no degradation compared to the first. Figure 5 shows a section of the first and second pictures for the BNL hydrogen chamber. For π exposures, this multiple pulsing will probably become standard practice, and, as accelerator intensities increase, it will become practical for the K and $\bar{p}$ beams also.

When budgetary limitations are becoming acute, multipulsing has an added impetus. To first order, only the extra cost of film is added in multiplying the picture output. The electric-power bill and the operators' salaries are independent of the number of pictures taken.

We seem to be keeping up reasonably well with the estimates made by W. B. Fowler¹⁰ that the number of bubble-chamber pictures taken in the United States Laboratories will increase from about 8 million in 1965 to 45 million in 1975--if a slight phase shift is inserted. At the next conference we look forward to reports of the pictures taken in this laboratory.

*The PPA laboratory has a 15-in. chamber that has pulsed many times per second in sympathy with the rapid repetition rate of the accelerator. However, the pictures taken with this chamber have used counter control of the flash. This technique has been used to select pictures in which an interaction occurred. The chamber is too small, compared to the wall thickness, for this to be very efficient.

137-1819

Fig. 5. Tracks in BNL 80-in. Chamber in Double-pulse Operation. The top is the first pulse, and the bottom is the second pulse 0.075 sec later. The chamber was operating at 30-psi overpressure. Insert at top shows piston stroke, chamber-pressure drop, and expansion-valve control pressure for the 2 pulses on a 0.010-sec/division time scale.

As beam energies increase, the cross sections for most two-body final states decrease in quite a drastic way; therefore, more pictures are needed to obtain the same number of events in any given channel. For example, the cross section for the reaction $K^- + p \rightarrow \Lambda + \omega$ goes down by an order of magnitude between 3.5 and 8 GeV/c. This effect can easily be

seen in the experiments scheduled. Today, exposures of several hundred thousand pictures in the big chambers are not uncommon, whereas the 20-in. chamber in three years at the AGS (September 1961 to December 1964) took 3.4 million pictures for 40 different experiments--an average of less than 90,000 per experiment.

As more pictures come from large (~2-m) chambers, the data-reduction load is increasing somewhat faster than the picture-taking rate and seems to double about every 2 years. Figure 6 shows a prediction made by Art Rosenfeld of the data-reduction load as a function of time. The only thing he has omitted is the predicted budget requirements.

137-1773

Fig. 6

Estimates of Annual Production of Events by U. S. Bubble Chambers. Based on Table III by W. B. Fowler, May 1, 1965. (Estimates made by A. H. Rosenfeld, June 1, 1965.) The lowest curve (o) is Fowler's totals, in millions of pictures per year. Call this Σn_i . The middle curve (x) shows the sum $\Sigma n_i L_i$, where L is the useful length of the chamber in feet. Since a cross section of 1 barn corresponds to a mean free path in liquid hydrogen of 1 ft, $\Sigma n_i L_i$ gives events/ μ barn if there were only 1 beam track in each picture. This is multiplied by 10, on the assumption that there will be about 10 tracks per picture. The top curve (+) is $\Sigma n_i L_i^2$; i.e., it corresponds to the middle curves times an extra factor of length, to account for the probability that secondary particles have a probability of interacting proportional to L . Since events with secondary interactions are more complicated to measure and compute, but much more useful, they represent an increasing load on the data-analysis facilities. To guide the eye, the dash curves (----) show a growth rate doubling each 2 years.

IV. HIGH-FIELD CHAMBERS

One chamber listed in Table I as coming on line for physics in the past 2 years is the Argonne-Carnegie Institute of Technology helium bubble chamber.⁷ This chamber makes a convenient bridge between the topics of existing chambers and the future since it uses a superconducting magnet, and so is pregnant with promise for the future. As far as I am aware, this marks the first use of the technique in the large-scale, elementary-particle physics experiment. Over 3 weeks, 468,000 pictures were taken in a low-momentum, separated K-meson beam. The chamber, shown in Fig. 7, had been operated more than 2 years earlier. The first magnet was built by the AVCO Corporation using single-strand, 10-mil NbZr wire. Although it achieved 32 kG on a test, by the time it had been completed (May 1964) it was obvious that superior techniques were available, so a second magnet was designed and wound at Argonne by C. Laverick.^{11,12} This magnet was operated on test at 45 kG in the 11-in. bore and at 67 kG using a liner of 7-in. bore. The new magnet is made of cable, as can be seen in Fig. 8, and was the one used

during the experiment. At the ZGS, we ran the magnet at 40 kG during the experiment because we were chicken. As you can tell from the picture-taking rate the entire equipment ran faultlessly, thanks to the careful work of Lloyd Hyman and the chamber crew. The magnetic-field regulation shown in Fig. 9 was excellent, the variation being less than 0.1% during the entire period. On test, the magnet and chamber were operated together, and the magnet quenched several times at different field values. Figure 10 shows this chamber set up in the low-momentum K beam at the ZGS. On the left is the Northwestern helium chamber, and on the right the Michigan-Argonne heavy-liquid chamber. With this experiment, supermagnets have come of age for bubble-chamber use.

137-1654

Fig. 7. Argonne-Carnegie Tech. Helium Chamber with Superconducting Magnet. Expansions are made by moving the plastic lens, which is attached to the chamber body by an omega bellows. Three 35-mm cameras photograph the entire chamber volume. Liquid hydrogen is used to provide thermal clamping of the support structure. Two helium reservoirs are used: the small central one operates at atmospheric pressure (4.2°K) for the magnet; the large side reservoir is pumped to 250-mm pressure and controls the chamber temperature.

Fig. 8. Photograph of Superconducting Magnet for Helium Chamber, Prior to Mounting in the Magnet Can. The 6-in.-bore central coil was only used during the test operation of the magnet. The cable construction is seen through the cooling holes provided in the end flanges.

