REPORT OF GROUP A
LARGE HYDROGEN BUBBLE-CHAMBER STUDY

G. Trilling
Lawrence Radiation Laboratory

I. INTRODUCTION

The bubble chamber technique has proved very powerful in the study of strong-interaction physics, particularly the identification of boson and hyperon resonances and the investigation of production mechanisms up to energies of about 15 BeV. At NAL these lines of research can be pushed to considerably higher energies, with very small fractions of the accelerator beam, provided that a bubble chamber of appropriate characteristics is available.

Studies of weak interactions by means of neutrino experiments, although in principle suited to bubble-chamber experiments, have, in present accelerators, not used operating hydrogen bubble chambers because of rate limitations. The development and construction of large-volume chambers at BNL and ANL will in the near future provide instruments with which, in spite of small cross sections, useful event rates will be possible. However neutrino energies available at BNL and ANL are only of the order of 1 BeV; it is therefore clear that the higher energies at NAL will be essential in order to continue the neutrino program, and should be matched by an appropriate bubble chamber.

The purpose of this report is to examine what bubble chambers

should be operated at NAL to fulfill both the neutrino program and the strong-interaction program mentioned above.

II. LARGE BUBBLE-CHAMBER JUSTIFICATION

Neutrino Physics

Studies of neutrino reactions with neutron and proton targets provide practically the only means for extending the study of weak interactions beyond the very limited information provided by the weak decays of a small number of particles. The bubble chamber, which combines (i) vertex visibility, (ii) good momentum measurements of charged secondary particles, and (iii) the possibility of a large mass of hydrogen or deuterium for a target, is a unique tool for studying neutrino interactions.

Processes of particular interest have been discussed by Block[1] and Snow[2] during the Summer Study. In a substantial fraction of these there are no unseen neutral particles produced (π^0 or neutrons). Monte Carlo studies have shown that such 3c events can easily be identified and reconstructed with even conventional magnetic fields in any bubble chamber of volume large enough to consider for neutrino physics (i.e., the ANL 12-ft chamber). This is not surprising since the neutrino energies are comparable to energies of hadron beams being studied in present accelerators and bubble chambers.

Other processes of interest involve the emission of a neutron or a neutral pion. The zero-constraint nature of such events makes their

identification somewhat difficult. However for the large bubble chamber under consideration the probability of seeing an n-p scattering or of converting at least one of the gamma rays from the π^0 in the hydrogen is substantial. Either of these situations can add one or more constraints to permit identification and fitting of the reaction.

Finally D. Cline[3] has pointed out that there is considerable interest in studying dissociation reactions of the type

$$\begin{aligned} \nu_\mu + Z &\rightarrow \mu^+ + \mu^- + \nu_\mu + Z \\ &\rightarrow e^+ + \mu^- + \nu_e + Z \\ &\rightarrow e^+ + e^- + \nu_\mu + Z \ , \end{aligned}$$

in a large bubble chamber filled with neon.

Hadron Physics

The justification of the large chamber for studies of hadron interactions is less clear for the highest energies, but the following considerations are relevant:

(1) It will be very desirable to have a survey tool to see what characteristics hadron interactions have at high energy. Events with high multiplicity and events involving strange particles may be particularly suitable for bubble-chamber analysis.

(2) Monte Carlo[4] and hand calculations[5, 6] indicate that the identification and reconstruction of events with no missing neutrals can readily be carried out to energies of at least 60 BeV (in a 40-kG field) and perhaps

higher. As in the case of neutrino reactions, neutrons and missing π^o can be detected (at least one gamma from the π^o) in the chamber liquid in a significant fraction of the events, thereby adding constraints which make these events also identifiable.

(3) Many user groups will want to continue their work on hadron interactions at higher energies than those available at BNL. Even for energies of 10 to 30 BeV, in principle available at BNL, the proposed 25-ft chamber will be a much better match than the 80-in. chamber presently in use.

Arguments have been made that the study of particular inelastic channels will, at high energy, suffer a serious rate problem in the bubble chamber and will be better done in appropriate spark-chamber configurations, or so-called hybrid rapid-cycling bubble chamber spark chamber combinations. However in order to define what channels or more generally what phenomena will be interesting at high energy, the exploratory data from the bubble chamber may be essential for the efficient and economical design of appropriate high statistics experiments. It has also been suggested that the streamer chamber may compete with the bubble chamber as an exploratory survey device. At this moment one can only say that the bubble chamber is a proven device which can certainly do the exploration effectively. Further development of the streamer chamber may show that it is even more effective as a survey device, but this is not demonstrated at present.

