INTERPRETATION OF RESULTS FROM PROPANE AND OTHER HEAVY-LIQUID CHAMBERS (*)

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A complete description of the published work on bubble chambers is impossible to give in an hour's talk, and therefore, as a start, there will be a brief outline of this work for liquids heavier than hydrogen. This will be followed by a more detailed description of the use of information obtained from a large propane chamber and from Glaser's xenon chamber. These have been chosen so as to give the two extremes in liquids heavier than hydrogen, and current experiments and methods of interpretation will be discussed.

The early "clean" chamber of Glaser [1] was followed by a "dirty" hydrogen chamber [2] $1^1/_2$ in. in diameter which showed tracks in liquid hydrogen. Then the first pictures of tracks of particles from a high-energy accelerator in a $13 \times 13 \times 27$ mm isopentane chamber [3] were obtained. Almost immediately this was followed by the construction of the $6^1/_8$ in. diam. 4 in. deep propane chamber [4] of Steinberger et al. Meanwhile, hydrogen chambers made an equally early start with a clean one in a 12 mm diam. tube [5] and a second "dirty" one measuring $2^1/_2$ by 4 in. in diam. [6]

This steady growth is continuing at such a rapid pace that no bubble chamber, however large, is likely to remain the largest for more than two years. By the time a descriptive paper is written [7], another larger chamber is nearly completed.

The excellent summary by D. A. Glaser in the Handbuch der Physik [8], gives much useful material on densities, radiation lengths, magnetic-field requirements, gas mixtures, sensitive times, etc.. It is appropriate to refer briefly to later work, giving only the latest references: chambers operating at room temperature and other temperatures utilizing various mixtures such as CO_2-propane [9], $C_2F_6-C_3F_8$ [10], methane-propane [11], and Freons [12]. We should also refer to work on ionizing power of particles [13], ionization measurements in hydrogen [14], and a rapid-cycling propane chamber [15]. The adjustable expanded pressure and its effect on sensitive time [13] is very suggestive, particularly when the long sensitive times may make bubble counting more reliable and go into the relativistic rise.

Finally, there are the "high-Z" chambers such as Glaser's xenon chamber with a radiation length of 3.0 cm [16]. Other heavy liquids used in high-Z chambers include WF_6 with a 3.8 cm radiation length and the highest stopping power [17]; pure $SnCl_4$, $SnCl_4$-$CCIF_3$ mixture, and other mixtures with radiation lengths from 8.6 to 14.3 cm; [17] and methyl-iodide mixtures.[19, 20] Probably by now there are many more papers describing various useful combinations of liquids and multi-liquid chambers with separate compartments containing liquid separated by thin material where one liquid will be a high-Z substance to convert gammas and the other will be of low Z to permit accurate measurement of angle.

The wide choice of liquids and shapes and sizes of chambers makes it possible to meet specific experimental requirements in much detail, and therefore a thorough appreciation of the particular advantages of the chosen liquid is very important in designing the best experimental arrangement.

This situation is continually changing as the result of the greater skill developed in interpreting the results obtained in a particular liquid. Most important in this is a careful analysis of the magnitude of all errors and methods for giving the measured quantities

*) Work done under auspices of the U.S. Atomic Energy Commission.

appropriate weights according to the accuracy of the information available.

Our procedure in the development of an experiment is not completely logical, chiefly because the effort necessary to make a complete analysis before interpretation starts is of the same order of magnitude as that of the experiment itself. The practical problem that there is no beam suitable for testing the chamber before an actual run is the greatest deterrent. Practice runs are so loaded with data in this new field that it is not possible to ignore the information obtained, and therefore one must immediately start interpreting results from almost any convenient beam from an accelerator.

The procedure that we use is, first, to decide on an experiment particularly suited to the chamber and liquid used. Then the experiment is run with as much concurrent scanning as possible. This is useful for such obvious things as track quality, timing, shielding from background, and overcrowding of the chamber with tracks. The finer points are necessarily left until later.