137-1776 Rev. 1

Fig. 9. Magnetic-field Regulation in Helium Chamber Magnet during Period of Stopping K⁻ Run at Argonne ZGS. The mean regulation is at least as good as that achieved with a conventional magnet.

used in the large MHD magnet built by AVCO. This latter is a bending-magnet configuration with a field of 40 kG in a 5-ft by 1-ft bore. The magnet uses a strip conductor, which can be current-overloaded without the magnet quenching. Figure 11 shows the current-voltage relationship of the material.¹⁴ At about 700 Amp, the superconductor has reached its limit; then the excess current flows in the copper. Provided the cooling is adequate to keep the superconductor temperature stable, anywhere on the line is a stable operating point. The normal operating point, of course, is in the zero-voltage part of the curve since the helium refrigerator must remove the Joule heat generated when the copper is being used to pass current. This important contribution enables one to design a magnet that then operates as predicted and need never quench.

Fig. 11

Current-Voltage Relationship of Stabilized Superconducting Strip. At about 700 Amp, the superconductor has reached its limit, and then the excess current flows in the copper substrate. Provided the cooling is adequate, anywhere on the line is a stable operating point, but a normal operating point is on the zero-voltage part of the curve.

As a result of these developments, ANL, BNL, and CERN decided to provide superconducting magnets for their respective giant chambers. This was done at Argonne, even though the magnetic field with a conventional or superconducting magnet would be the same, and so result in no better momentum accuracy on the tracks in the chamber. The capital cost of the 2 magnets is the same, but the supermagnet will cost about \$350,000 less a year to operate. The specifications of the ANL magnet are given in Table III.¹⁵ Pancakes will be wound of 2-in. by 0.1-in. copper strip with the superconductor embedded in it, as shown in Fig. 12. The magnet circuit

TABLE III. 12-ft HBC Magnet--Summary of Design

Field:	20 kG	Coil axial compressive force:	6.8×10^5 kg
Ampere turns:	5×10^6	Weight of iron:	1.45×10^6 kg
Current:	2,000 Amp	Inside diameter of coil:	478 cm
Conductor dimensions:	5 cm x 0.254 cm	Length of coil:	304 cm
Inductance of windings:	40 Henrys	Power-supply voltage:	10 V
Number of pancakes:	30	Charging time:	2.25 hr
Energy stored in field:	80×10^6 Joules	Heat-transfer rate required for 100% stability:	100 mW/cm ²
Weight of copper in windings:	45,000 kg	Resistivity of stabilizing copper at 20-kG field:	1.7×10^{-8} ohm/cm
Weight of superconductor:	300 to 450 kg		
Hoop stress on winding:	420 kg/cm ²

138-2625

Fig. 10. ZGS Experimental Floor with Supermagnet Helium Chamber during Period of Stopping K^- Run. The chamber is directly below the exhaust hood in the center of the picture. The supermagnet power supplies and controls are located in the trailer (right center). The Michigan-Argonne 40-in., heavy-liquid chamber is at far right center, and the Northwestern helium chamber at left center.

The development of supermagnets has made such rapid progress in the past 2 years, and they promise to be so important in high-energy physics, that it is appropriate to review the situation.¹³ Small coils, a few inches in size, providing magnetic fields in the tens of kG, have been made for some years, but before these could be successfully extrapolated to large coils several problems had to be solved.

This is not the place to go into the historical evolution of the ideas and experiments. I shall merely give the conclusions that have resulted in the building and operation of what are called stable superconducting magnets. Three ingredients go into a state-of-the-art large magnet. First, many parallel paths of superconductor are provided; second, the superconductor must be well-bonded to a relatively large amount of normal conductor (usually copper); and last, the coils must be well cooled. The actual conductor can be made by cabling strands of superconductor and copper, as originated by Charles Laverick for the helium bubble-chamber magnet, or a strip conductor can be made. This type of conductor was

137-1756

Fig. 12. 12-ft Hydrogen Chamber Magnet. The pancakes are wound of 2-in. x 0.1-in. stabilized superconducting strips, which are then stacked to form the coils. Spacers between the pancakes allow for edge-cooling by liquid helium. The coils are suspended by tubes from the top of the iron. The small inserts show the magnet iron configuration.

is shown in Fig. 13. Under normal conditions, the stabilizing resistor of 1 milliohm will be in parallel with the coil. The time constant of 40,000 sec

137-1752

Fig. 13. Circuit of 12-ft Hydrogen Chamber Magnet, Showing the Protective System

are both radial and tangential. The coils are relatively inaccessible, and a large differential contraction occurs between the magnet coils and the room-temperature support system. At the other end of the scale, several magnets with bore sizes of 1 to 3 in. and magnetic fields in excess of 100 kG have been operated.¹³ In these magnets, current density is very important, and so in general they are not stabilized in the sense mentioned above.

An alternate approach to the high-field problem has been used in Munich, where a group under W. H. Bergmann has constructed a 7-cm-diam propane bubble chamber inside a pulsed magnet giving fields up to 300,000 Gauss.¹⁶ Figure 14 shows this chamber. Formidable technical problems have been overcome in making this device work. Tracks in the chamber are photographed life-size to enable track points to be reconstructed to an accuracy of about 1μ in real space. The $B\rho$ and measurement accuracy of this chamber are quite good, but it is too small even for doing hyperon moment experiments. If hyperon lifetimes were $\sim 10^{-11}$ sec instead of

Fig. 14

300-kG Pulsed-field Chamber Constructed in Munich. The chamber body is made of the single-turn coil shown with horizontal axis. Expansion is made by an annular rubber diaphragm. Windows at left and right allow for illumination and photography. The chamber diameter is 7 cm.

The coil support is the only difficult remaining problem. This is particularly true of the BNL and CERN magnets, where the forces

137-1774

10^{-10} sec, it would be a great device. One cannot help but feel that for high-energy physics experiments, superconducting magnets (which are d.c.) have made pulsed magnets obsolete.