III. BUBBLE-CHAMBER PARAMETERS

Volume

Large volume is dictated by the necessity of obtaining reasonable neutrino interaction rates. Indeed one can say that the neutrino program demands the largest volume chamber compatible with (i) available funds, (ii) technical feasibility, (iii) a not too excessive cosmic-ray background. In speaking of available funds, one must include both the construction cost and the cost of deuterium fill. The proposed 25-ft BNL chamber at an estimated cost of \$13 million plus \$3.8 million of deuterium is probably not too far from the limits imposed by the above considerations.

It is of interest to consider what useful neutrino event rate is available from the 25-ft chamber. We assume that half the circulating beam, namely 2.5×10^{13} protons per pulse, is available to the neutrino beam. From calculations by Hyman,[7] and by Camerini and Meyer,[8] we assume a flux of 0.06 ν per interacting proton incident on the chamber (considered as a target of circular cross section of 1.8-m radius). Finally we assume 5 m of fiducial length, a factor of 1/3 to go from circulating to interacting protons, and a neutrino cross section on a proton of 10^{-38} cm^2. This gives us a rate of one neutrino event every twelve pictures in hydrogen, and one event every six pictures in deuterium. For antineutrinos the rates are about half as large. Furthermore if there are further efficiency factors, such as Λ^0 detection, γ conversion, neutron secondary interaction, the rates become smaller. These

numbers provide the justification for the statement that one wants to build the largest chamber compatible with other outside boundary conditions.

It is perhaps of interest here to compare the effectiveness of the 25-ft chamber with that of the 12-ft ANL chamber. From curves given by Stevenson,[9] it appears that for the bulk of the neutrinos the ratio of gross numbers of events in the two chambers is about 20% less than the ratio of visible volumes, namely 3/1. This result is not very sensitive to exact shield lengths or details of beam design. The real effective ratio, however, must also take account of the fact that the whole chamber volume is not available if one wants to measure secondaries, or require neutrals to interact or convert, or put plates of some sort in the chamber. Taking these factors into account suggests a ratio of 4-5/1 between the effective rates in the two chambers. In view of the actual rates given above for the 25-ft chamber, it is clear that the 12-ft chamber is inadequate for a serious neutrino program.

For strong interactions there appears to be not much difference between the 12-ft chamber (with a field of 40 kG) and the 25-ft chamber.

Aspect Ratio

Strong interactions at high energy are most effectively analyzed in chambers whose ratio of length to width is of the order of 3 or 4, since for a given volume this provides long lengths for high-energy forward-moving particles. There are however other considerations,

particularly applicable to neutrinos, which favor a ratio closer to 1:

(1) To rough approximation neutrino rates depend principally on volume (this seems to be more true for the wide-band systems with large shields than for narrow-band systems; the LRL 1966 Summer Study based on a narrow band system claimed that a ratio of 3 was most favorable for maximum neutrino rates). For a given volume, a 1/1 aspect ratio decreases cost of magnetic field (especially for high fields), makes for easier camera design, and increases the ratio of visible to total volume.

(2) Detection of sideways moving neutrons produced in reactions like $\bar{\nu} + p \rightarrow \mu^+ + n$ is more efficient for a fat chamber.

In view of these considerations, the suggested aspect ratio in the BNL proposal of 1.5/1 appears reasonable. If any volume increase in the chamber were contemplated it should probably be in the direction of increasing the width (but not the height) of the chamber.

Magnetic Field

Monte Carlo studies[4] have shown that a conventional 20-kG field is adequate for kinematic reconstruction of neutrino events in the energy region where they are most numerous. The advantages of not going to higher fields are the following:

(1) Smaller coils further away from the median plane lead to fewer background muons from neutrino interactions in the coils.

(2) Low fields simplify the coil support problems; smaller supports

again lead to fewer background muons and give more flexibility in placing counters or spark chambers near the bubble chamber.

(3) Cost savings in the magnet can perhaps be used to increase the chamber volume slightly.

On the other hand, the availability of appropriate superconductor permits the design of coils to provide a field of 40 kG without a large increase in cost. The advantages of the high field are

(1) Strong-interaction experiments and neutrino experiments with the highest-energy neutrinos probably require it.

(2) Charged particles with momentum up to 1.5 BeV/c can be trapped in the chamber. This feature may be useful in neutrino interactions, where the energy per secondary may not be much higher than this figure.

(3) Experiments with neon will benefit from the high field.

It appears from these considerations that study should be given to the spreading of the coils to leave considerably more free space between them. In the present design the free space is about 5 ft, whereas a quick look indicates that without severe modification of the vacuum tank this free space can be increased to 14 ft, leaving essentially the full chamber cross section clear. An estimate shows that without changing the coil design, this modification reduces the field from 40 kG to about 28 kG. The cost of additional conductor to bring the field back up to the 40-kG design figure might be about $1 million. If this additional

cost is considered excessive, one could consider a design in which only the 28 kG is initially provided with the potential option of adding more conductor at a later time.