After the experiment has been run, events are chosen which are over-determined so that internal cross checks can be made. These are studied in a statistical way. An example of this would be the following:

Suppose that incident pions have a known energy spread due to analysis by means of magnets between the target and the chamber. A set of pions restricted in angle so as to come from the target is measured, and the error curve plotted.

Cases where the error is very large are carefully examined to see what may have caused this error. When no obvious cause can be discovered, this error is included in our estimate of background. Likely causes are (1) errors in digitizer output, (2) small single scatters, and (3) optical distortions due to temperature differences in the oil or liquid propane.

Our procedure with these three types of errors is as follows: The only way we have to detect small scatters (less than 2 degrees) in a curved track is to place a template on the track and compare the template curve with the track. Small distortions due to temperature differences in the oil or propane are detected this way. We have no systematic way of detecting these errors by measurement alone. Very small digitizer errors are not detected.

When a track is measured, any single point out of eight consecutive points which is out of line is deleted on the assumption that it is a digitizer error. If there are more than four in a track it is sent back to be re-examined on the assumption that there is a large scatter or optical distortion, due to the liquids, which can be by-passed in future measurement.

Wherever possible, range measurements are used to determine momentum. Here it is necessary in scanning to use curves of stopping particles and match them so as to be sure that the track does not charge-exchange or disappear before coming to rest.

An example of experimental planning is contained in a proposed run to study the leptonic decay of the Λ. K^- mesons stopping in the propane will produce in hydrogen reactions very slow lambdas, both prongs of which will come to rest in the liquid for the pionic decay. In the electronic decay, the electrons will have a range much greater or a curvature much greater than that of the pion in pionic decay. The scanning of pictures then reduces to discarding all events in which the proton has a short range—less than 4 mm in this case—and the negative track stops in the liquid in a distance of 20 cm, with the characteristic curvature near that of a stopping π meson. There is no problem in distinguishing electrons of this short a range from pions, because of their very large curvature. Only those events in which the negative track has left the chamber or is highly curved need be measured, and these comprise only a small fraction of the events. To do this in a hydrogen chamber with the much greater range for the decay fragments is possible, but it demands a radius measurement on all events and great accuracy, so that the tail of the error distribution does not contribute enough to cause serious error. Therefore, this experiment is more suitably done in a propane chamber of size sufficient to show 20 cm tracks.

Another experiment already performed uses the polarization properties of protons scattered on carbon where the protons come from the decay of the Λ. This experiment is designed to determine the proton helicity. It is necessary to know quite exactly the energy of the proton at the time of scattering. Results are greatly improved in the following way: By the use of the origin of the Λ made by K mesons in propane, the requirement is placed on the event that it is a Λ with its characteristic Q-value. The two