V. HIGH-FIELD OR GIANT CHAMBER

Now what of the future? The most obvious extrapolation is to significantly increase either the chamber size or the magnetic field (or both). The higher-field tendency is already apparent at Argonne, where no chamber has a field of less than 28 kG and the highest is 46 kG. With the great developments in superconducting-magnet technology just discussed, higher fields are an obvious must for the next round of chambers. As we all know, larger chambers are also being built. To provide some orientation, I have listed in Table IV some of the important numbers for three hypothetical hydrogen chambers, taking a typical present-day chamber and comparing it with a 4-m-diam chamber and a 1.5-m-diam 70-kG chamber.¹⁷ These chambers do not exist, but all are typical of what can be done. As you can see, both of the new possibilities are like the curate's egg--excellent in parts--and the choice you make depends on the relative importance you place on the different parameters.

TABLE IV. Comparison of Present Chamber with Giant Chamber and High-field Chamber

	Present Chamber	Giant Chamber	High-field Chamber
Size, m	1 ϕ x 0.5	4 ϕ x 2	1.5 ϕ x 1
Magnetic field, kG	20	20	70
Point precision, x,y	30	200	100
microns z	100	400	300
Momentum precision, $\Delta p/p$ %	1.5	1.0	0.3
Angle precision:			
Azimuth, $\Delta \phi^\circ$	0.02	0.04	0.03
Dip, $\Delta \lambda^\circ$	0.04	0.05	0.04
$B\rho$, kG-m	5	20	26.25
Event rate, μb for one event per day	0.7	0.4	0.2
Neutrino experiments	No	Yes	No
π° and neutron detection	No	Yes	No
Other points	Chamber exists	Can use H_2 production and H_2 -Ne secondary-particle detection.	Best precision for 4 c events. Can measure charged Σ tracks. Do hyperon magnetic-moment experiments.

Although the point-reconstruction accuracy of the giant chamber is relatively poor, the longer tracks mean that the momentum and angle precision is good. In practice, the point-reconstruction accuracy and the angle precision are worse than the numbers given by a factor of between two and three. This arises from a number of causes, of which the following are probably the most important:

1. Setting error on film
2. Lens distortion
3. Optical distortion from window
4. Thermal turbulence in chamber
5. Displacement of tracks by liquid motion between beam and flash.

With some development work, most of these things can be controlled. With the smaller chambers (≤ 1 -m diam), the errors seem at the moment to be smaller than with the 2-m chambers. The setting error is not very important (except for the highest-energy work $> \sim 6$ GeV/c), as multiple scattering is the dominant source of error for the low-momentum tracks.

It is normal to put floors on the angle and momentum errors calculated for the long tracks to account for the errors coming from the points mentioned above. The track lengths for a hydrogen bubble chamber are usually shorter than those given as optimum in Fig. 15, although the

137-1817

Fig. 15. Angle Errors on Tracks for Three Typical Chambers. The angle errors are given for the optimum track lengths shown and are all calculated for a hydrogen filling of the chamber.

chambers are of comparable size to these optimum lengths so the overall angle errors are considerably larger than those given. The values shown in Fig. 15 should be considered minimum values obtainable with careful optical calibrations.

A single number cannot be given for the trapping probability of the chambers; therefore the fraction of π , K, and p tracks that will be contained in the different chambers is shown in Fig. 16. The particles are assumed to originate isotropically from the center of the chamber. The high-field chamber and the giant chamber are very comparable here. The event rate number is the cross section that will yield one event per day. A day is to produce 30,000 accelerator pulses. The giant chamber has a larger fiducial volume and so a

137-1789

Fig. 16. Trapping of Particles for Three Typical Chambers. All particles are assumed to originate isotropically from the center of the chamber. The curves give the fraction of particles contained inside the hydrogen volume.

better event rate. The high-field chamber is best only because I have assumed multiple pulsing as standard for the future chambers.

A conventional chamber with 70 kG will greatly improve precision for reactions already studied. The improved accuracy is useful in two ways. First, to improve the accuracy on effective mass measurements, Fig. 17 shows the result of a computer study of the $K^*(1400)$ produced in K^-p collisions in a bubble chamber with a 70-kG field.¹⁷ Since the angle and momentum contributions to the mass error are comparable, there is not much point in going to higher magnetic fields without at the same time improving the spatial resolution. The overall precision is a few MeV. Second, and perhaps most important, ambiguities in separating events

into the different final states would be much reduced. This is a complex subject and has not been studied very systematically. It is difficult to point to any experiment where the ambiguity problem is definitely biasing the result, but most physicists are somewhat uneasy about the problem--especially at the higher energies. Everyone has a favorite bump, which he thinks can be explained by event misidentification. Efficient gamma-ray detection and good electron-energy measurements will also help this latter problem for 1 c events. Considering that the large chambers allow events with multineutrals to be studied when filled with neon hydrogen mixtures, my personal vote would go to the larger chamber rather than the higher field, even though some experiments are unique to the high-field chamber. Magnetic-moment measurements and precision-resonance masses and widths are the two obvious examples.

137-1784

Fig. 17. $K^*(1400)$ Effective Mass Errors as a Function of the K^* Momentum. The calculations are for a 1.5-m-diam, 70-kG hydrogen chamber.

For CERN and Brookhaven, the neutrino possibility alone has forced the large-chamber choice. Argonne is also very much in that camp, whereas at the Rutherford Laboratory the high field has won out, and a high-field chamber is under design there. The ideal is obviously large size and high field, and both CERN and Brookhaven are attempting to come closer to this with multimeter chambers and 30- to 40-kG fields.

VI. LARGE BUBBLE-CHAMBER PROJECTS

Now we will briefly review the large hydrogen-chamber projects. Three are in an advanced state of design, and I will discuss them in the order of probable completion. At Saclay, a 6,000-liter chamber, Mirabelle, has been constructed.¹⁸ Figure 18 shows the completed chamber. As yet no magnet has been procured and will probably not be needed before the chamber is operated in Serpukov. The design is similar to that of the BNL 80-in. chamber, except the big window is eliminated. Four cameras are used (70-mm film, 140° lens) on a square of 35-cm side. The positioning of the camera on a single plate simplifies the problem of obtaining the optical constants of the system, but means that the reconstruction accuracy at the ends of the chamber will be poor.