Pulsing Rate

A repetition rate capability of about one expansion per second appears very desirable for the following reasons:

(1) Such a capability will permit the chamber to keep up with accelerator operation at 50 BeV. It has been shown by Camerini and Meyer[5] that such operation with a correspondingly thin shield maximizes the neutrino flux in the energy region of a few BeV.

(2) If the accelerator is operated at full energy with a 1-second flattop, the chamber could be double pulsed, one expansion at the beginning and the other at the end of the flattop. In this mode the first pulse could be used for the neutrino operation, and the second, taking only a negligible amount of accelerator beam, could be used to provide a hadron beam.

Iron Return Path

The absence of iron in the proposed design simplifies many things and adds flexibility in the placement of spark chambers or other peripheral equipment in the neighborhood of the bubble chamber. Although the impact of the presence of such a large field is a subject which requires further study, it is hard to see any compelling reason for an iron yoke. This view would of course change if detailed study indicates

that a "flux grabber" which channels the bubble-chamber magnetic field in such a way as to remove regenerated muons from the neutrino filter is a desirable device.

IV. TWO BUBBLE CHAMBERS AT NAL

It has been shown that the ANL 12-ft chamber is inadequate in volume for a program of neutrino physics matched to the capabilities of the accelerator. On the other hand, one can ask if, assuming that the 25-ft chamber is built, there is a useful role for the 12-ft chamber. In a general way it appears rather obvious that after the 200-BeV machine turns on, the 12-ft chamber can be far more useful at NAL than at ANL. Some possible uses of the chamber might be:

(1) Hadron physics. For example if it turns out to be difficult to bring in hadron beams into the neutrino area, the 12-ft chamber might be placed in a more convenient location for such beams. Preliminary Monte Carlo calculations indicate that the 12-ft chamber with a 40-kG field is almost as good as the 25-ft chamber for hadron experiments.

(2) It has been suggested by D. Cline[3] that the 12-ft chamber might be placed ahead of or behind the 25-ft chamber and operated with neon to permit a neutrino-heavy nucleus program simultaneous with neutrino-nucleon program.

(3) M. Block[1] has emphasized the importance of 1-BeV neutrino physics. It is conceivable that a separate low-energy neutrino facility could be set up to operate with the 12-ft chamber.

These examples are not exhaustive but indicate the added flexibility and capability if the 12-ft ANL chamber is brought to NAL.

V. SUBJECTS OF FURTHER STUDY

It is obvious that the summer study has been able to just touch on various subjects which may have impact on the bubble-chamber program. Many of these areas need much more detailed study, presumably by a group at NAL. Some of these areas could be:

1. Muon background problems in the neutrino beam. Is the "flux grabber" the appropriate way to remove this background?

2. Boundary conditions imposed on the chamber by the desirability of putting muon-detecting spark chambers downstream.

3. Problems involved in bringing hadron beams into a chamber in the neutrino area.

4. Further Monte Carlo "FAKE" calculations on event reconstruction problems especially with missing neutrals. These calculations should be updated when test results are available from the BNL 7-ft chamber and the ANL 12-ft chamber.

5. Various problems associated with the bubble chamber, which probably should be handled through collaboration between BNL and NAL. For example, should other cameras be placed downstream to see plates if these are put in the chamber? What is the impact of the hydrostatic pressure in operation with neon, etc.?

VI. SUMMARY

The main conclusions of the study on large bubble chambers are the following:

1. Neutrino programs require the largest volume bubble chamber which can be built subject to the constraints of budgets, technical capability, and cosmic-ray backgrounds. The 25-ft BNL chamber is probably not far from the limits imposed by these constraints. The 12-ft ANL chamber is less efficacious insofar as rates are concerned by a factor of 4-5/1 which makes it much less desirable for a serious neutrino program.

2. Hadron physics can be done up to energies at least as high as 60 BeV with either the 25-ft chamber or the 12-ft chamber with a 40-kG field.

3. A magnetic field of 20 kG is adequate for the neutrino physics at energies 1-10 BeV. For high-energy neutrinos, hadron physics, and operation with neon a field of 40 kG is very desirable. Whatever field is achieved, it is recommended that the coils be spaced from their present 5 ft to about 14 ft to reduce muon background in neutrino experiments and give more accessibility for conters or spark chambers.

4. Operation of both the 25-ft and the 12-ft chambers at NAL appears very desirable to provide the flexibility necessary to properly match the potentialities of the accelerator.

REFERENCES
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[8] U. Camerini and S. L. Meyer, B. 1-68-82.

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