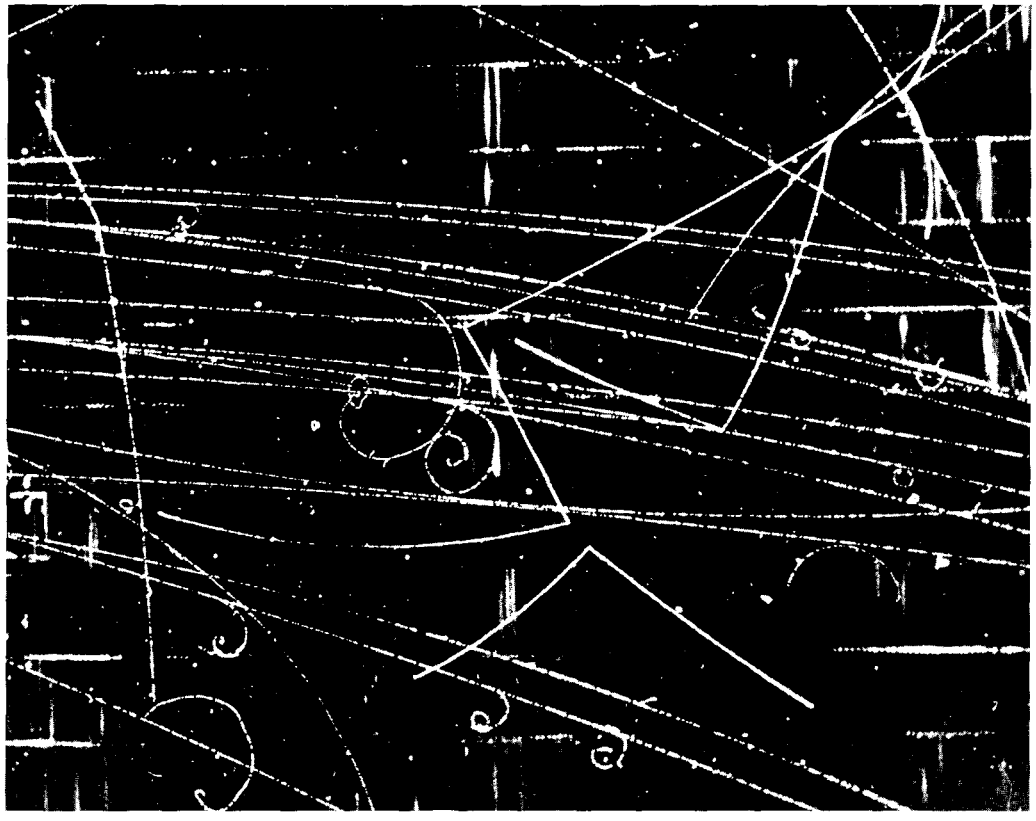

Fig. 1 Ξ^- event.

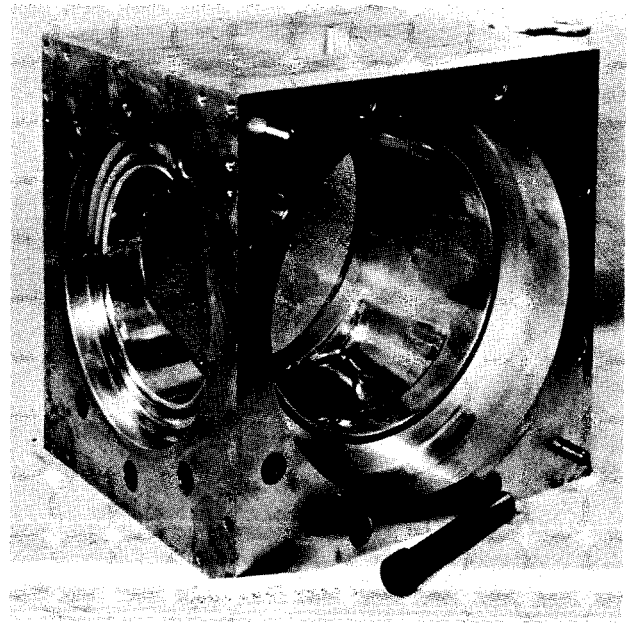

Fig. 4 View of Glaser's xenon chamber.

prongs of the decay must satisfy the Q-value requirement and must balance transverse momentum. By application of these two constraints in the calculation, the accuracy of the determination of the momentum of the proton is very markedly increased. Frequently the proton comes to rest in the propane after scattering. The momentum at the point of scatter derived from the range of the scattered proton is compared with that computed from the Λ and its origin. If the two momenta, incoming and outgoing, are consistent with an elastic collision with carbon, then the event is accepted and the range-determined momentum is used. By this procedure inelastic-scattering events are not included in the data, and accurate momenta at collision are obtained.

Here there is much side information used to improve the results, and these improvements increase the value of the results very markedly.