Fig. 18. 6,000-liter Hydrogen Chamber, Mirabelle, Constructed at Saclay. The photograph shows the chamber body and expansion system. Expansions are made by the piston located in the top cylinder, communicating to the main-chamber hydrogen by the eight vertical pipes. The cameras will be located on a plate mounted over the rectangular opening on the center of the chamber body.

At Argonne a 12-ft chamber has been studied in detail by a group under the direction of Gale Pewitt, and the design is frozen.¹⁹ The expansion is made by moving the bottom of the chamber as shown in Fig. 19. This uses an omega bellows in the way that is becoming standard west-coast

137-1791

Fig. 19. 12-ft Hydrogen Chamber Under Construction at Argonne National Laboratory.
Four cameras on a 7-ft-diam circle photograph the chamber.

practice. Four cameras on a 7-ft-diam circle photograph the chamber with 70-mm film. Superconducting coils provide a 20-kG field. An iron yoke is used to shape the field in order to minimize the coil support problem and reduce the eddy-current heating in the bottom expander to negligible size.

The BNL 14-ft chamber was described by Bill Fowler⁹ and is shown in Fig. 20. The latest design differs from that originally proposed in using a superconducting magnet. By not using an iron return yoke, one can obtain

137-1818

Fig. 20. 14-ft Hydrogen Chamber Proposed by Brookhaven National Laboratory. A 30-kG magnetic field will be provided by a superconducting magnet without a return iron yoke. Also shown on the same scale is the existing BNL 80-in. chamber.

30 kG for the same money as bought 20 kG previously. The large stray field from such an enormous unshielded magnet introduces some bizarre problems, such as whether the building will collapse when the magnet is turned on and off. The higher field will be especially valuable when hydrogen-neon mixtures are used in the chamber. Since no iron yoke is provided, the expander must be made of nonmetallic material, or special field-shaping coils must be provided to keep the eddy-current heating small. Fiberglass-reinforced epoxy seems to have all the desirable properties for this part of the chamber. A flexible Fiberglass diaphragm isolates the good chamber hydrogen from the liquid around the piston so that the liquid below this diaphragm can be operated colder than the main chamber to minimize parasitic boiling. With the iron missing, the chamber can be made higher, giving an increase in volume, good for neutrino experiments, and enabling smaller-angle lenses (90°) to be used to cover the good-field volume. Three large-magnification lenses to see the entire chamber, and two of half the magnification, focusing on the central region, are proposed. The latter views are used to count bubbles and see spectator protons. Although valuable volume is gained by raising the top of the chamber, the cameras must look through more hydrogen with the increased possibility of distortion because of refractive-index variation. This will obviously be a most powerful chamber when completed, but the Brookhaven group feels a model test is appropriate to experimentally test the unusual features of the design. Figure 21 shows the 7-ft test vessel now under construction at BNL. This is to be a fully working model with everything needed to make and photograph curved tracks. It will be used to test all the critical features of the 14-ft chamber under the most realistic conditions.

A group at CERN is making a design study, which should be completed this year.²⁰ They also propose a high-field (35-kG) superconducting magnet and suggest building an iron house around the entire system to provide magnetic shielding for the auxiliary experiment.

It is obvious that the first three chambers are novel in inverse proportion to the expected completion date. Samuel Johnson had a contribution to make on this subject when he said, "Depend on it, Sir. Nothing clarifies a man's mind like the knowledge that he is to be hanged in a fortnight." Having funds appropriated certainly makes for a conservative design.

Two groups, one in Paris and one in Madison, Wisconsin, are constructing large heavy-liquid chambers.²¹ The designs are essentially identical; the French chamber (Gargamelle) is shown in Fig. 22. The long cylinder is viewed by 8 cameras. Extracting the physics from this battery of views presents some difficult problems. Since scanning has been very important for the heavy-liquid chambers, particularly the question of which electron pairs point to a given vertex, some effort has gone into obtaining distortion-free lenses. Scanning projectors are under design to project all views on the same table, a la Cinerama. One hopes the overlap problem

Fig. 21. 7-ft Test Vessel Under Construction at BNL to Test the Critical Features of the Proposed 14-ft Chamber

Fig. 22. Gargamelle, the Large Heavy-liquid Chamber Under Construction at Saclay for Use at CERN. The drawing shows the 8 cameras and the rubber expansion diaphragms.

will not be as annoying as it is at the movies. Expansions are made with a rubber diaphragm in the usual way (1.5 MW of compressor power is required). The design appears to be straightforward except for the problem of temperature control, which may be worse here than for the cryogenic chambers because of the high refractive index of the liquid. To overcome this problem may require some stirring of the liquid between expansions, as discussed later.

The main impetus for the chambers comes from the possibility of doing good neutrino physics. With (1) a Freon filling of the chamber, (2) the expected improvements in accelerator intensities per unit time, and (3) improved focusing devices, gross rates of some thousands of neutrino interactions per day will be obtained when the chambers start operating in a few years. If propane is used as a filling, one-third of a ton of free protons will be available as a target. This is about one-fifth of that in the large hydrogen chambers. Some typical expected neutrino event rates are given in Table V. Although neutrino interactions on free nucleons are most needed at the moment, in the future the very high counting rate of the Freon chamber will allow rare processes, such as final states involving strange particles, to be studied for the first time with good statistics. A great

TABLE V. Neutrino Event Rates Expected
with Gargamelle at CERN

Reaction	Nucleon	No. of Events per day*
<u>Liquid C₃H₈ + 13% CF₃Br</u>		
Elastic	n	630
Production of N* ⁺	n	220
Production of N* ⁺⁺	$\begin{cases} p_{\text{free}} \\ p_{\text{bound}} \end{cases}$	$\begin{cases} 240 \\ 860 \end{cases}$
Multipion production		945
		Total 2,895
<u>Liquid CF₃Br</u>		
Elastic	n	2,820
Production of N* ⁺	n	1,000
Production of N* ⁺⁺	p _{bound}	2,320
Multipion production		4,200
		Total 10,340

*The antineutrino rates are less than these by a factor of 3 to 4.