In determining the Q and lifetime of the negative Ξ particle, several steps of a similar nature were taken to improve the result (Fig. 1). Fig. 2 shows the unconstrained weighted histogram of the Q's of seventeen cascades. The actual procedure used was as follows. After determination that the V particle was consistent with Λ dynamics, the Λ was constrained to balance transverse momentum and to have the proper Q-value. Here the point of decay of the cascade was used to determine the direction of flight of the Λ. Using these constraints, the momentum of the Λ was redetermined. It is obvious that a second improvement can be made by requiring that the pion and Λ transverse momenta should balance around the line of flight of the Ξ particle. After this additional

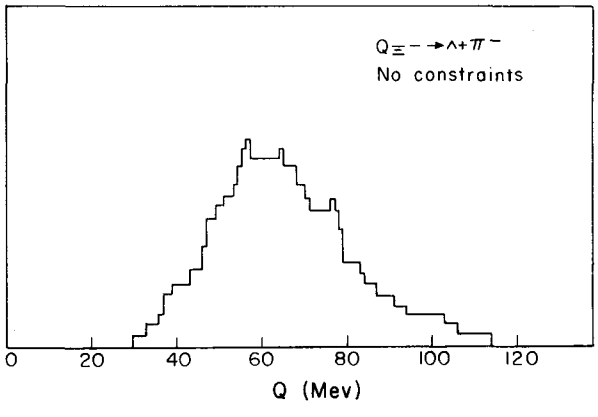

Fig. 2 Weighted histogram of the Q—values of the Ξ^-'s with no constraints.

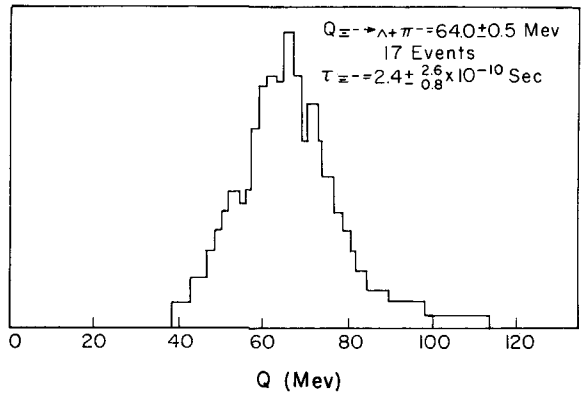

Fig. 3 Weighted histogram of the Q—values of Ξ^-'s with three constraints:

(a) Q—value of Λ at 37.4 MeV.

(b) line of flight of Λ.

(c) transverse momentum balance at the cascade decay point.

constraint was applied, Q-values thus obtained gave the results shown in Fig. 3.

Quite emphatically, it can be seen that putting in all the available information improves the results. Furthermore, it is obvious that the heavier the liquid, the more attention must be paid to the use of all the data available in order to get the best results. This arises from the fact that most of the errors come from multiple or single scattering, either coulombic or nuclear, and these increase with the amount of matter in the chamber.

The proper estimate of errors is of prime importance in making constrained solutions. In every case, adjustments of input data are made in the following manner: The errors in angle and momentum are estimated so as to give limits within which the measured value must lie. When an adjustment is made, all measured quantities are moved in the proper direction to tend to meet the requirements and by the same fraction of the estimated error. A poorly measured quantity where the estimated error is large then has little weight in making the adjustment.

One quantity frequently used is called the M value. This value, M, is a function of the measured quantities X_i^m, which are usually the momentum p, the dip angle a, and the beam angle b. It is also a function of the constraints that are represented by Lagrangian multipliers α_j such that

$$M(X_i,\alpha_j) = \sum_{i=1}^{3}\left(\frac{X_i - X_i^m}{\Delta X_i}\right)^2 + 2\sum_{j=1}^{n}\alpha_j F_j .$$

Here the X_i are the adjusted values, ΔX_i are the estimated errors, and the F is assumed to be constant for small changes in the X values and should be zero for a case in which the constraints were exactly satisfied by the data.

The partial derivatives $\partial M/\partial X_i$ and $\partial M/\partial \alpha_i$ are set equal to zero, and the values of X and α determined. These are substituted for the data and, by an iterative process usually carried through three times, the minimum value of M is obtained. This is used as an inverse measure of the goodness of fit to the assumptions made about the process assumed.

This is used very effectively and seems to be a good measure of the reliability of an assumption. When it exceeds a certain value, it is usually found to be impossible from the data available to decide whether the assumed process is the correct one. Needless to say, the border-line cases are the most troublesome ones, but this quantity gives us a more objective way of stating how much trouble we are having.

Precision of measurement is a very important factor in discriminating background events from those of interest. In a small propane chamber measuring 2 by 4 by 6 in. used by Glaser, it was possible to measure the location of a bubble in the chamber to within 6 micron. With this precision of measurement and without a magnetic field, those events that could be identified by track angles and ionization were quite readily distinguished from background.

As our experience grows the demand for more calculations increases. For instance, it would be very desirable to use a third-order or higher-order curve for matching tracks in the chamber so that the mass of a particle near the end of its range could be determined. In all calculations it is good to have the least possible estimate of errors depending on both the $p\beta$ of the particle for errors due to multiple scattering and measurability depending upon the accuracy with which the sagitta of a track may be measured. We plan to introduce these better estimates of error as soon as possible.

There is a best length of track for measuring angle and a different one for measuring curvature. The multiple-scattering error is least for very short tracks. Errors in the measurement of angle increase for short tracks inversely with their length and therefore there is a region where the measurement errors exceed those from multiple scattering. The curvature due to a magnetic field is best determined by the longest possible tracks. Therefore, proper measurements should use different parts of the track to determine angle and curvature. Shortly we will program this and use two different lengths of track, each the most suitable for the quantity desired.

At the opposite extreme from hydrogen is xenon with a density of 2.18 g/cm^3 and a radiation length of 3.9 cm. Xenon requires a 140 000 gauss field for a 10% error in momentum for a 5 cm long track (Fig. 4). Here there is no experience with magnetic fields, so that the results must depend upon the measurement of angles or the directions of lines of bubbles in the chamber. Estimates of ionization can be useful in determining masses of particles.

Although xenon is useful because of its short radiation length, one of the main problems is to determine the direction and energy of a pair produced in the liquid. The direction of a pair becomes less well-defined as more of the track of the pair is used and the problem here becomes one of a struggle between the measurement of the location of the first few bubbles of a track, which are the only ones really in line, and the optical distortions due to local temperature differences in the liquid. Loss of energy by radiation and multiple scattering compete with measurement difficulties to make this a severe problem.

To give orders of magnitude: with lenses with a stereoscopic angle θ, given by $\tan \theta = 7/21$ and an average demagnification of 7, it is possible to measure the location of a bubble to within 300 micron in the direction of the cameras and 100 micron perpendicular to this. A track 10 mm long will yield an angle accurate to 2 degree if there is no multiple scattering. The multiple scattering and distortions of an electron in this length produce a root-mean-square error in the projected angle of 2.8 degree at a momentum of 100 MeV/c. This is shown in Table I. The assumptions upon which Table I is calculated are:

(a) The average coordinate error is 100 micron perpendicular to the lens axis and 300 micron parallel to the lens axis.

(b) The optimum length of track for measuring the angle of a particle is $t = 0.04\ (p\beta)^{2/3}$.

(c) The root-mean-square error in the projected angle measured with the optimum track length is $\Delta\theta = 61\ (p\beta)^{-2/3}$.