Fig. 23. Momentum Errors Expected in Gargamelle Compared to BP3, the Existing 1-m x 0.5-m Heavy-liquid Chamber

Fig. 24. Range-momentum Curves for Propane and Freon to Illustrate the Stopping Power of the Large Heavy-liquid Chambers

disadvantage of the high stopping power compared to the hydrogen chamber is that no free-neutron target is available since proton recoils from deuterium do not travel far enough to be seen, making quasielastic neutrino interaction difficult to study. For neutrino experiments then, the heavy-liquid chamber and the hydrogen chamber are complementary.

Another area in which the great mass of material in the chamber (~10 tons) will be useful is in the study of decays of the very strange hyperons Ξ^0 and Ω^- . Many hundred examples of Ω^- can be obtained in which the decay parameters can be measured in a modest exposure (200,000 pictures) to a 5-GeV/c K^- beam. Finally, the chambers are well suited to studies of high-energy muon interactions.

The momentum precision of ~3% for heavy particles is shown in Fig. 23 and compared to the 1-m Saclay chamber BP3. The momentum uncertainty of a π^0 measured by the electron pairs is about 6%. The angle precision is in the range 0.05 to 0.2°. Many secondary particles will stop in the chamber, as shown in Fig. 24, which gives the range-energy relation for propane and Freon, CF_3Br . When filled with heavy Freon, the chamber is large enough to act as a total absorption device for gamma rays; therefore a calorimetric method can be applied to measure gamma-ray energies. This will be a tedious method, but could be applied to specially interesting events.

It is clear that overall the hydrogen and heavy-liquid chambers are

complementary, as has been true in the past. A well-equipped, high-energy proton accelerator should have both chambers. If only one chamber can be built, then I think it clearly should be the hydrogen chamber, particularly in view of the neon possibilities discussed later.

Table VI lists the parameters of the large chambers under consideration, design, or construction. An interesting thing is that the chambers come in two basic shapes--either spheres or cylinders. The reasons for choosing a basic spherical shape are:

1. Fabrication is simple, particularly for a superconducting magnet, where the coil-support problem is severe. The expander can be simpler for a cryogenic chamber.

2. A small number of cameras can see the entire volume of the chamber, thus simplifying the data-reduction problem. It seems out of balance for the two heavy-liquid chambers to use eight 70-mm views, whereas the larger hydrogen chambers get by on four.

3. Proton recoils associated with quasielastic neutrino reactions

$$\bar{\nu} + p \rightarrow n + \mu^+$$

$$n + p \rightarrow n + p$$

can be obtained with higher probability since the neutron comes off at a large angle.

TABLE VI. Parameters of Giant Chambers

	Mirabelle	12-ft	7-ft	14-ft	3.5-m	Gargamelle	Wisconsin 10-ton Freon
Size, m	4 x 1.5ø	4ø x 2	2ø x 2	4.25ø x 5	3.5ø x 3	4.8 x 1.9ø	4.35 x 1.7ø
Liquid	H ₂ , D ₂ , Ne	H ₂ , D ₂ , Ne	H ₂ , D ₂ , Ne	H ₂ , D ₂ , Ne	H ₂ , D ₂ , Ne	C ₃ H ₈ + Freons	C ₃ H ₈ + Freons
Visible Volume, k liters	6	24	6	46	~20	10	6
Magnetic Field, kG	20	20	22	30	35	19	19
Cameras	Four on 35-cm square	Four on 2-m square	Three on 1.1-mø circle	Five on 2.4-mø circle	4	Eight in two rows of four, 56° angle between pairs in same ver- tical plane	Eight in two rows of four, 60° angle between pairs in same ver- tical plane
Film	70 mm	70 mm	70 mm	70 mm	70 mm	70 mm	70 mm
Lens Angle	140°	120°	90°	90°	Undecided	110°	110°
Laboratory	Saclay	Argonne	Brookhaven	Brookhaven	CERN	Saclay	Wisconsin-ANL
Completion Date	1968	1969	1968	Four years after funds appropriated	1966, design study only	1969	1970

4. Charged-particle trapping by spiraling can be done at a higher momentum. This is not so important for the heavy-liquid chambers since the range of particles is so much less than in hydrogen.

5. The cameras can more easily be moved further from the median plane. This is done in the BNL design.

6. Beam entry problems for low energy particles are simplified.

The advantages of a long cylinder are:

1. The event rate is higher; for the same volume, a long cylindrical chamber will have about one-third higher ν interaction rate than the spherical chamber.

2. It is easier to make a vessel of 2-m diam than one of 4-m diam to withstand high pressures. This is most important for the heavy liquids.

3. All the arguments for high-energy strong interactions about the forward collimation of secondaries still point to a long, thin chamber. The argument is much weakened if gamma rays from π^0 decay are considered. As an example, Table VII gives the laboratory angular distribution of gamma rays from various resonance decays.²² Especially for high-resonance masses and spins, one sees a weaker forward collimation of the gamma rays. The gamma rays are correlated; therefore the fraction of events having all gamma rays converting is not simply related to the numbers given in the table.

4. A higher magnetic field over the good cylindrical volume of the chamber is possible for a given electrical power. High field is more important for the heavy-liquid chambers than for the hydrogen chambers.