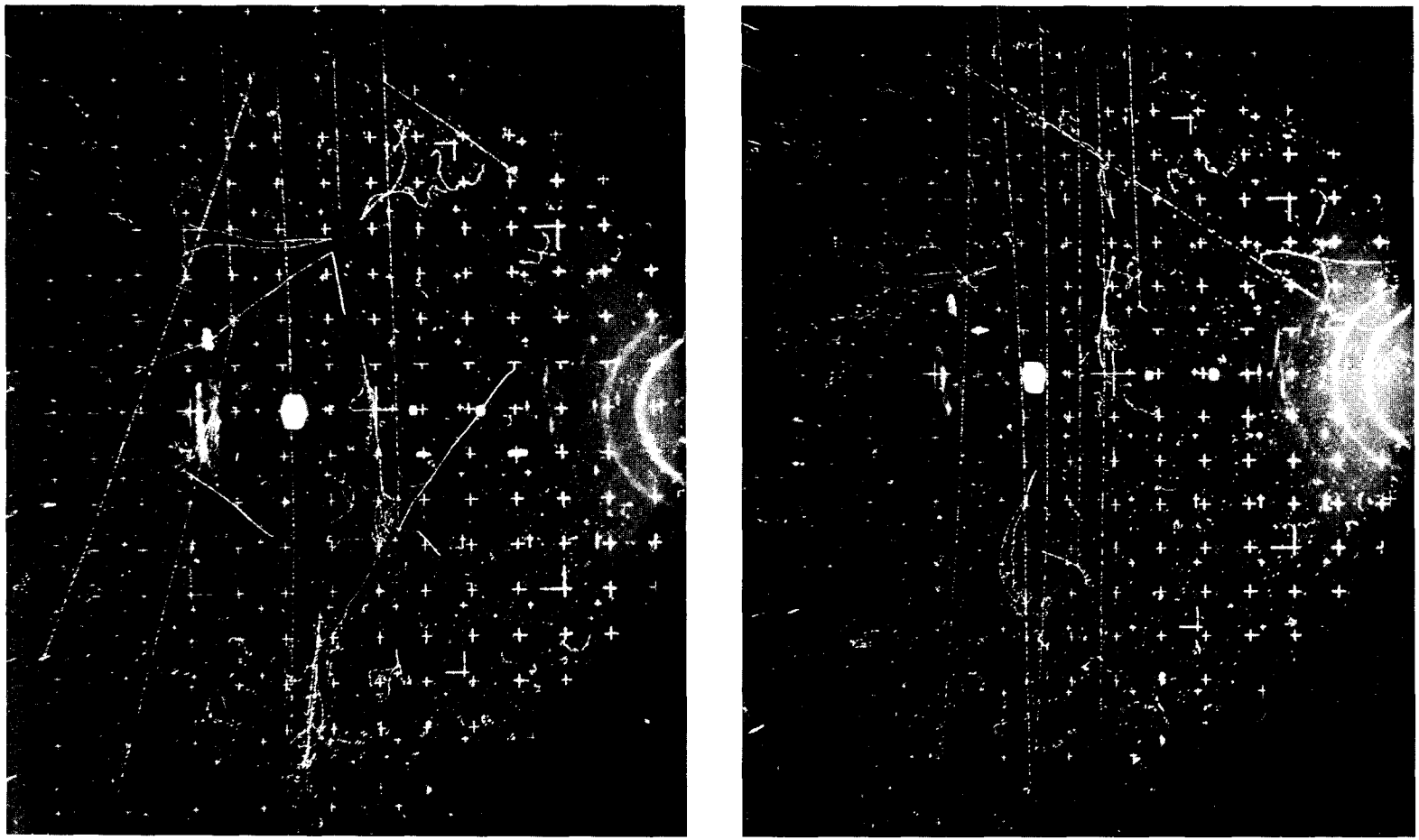

Fig. 5 Four pairs from a θ_1^0 decay.

a

b

TABLE I

Errors in the measured angles of pairs in xenon

Particle	p (MeV/c)	$p\beta$ (MeV/c)	t (cm)	$\Delta\theta$ (degree)
Electron	50	50	0.55	4.5
Electron	100	100	0.9	2.8
Electron	500	500	2.5	1.0
Pion	50	17	0.27	9.2
Pion	100	58	0.6	4.1
Pion	500	480	2.5	1.0
Proton	500	236	1.5	1.6

To see how this is applied in practice is interesting. Suppose that four pairs point back at the neutral decay of a K^0 as shown in Fig. 5. The most refined method used thus far for analyzing the gammas from neutral mesons can be illustrated by the problem presented by the presence of four pairs appearing to come from the neutral decay of the K_1^0 meson.