TABLE VII. Laboratory Angular Distribution of Gamma Rays from Resonances Decaying into $2\pi^0$

$$\pi^- p \rightarrow X^0 n$$

$$X^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$$

Beam, Momentum GeV/c	X^0 Mass	X^0 Spin	X^0 Prediction Angular Distribution	Fraction of Gamma Rays inside Cone of Semiangle			
				10°	30°	60°	90°
6	700	0	Peripheral	0.63	0.94	0.98	0.997
6	700	0	Isotropic	0.10	0.49	0.81	0.92
8	1670	0	Peripheral	0.38	0.86	0.94	0.97
8	1670	2	Peripheral	0.47	0.72	0.92	0.97
6	1670	2	Isotropic	0.16	0.50	0.73	0.88

VII. CAMERA LOCATION

The location of the cameras in the spherical chambers has been the subject of some interesting work.²³ The original 12-ft chamber design had the cameras on the corners, with axes pointing down at 45° . This had the advantage of covering all the chamber volume with 90° lenses, and also provided a very good stereo over all but the top central region of the chamber. It was obvious that things would look peculiar if one's eye were put at the corner, but no one knew how peculiar. The large stereo angle, which makes for good accuracy, also means that the events look different. In fact, they only look different to the extent that one has stereo perception.

To investigate the scanning problem in a reasonably realistic manner, artificial events were generated in the chamber using a Monte Carlo method.²⁴ A beam of 5.5-BeV/c K^- mesons was chosen as a reasonably representative example. This is also an experiment we happen to be working on now, so we know what happens. The events were then projected on to four cameras placed in three different arrangements: (1) on a 2-ft-diam circle to simulate a set similar to present-day chambers; (2) on a 7-ft-diam circle, and (3) on the corners at 12-ft diam. The film was scanned by about ten physicists. Figure 25 shows one of the more complex frames in the three camera orientations. It was possible to identify all the events for any camera location, but complicated frames took a few minutes to scan and required looking at all the views. What one might call the "conical-projection" distortion coming from the large angle between the median plane of the chamber and the film plane was considered serious by some people. In the meantime, lens-design studies had shown that 120 or 130° lenses of the desirable properties could be procured; therefore the objection about losing visible volume by moving into the center was removed. On the small circle, since the stereo angle becomes bad for many parts of the chamber (equal to that now used in large window chambers), the precision of reconstruction goes down. We therefore chose the 7-ft-diam circle to locate the cameras and decided to go with a wide-angle lens of telecentric design to minimize film-flatness problems. The resulting lens distortion, which contracts the edge of the field of view, was not considered to be very serious.

At Brookhaven a different approach has been taken. If the lens is moved up, a 90° angle is sufficient to cover the interesting volume of the chamber, and then, if a nontelecentric lens is used, lens distortion is avoided. The film will be held flat by a fused-glass vacuum platen.

You will have noticed that all the chambers used spherical windows at the liquid interface. This provides an elegant solution to the problem of chromatic aberration, which would otherwise be the dominant effect in smearing out the bubble images for the wide-angle rays.²⁵ With the spherical window, the light rays are normal to the hydrogen-glass interface. An alternative solution is to use laser light to illuminate the chamber.²⁶

Fig. 25. Computer-reconstructed Events in the ANL 12-ft Hydrogen Bubble Chamber for Three Different Camera Geometries. The beam particles are 5.5-GeV/c K^- mesons.

VIII. ILLUMINATION AND PHOTOGRAPHY

As originally proposed, the illumination system of the chambers uses Scotchlite. Gargamelle is the exception, since it uses a battery of lights on the opposite side of the chamber with masks to shield the direct light.²¹ In the past 2 years, several laboratories have made many tests--both optical and thermal-mechanical--on various batches of Scotchlite.²⁷ Particularly interesting were the photographs made at SLAC of bubbles in liquid hydrogen generated by a hot wire.²⁸ Apparently no problem will be encountered with the use of Scotchlite in liquid-expanded chambers; the worst that can happen is that, for some lots of material, more light will be needed to produce pictures of adequate contrast. In a few months the BNL 31-in. chamber will be operating in a beam and using Scotchlite as a retro-director. This will conclusively prove the material for hydrogen chamber use. The original chamber that pioneered the material was the Wilson Powell 30-in. propane chamber in Berkeley.

The pictures will be bright field, of course, and since the demagnification from chamber to film is approximately 70 for the giant chambers, it will be necessary to allow the bubbles to grow to about 500 μ diam before images of adequate contrast can be obtained. In a dark-field illumination system, this problem would not exist. To grow 500 μ bubbles (if the new larger chambers work with the same expanded pressure as present-day chambers) will require operation at about 26°K for a 2-msec flash delay. The low temperature requires more refrigeration and also limits the range of possible operating conditions.

Some tests have been made photographing tracks with high magnification. Figure 26 compares tracks in the BNL 80-in. chamber taken under normal demagnification (15X) with those taken under a 100X demagnification.⁹ Something is obviously lost, but the quality is still surprisingly good with the high-resolution film. For bubble counting, one will want to operate with a small bubble density. The implication for existing bubble chambers is clear; 35-mm film would probably be adequate for many experiments, and indeed, at Argonne, 35-mm cameras are planned as an alternate to the 70-mm camera now used on the 30-in. hydrogen chamber.

Things may be much better than this, since it is possible, even likely, that the large chambers will behave more like the old clean chambers. Back in the early 1950's, the all-glass bubble chambers that were built could be expanded to atmospheric pressure, since parasitic wall boiling and consequent self-pressurization did not occur. In fact, Pless and Plano²⁹ even went to negative pressures in a small pentane chamber. The bubble growth time was then very fast (a few microseconds). Now we may be approaching a situation in which we are producing a clean chamber not making the walls very smooth but by taking them to infinity. It seems clear

(a)

(b)

Fig. 26. Tracks in BNL 80-in. Chamber Taken (a) with Normal Demagnification (15X) and (b) with 100X Demagnification

that the main source of the dynamic heat load in today's chambers (variously measured to be 0.1 to 1.0 Joule/liter/pulse) comes from parasitic boiling, and so one can expect a very small specific dynamic load for the new chambers. This will help in the temperature-control problem.

The temperature-control question is the only one in the large chamber designs where one must still use some hand waving to convince oneself that there will be no problems. This very uncertain area has been discussed theoretically by Thomas in a Rutherford Laboratory report,³⁰ and by Reinhard of CERN,³¹ who considered the application to an ideal hydrogen bubble chamber. Thomas and Reinhard point out that for a reasonable temperature gradient in a hydrogen chamber, the heat flux carried by conduction is so small, compared to the irreversible heat input coming from the expansions, that convective heat transfer will inevitably take place and the resulting liquid hydrogen will be in a highly turbulent state. Under these conditions, the temperature drop between the top and bottom of the chamber will all occur in thin boundary layers, the main body of the hydrogen being at a rather constant temperature. It is most important to keep the camera windows away from these boundary regions. The shroud planned for the 12-ft chamber is an attempt to keep the regions of high heat flux out of sight, in addition to providing forced convection for stirring the liquid. These turbulent eddies have a characteristic size of a few millimeters and cause track distortion by two obvious mechanisms. First, bubbles caught in the eddies will be displaced, and, second, light rays scattered from the bubbles will undergo a multiple scattering between the bubble and the camera lens. The multiple scattering is a result of the refractive index variation in the liquid and gives an apparent displacement proportional to the $3/2$ power of the depth.

Reinhard's estimates for an idealized chamber are given in Table VIII from which one can see that the turbulence effects are not large. They are

TABLE VIII. Optical Effects of Thermal Turbulence in Ideal Chamber

Model chamber size	3.5-m diam x 3.15-m deep		
Axial heat flux	100 watts		
RMS temperature fluctuation	$2.3 \times 10^{-3} \text{ }^\circ\text{K}$		
Eddy size	2.7 mm		
Eddy velocity	92 μ /msec		
	Top Chamber	Beam Height	Bottom Chamber
Point error, mm	0.6	1.1	1.9
Sagitta error, mm	0.3	0.5	0.8
$\delta p/p$ for 1-GeV/c track for 20 kG and 1-m length, %	0.36	0.66	1.11

close to the known errors coming from the optics and Coulomb scattering of the tracks. The effects increase with the heat flux, which points to the importance of controlling the parasitic boiling in the chamber.

The model used, of course, is very simplified, and more work, both experimental and theoretical, is needed before the problem can be considered solved.

The Madison group has operated a model Freon chamber, 2 ft ϕ by 6 ft long, to investigate the problem for the heavy liquids. One expects the problem to be more severe here for the following reasons: (1) The expansion ratio is much larger, (2) the rubber diaphragm makes a large amount of parasitic boiling, and (3) the refractive index is much larger than in hydrogen. The technique was to photograph a grid through 6 ft of Freon making sure the chamber was sensitive by observing cosmic-ray tracks. The thermal turbulence after expansion was so severe that the image of the grid lines in some regions completely washes out. Equilibrium can be

restored by combing the chamber liquid using a rake made of 1/4-in.-diam rods on 1-in. centers. These tests show it will be quite difficult to double-pulse the large heavy-liquid chambers.

137-1706

Fig. 27. 2-ft Model Chamber in Operation at ANL to Test Thermodynamic and Optical Problems of Small Window Chambers

A series of tests is planned with a 2-ft model bubble chamber constructed and operated at ANL.³² This is the only hydrogen bubble chamber built to learn about bubble chambers rather than to do elementary-particle physics experiments. The general configuration is similar to the large chamber, as can be seen from Fig. 27. Initial operation of this chamber with a gamma-ray source has shown a very small dynamic heat load. The displacement of fiducial marks placed on the bottom of the chamber was consistent with the numbers estimated by Reinhard. The next few months should see much important design data coming from this chamber.

IX. USE OF NEON-HYDROGEN MIXTURES*

A development that shows a promise of being most important, particularly with the giant chambers, is the operation of hydrogen bubble chambers with hydrogen-neon mixtures. There is still much experimental work needed, but the basic possibilities are very clear. The suggestion of using neon-hydrogen mixtures originated at BNL, and the first tests were done with the 20-in. chambers there.³³ It was found possible to obtain track sensitivity with atomic fractions of neon varying from 6 to 28%, and for part of the run a phase separation occurred with the neon-rich fraction showing tracks at the same time as the neon-deficient fraction. Later analysis showed the neon-rich fraction to be 94% neon. So it appears that a chamber can be operated with any percentage of neon. Somewhat higher pressure and expansion ratios are needed for hydrogen-neon operation. A short exposure of the BNL 30-in. chamber to stopping K^- and $\bar{p}$ with small fractions of neon has been made, so the first physics results using the new technique will be available soon.

137-1787

Fig. 28. Radiation Length of Neon-Hydrogen Mixture

The potentially most important application, however, is in the use of neon to modify the radiation length of the liquid so that final states with two or more π^0 's can be studied. Figure 28 shows the radiation length of neon-hydrogen mixtures.²² The most striking feature is the order-of-magnitude reduction in radiation length obtained by adding a modest fraction of neon (10-20%). Assuming now that we have a large cryogenic chamber filled with a homogeneous neon-hydrogen mixture and the chamber is big enough to provide a 2-m potential flight path for gamma rays from π^0 's made in a primary interaction, then we can define a figure of merit for the system (if we wish to study interactions on hydrogen leading to final states containing many π^0 's). This figure of merit is the product of the fraction of events occurring on hydrogen, multiplied by the probability of converting all the gamma rays. The result of this calculation is shown in Fig. 29. For this large a chamber, one sees at about 30% neon concentration only a difference of a factor of 2 between the $1\pi^0$ and $4\pi^0$ cases. The fraction of events occurring on hydrogen is shown separately in the figure as the dotted line. The circles show the corresponding values for propane plotted at that neon fraction, giving the same radiation length as propane. The similarity is most striking. Neon is indeed rich man's propane. In fact, the situation is somewhat worse because the hydrogen density in the 20% neon mixture is somewhat less than in pure hydrogen,

*Most of this section is based on work of the Notre Dame group.²²

137-1785

Fig. 29. Figure of Merit for Hydrogen-Neon Chamber. This is defined as the product of the fraction of events occurring on hydrogen and the probability of converting all the gamma rays occurring in the final state. Also, separately shown is the fraction of events occurring on hydrogen.

neon operation. The fact remains, however, that if a critical experiment turns up involving multigamma-ray detection, it can and would be done in a laboratory equipped only with a large hydrogen-neon chamber.