An electron-positron pair scatters on leaving its origin until the two tracks separate. The $p\beta$ of each particle is unknown in advance. However, usually that part of the event before the tracks separate gives the best indication of the direction of the gamma ray. By picking those pairs that appear to have the highest momentum, a point in the chamber is chosen near the true point. Low-energy pairs can be useful, as can be illustrated by the presence of two high-momentum pairs with lines-of-flight nearly parallel and a third low-energy pair nearly at right angles and close to these lines of flight. The low-energy pair fixes the point along the nearly parallel lines of flight of the other two. After a point indicated by this rough procedure is chosen, a program is used which calculates the directions in space of the lines joining this point and the starting points of the pairs. These are compared with the directions obtained from a measurement of the pairs alone without reference to the chosen point. The angles between these directions are divided by an estimate of the error made in determining them. The sum of the squares of these quantities is taken as an indication of the goodness of fit. Then the chosen point is moved until this sum goes through a minimum. The point found in this manner is assumed to be the closest fit to the true point.

There is always the possibility that one or more of the pairs is spurious. Therefore, the same process is repeated for 3 gammas or 2 gammas as may be indicated by the behavior of one of the errors.

It may be stated that under the usual running conditions the effect of background gammas is negligible when there are 3 or 4 gammas from the event, and amounts to about 3.5% when only two gammas are present, such as in the neutral decay of the Λ.

An interesting calculation was performed using the following data: the picture contained 4 gammas coming from a K_1^0 decay by the neutral mode where the production origin of the K_1^0 was visible in the chamber. If angles alone are known, then there is sufficient information, when the process is assumed, to determine the Q of the K_1^0. In order to do this it is necessary by trial and error to pair off the gammas from each neutral meson correctly. If all information other than angles was discarded, the number of solutions was too great for a definite answer to be obtained because of the quadratic nature of the equations. This situation was markedly simplified by first setting the minimum momenta of the gammas equal to that indicated by the visible ionization loss in the tracks. This reduced the number of solutions.

The Monte Carlo calculations on shower theory made by R. R. Wilson [21] were applied to xenon, using some approximations. It became evident that a greater safe minimum energy of a pair could be set than that indicated by ionization alone. When a higher minimum was used, consistent values of the Q of the K_1^0 were obtained.

It should be emphasized that this procedure has been used only once, and that therefore it is in no way a proof of the validity of the method. The purpose of presenting it here is to show how people are thinking, particularly to emphasize the importance of using every piece of information available in calculating events.

The errors E used in calculating the goodness of fit of an origin for four gammas are difficult to estimate because the $p\beta$ of the electron and positron are not known. Obviously, the minimum $p\beta$ obtained from ionization and shower theory is useful and gives some hold on the problem. At very high values of $p\beta$, the scattering error becomes smaller than the measurement error, and the appearance of the pairs is a good indication of their measurability.

The error in the angle of a proton where the range is between 0.5 and 1.0 cm is 5 degree, and for a

meson, 11 degree. These are measured to the end of the track, and there large angle errors make it difficult to get good Q-values on lambdas where both particles stop in the chamber.

The usual accuracy for locating a point where a K_1^0 decays into four gammas is about $\pm$ 2.5 mm. This results from the types of errors shown in Table I and from the fact that usually one gamma pair is rather low in momentum and therefore a poor indicator.