The things I have mentioned so far are obviously possible today. The aspect that many of us feel will be the real killer in this neon business is the possibility of separating the pure hydrogen from the hydrogen-neon mixture. In the proceedings of the 1962 Instrumentation Conference,¹ one can find a picture of a small hydrogen chamber inside a propane chamber, but now the whole thing is much simpler. In the original big-chamber proposals,^{8,9} both ANL and BNL made much of the fact that the chambers were big enough to allow the insertion of metal plates for gamma-ray conversion. It was shown that, for a given conversion probability, plates embedded in the hydrogen could give better momentum accuracy than a homogeneous heavy liquid.

whereas (as physicists using propane chambers never cease to tell us) the hydrogen density in propane is greater than in liquid hydrogen. So the counting rate will be down by about a factor of two over a propane chamber.

What advantages does neon have? First, the region of radiation length below 20% of neon is not covered by the propane chamber, and for events involving a modest (<3) number of gamma rays, the extra momentum precision on the primary charged tracks may be an important advantage. This momentum precision is shown in Fig. 30. Second, one does not need an extra facility. The chamber, operating crew, beam arrangements, and so on, are all set up for the hydrogen experiments. This is counter-balanced by the argument that the demand for pure hydrogen pictures is so great that no time is left for

137-1788

Fig. 30. Momentum Errors in Hydrogen-Neon Mixtures

Of course the system was very unethetic and reminded some people of spark chambers. Now we are released from the possibility of committing that sin and can go back to the beautiful isotropy of the bubble chamber. Changing the plate array is no small job compared to changing the neon fraction in the liquid, which is another important practical advantage.

Now how can one separate the liquids in a practical way? The immediate thing that springs to mind is to insert a coffin of pure hydrogen at

137-1786

Fig. 31. Separation of Hydrogen and Hydrogen-Neon. The ANL 12-ft hydrogen chamber is shown with a vertical wall dividing the volume into a pure hydrogen production region and a hydrogen-neon gamma-ray detecting region. The cones contain the noted fraction of the gamma rays from the reaction illustrated.

the hydrogen and two the neon mixture. In Fig. 31, I have also shown the angular distribution of gamma rays from the reaction

The X^0 of assumed mass 1,670 MeV and spin 0 is produced peripherally with an angular distribution e^{-6t} . In this typical reaction, the half-plus-half chamber does quite well.

Now we must worry about the operating conditions for the 2 chambers. The most similar conditions are obtained for low temperatures and low expanded pressures. Figure 32 shows the bubble density for 26°K operation as a function of expanded pressure and neon concentration. At about 30 psi expanded pressure, the bubble densities in mixtures varying from pure hydrogen to 20% neon are very close. For higher neon concentrations, one must operate with the hydrogen tracks completely black. Of course the primary tracks will penetrate into the neon region, and bubble

137-1783

Fig. 32. Bubble Density
in Hydrogen-
Neon Mixture

counting can be done there. To get the same bubble density on both sides requires a modest temperature difference with the hydrogen colder. In general, the bubble growth rate is faster in neon, but this should not be a serious problem. An experimental program to check these calculated predictions is starting at ANL using the 2-ft model chamber.

X. CONCLUSION ON LARGE CHAMBERS

In the past few years, a large design and development effort has gone into solving these large-chamber problems. All the remaining engineering difficulties seem to have straightforward solutions.

Perhaps the only other major problem area is the one encountered in all big construction projects, that is, how to organize the effort to produce the best chamber for minimum cost in the shortest time.

XI. CODA

When preparing this talk, I read through a lot of old reports and came upon one by Ralph Shutt that I would like to quote from. The title is: "Proposal and Cost Estimate for a Large Liquid Hydrogen Bubble Chamber Provided with a Magnetic Field." It starts by saying:

"In the following paragraphs it is proposed that a large hydrogen bubble chamber (20-in. x 10-in. x 10-in.) provided with a magnetic field (14,000 to 19,000 gauss) be built at the Brookhaven National Laboratory. With such a chamber the investigation on production of π -mesons and heavy unstable particles started with diffusion cloud chambers could be continued with about 100 times improved statistics and about 10 times improved accuracy of measurements. Both of these improvements are now very much needed. Furthermore, new experiments on reactions with very small cross sections could be performed."

Then after the technical discussion, it ends:

"It is realized that the above program would constitute a major effort for Brookhaven. The total cost would amount to approximately \$250,000, including materials and instruments, shop time, technicians, designers, engineers and physicists, but not including facilities such as hydrogen liquefiers, cooling water disposal, and electronic computers. It seems to the writer that the very promising aspects

of a large liquid hydrogen bubble chamber should justify such a major effort, and furthermore should warrant a special effort to complete this instrument at the earliest possible date.

"It is proposed that the large chamber should be used as a facility to provide material for analysis by Brookhaven groups as well as by University Groups." R. P. Shutt, June 1955.

This single report makes the technical advances in the past 11 years seem very dramatic. Ralph was also obviously influential in making the chamber part of the accelerator facility, which has been an important ingredient in maximizing the physics output of the technique.

In the process of growing up, we have also lost a great deal, and some of us may wonder whether we are still scientists or just managers. Wordsworth knew the feeling very well:*

"The world is too much with us; late and soon
Getting and spending we lay waste our powers."

ACKNOWLEDGMENTS AND APOLOGIES

This report represents the state of the art as seen by one man in one place at one time. Most of the bubble-chamber literature is in unpublished reports and proposals. I naturally have best access to the reports originating from United States laboratories, and I would like to apologize to any group whose work is not adequately covered. I plead the same as Dr. Johnson when asked by a lady to explain why he made an error in his dictionary, "Ignorance, madam, pure ignorance."

*New Oxford Book of English Verse, Poem 549, Oxford University Press (1939).

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