An interesting comparison can be made between small chambers of high Z and short radiation length and larger chambers of lower Z but large in proportion to the radiation length. If we consider only the accuracy of location of a source of gamma rays, then the error in location goes as $L^{2/3}$. This dependence arises in the following way. The scattering error in the space angle of a pair for the same length of track is proportional to Z^2, and the distance to the origin is proportional to radiation length, which in turn is proportional to the reciprocal of Z^2. These two factors cancel each other in determining the error in location of the origin. However, the best length of track, t, suitable for determining the space angle goes as $L^{1/3}$. The error in angle goes as $L^{-1/3}$ and in location of the origin as $L^{2/3}$.(*)

CONCLUSION

In conclusion it probably is worthwhile to state future trends as we see them in heavy-liquid chambers. The advantage of these chambers is their relative cheapness compared with hydrogen. They are less costly to run and can be put into operation in a matter of hours instead of days. Certainly higher magnetic fields from 50 000 to 100 000 gauss will be a great advantage, though the problem of stray fields affecting the operation of accelerators and the orbits of particles entering the chamber is not negligible. Accurate bubble-count work both at low and very high energies is certainly very important in these chambers in distinguishing background events from those of interest. Interpretation of results can often be more costly than in hydrogen because of the larger number of background events. Careful planning of experiments can change this picture completely, however. The amount of data obtainable in a given time can often be greater than for the same size hydrogen chamber because of the higher density of the liquid. Although the additional complication of the carbon can often create a difficulty in interpretation, still the fact that unexpected results often yield very interesting conclusions can make the experiment double or more in value.

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(*) $(\Delta\theta)^2 = 2\,\delta^2/t^2 + (A/p\beta)^2\, t/L$, where δ is the error in measurement of a track and A is a universal scattering constant. Setting $\frac{\delta(\Delta\theta)^2}{\delta t} = 0$, one obtains the best value of $t = t_B = (p\beta/A)^{2/3}\, L^{1/3}\, (4\delta^2)^{1/3}$. Substitution of t_B into the expression for $(\Delta\theta)^2$ makes it proportional to $L^{-2/3}$, etc.

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DISCUSSION

ROSENFELD: You state that you do not get as good location accuracy with a larger chamber and larger radiation length, but actually, of course, just position accuracy is not the whole story. If you want to analyze an event you also want to take advantage of the fact that you measure the momentum of these pairs after you see them and then presumably fit them. And in a larger chamber you can presumably measure their momentum more accurately, so I would think this would tend to make the propane chamber compete rather favourably. Now, is this true?

POWELL: I agree completely with that. I presented a one-sided argument. If you also measure the momentum, I am sure that you get a much better result with a large chamber and you certainly have more on the dynamics. I think, however, it still is true that you do not locate a point any better.

PROPANE AND HEAVY LIQUIDS BUBBLE CHAMBERS AT THE ECOLE POLYTECHNIQUE, PARIS

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(presented by A. Lagarrigue)

After the construction of a small experimental bubble chamber in 1957, the Ecole Polytechnique Group built a 20 liter chamber, which has been recently operated in connection with the Saclay synchrotron. Construction of a larger chamber ($100 \times 50 \times 50$ cm^3) is nearly completed. This chamber will be operated in a 20 kG magnetic field.

THE 20 LITER CHAMBER

General characteristics

The chamber is rectangular in shape and its useful dimensions are: length 34 cm, width 20 cm and depth 24 cm (see Figure 1).

It was designed for operation with a mixture of 50% methyl-iodide and 50% propane by volume as suggested by I. Pless (MIT). This mixture combines the advantages of a short radiation length (10 cm) and of a concentration in hydrogen which is 80% of that of liquid hydrogen. On the other hand, methyl-iodide is highly corrosive and somewhat toxic. Moreover, the mixture has to be heated to at least 115°C for correct operation in our chamber. A chamber which can withstand these severe conditions can be operated without modification with a number of heavy liquids used in bubble chamber techniques, such as propane, freons, etc.