STRONG-INTERACTION STUDIES WITH BUBBLE CHAMBERS AT NAL

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ABSTRACT

Studies of strong interactions up to the highest energies at NAL require an active bubble-chamber program. The varieties of experiments and some technical requirements for such a program are outlined in this report. We strongly recommend that an existing bubble chamber be moved to NAL to strengthen and add flexibility to the program for strong interactions which already includes the 15-ft chamber under construction.

I. INTRODUCTION

The bubble chamber will be a valuable instrument for strong-interactions studies at NAL because it is the only proven instrument where all charged secondaries, including the interaction vertex, are visible. This capability of the bubble chamber makes it possible to do exploratory studies of unexpected phenomena. It is possible to detect complex high-multiplicity events which are important to study up to the highest available energies at NAL. These studies are made to learn more about particle production in general and to test specific ideas on high energy limiting behavior as expressed, for example, by Feynman and by Yang and his coworkers. There is also an important need to extend to higher energies the kinds of investigations for which the bubble chamber has proven very successful in the < 30 GeV/c energy region. The latter includes searches for new particles and determination of their quantum numbers as well as studies of production mechanisms in general. Results from bubble-chamber experiments will also be valuable for designing more specialized experiments involving either counters or more bubble-chamber pictures.

In Section II, Physics Justification, we discuss in more detail bubble-chamber capabilities and experiments that would be of interest at NAL. A summary of proposals for strong-interaction studies with bubble chambers is given in Section III, and the requirements in terms of beams and on the bubble chamber are pointed out. In Section IV we discuss our recommendations for bubble-chamber beams. We argue in Section V in favor of moving a second bubble chamber to NAL in order to insure an adequate strong-interactions program. Section VI is devoted to a summary of our conclusions and recommendations.

II. PHYSICS JUSTIFICATION

A. Bubble-Chamber Capabilities

The kinds of physics one wants to do with a bubble chamber naturally depend on what the bubble chamber is best for. In this section we make explicit some well-known capabilities of bubble chambers. We do not include in this report any calculations on the quality of bubble-chamber measurements since these have been done at previous NAL summer studies. A brief review of pertinent facts from these studies is included in Appendix A Furthermore, we take the point of view that there is no high energy cutoff beyond which bubble-chamber information is useless As we point out below, there are a wide variety of studies to be made in an almost totally unexplored region of energies so that bubble-chamber data provides important information up to 500 GeV/c.

The important capabilities of bubble chambers are the following:

1. Excellent Multiparticle Detector

The bubble chamber is a relatively unbiased 4π detector which makes possible the simultaneous viewing of an essentially unlimited number of tracks with good resolution. Since the chamber liquid is both the target and the track-sensing detector, it is possible to see the vertex of the primary interaction as well as decays or interactions of secondary tracks.

2. Momentum Measurements and Particle Identification

Bubble chambers are not capable of providing high resolution momentum measurements, but they provide excellent information on low-momentum tracks. The backward-hemisphere particles have small laboratory momentum making possible measurements of single particle spectra in pp interactions by exploiting the backward-forward symmetry. Therefore, we see immediately that there is an area where the limitation on high-momentum tracks is not serious.

Good separation between p and π (and to a lesser extent K) is obtained by bubble-density measurements for particles of momenta less than ~1.2 GeV/c. Delta-ray information is useful over a wide range of momenta.

Low-momentum tracks can be stopped and, if they decay, identified by their decay products. Since the vertex of interaction can be seen, range measurements of recoil protons ($\gtrsim$ 90 MeV) can be made--an important measurement for diffraction dissociation studies or for the selection of the "spectator" proton with deuterium in the chamber.

3. Existing Data Processing

Sophisticated data-reduction systems exist for analyzing bubble-chamber data. We do not rule out the possibility of unambiguous kinematic fits to final states with no neutrals, up to 500 GeV/c. The ability to obtain unambiguous fits depends upon many factors including the setting error, length of track, magnetic field, and the accuracy of the momentum and angle determination of the beam. It may be necessary at the highest energies to have a track-sensitive hydrogen target inside a neon-filled chamber to provide identification of π^0's in order to make reliable fits. In any case, complex events in bubble-chamber data have been successfully analyzed and whether or not unambiguous kinematic fits will be made at the highest energies at NAL, valuable unfitted track data will be available with existing techniques.

4. New Developments; Hybrid Systems

Track-sensitive targets (TST) are currently being developed at NAL and Brookhaven and were described in the NAL 1969 summer-study reports.[1] It is expected that a TST will be constructed for the 15-foot chamber thereby significantly extending its capabilities.

Other developments include downstream detectors to aid in the momentum determination of high-momentum secondaries, possibly along with Cerenkov counters for particle identification. Wire spark chambers or Charpak counters and Cerenkov counters could be placed upstream for beam definition and tagging.

B. Experiments

1. New Phenomena

The good spatial resolution and 4π solid-angle coverage of the bubble chamber make it unique for the search for unexpected phenomena. A specific possibility might be the discovery of new short-lived particles (10^{-13} - 10^{-10} sec lifetime) for which the bubble chamber will be the only technique capable of detecting complex decay sequences.

2. Multiparticle Studies Up to the Highest Energies

The bubble chamber makes possible gross studies of all inelastic channels up to the highest energies at NAL. These results will be far superior to cosmic-ray experiments covering the same energy range. Such studies are very important for developing a theory of strong interactions because unitarity requires that all channels be tied together.

Both Feynman[2] and Yang and his coworkers[3] have predicted limiting behavior (scaling) as the colliding energy becomes very large. According to the hypothesis of limiting fragmentation (HLF) of Yang, the beam and/or target particles fragment separately. In pp collisions, according to HLF, either one or both colliding protons fragment and produce clusters of particles, $p^{\dagger}$, i.e.,

$$p + p \rightarrow p + p^{\dagger}$$

or

$$\rightarrow p^{\dagger} + p^{\dagger}.$$

The distribution of beam (target) proton fragments give limiting distributions in the beam (target) rest frame. As a separate hypothesis, Yang and coworkers argue that there will be no particles which do not approach limits in either beam or target-rest frames; this is an assertion that there is no "pionization."

The parton model of Feynman makes some specific predictions including limiting behavior equivalent to HLF, Regge power-law behavior for two-body reactions, and the existence of pionization resulting from so-called "wee" partons.

Other models relevant for high-energy studies are the quark model and the multiperipheral model.[4] One version of the quark model relates pp cross sections to πp cross sections at 2/3 the pp energy.[5] A general prediction of the multiperipheral model is that mean multiplicity ($\bar{n}$) varies $\sim \ln (p_{lab})$ and the distribution of multiplicities at a fixed energy is a Poisson distribution.

Data from present accelerators (< 30 GeV/c) seem to be not high enough to properly investigate highly inelastic channels. This is because kinematics, for example, prevents the clean separation of beam fragments, target fragments, and pionization. Studies of bubble-chamber data at NAL should show how various quantities including multiplicities, momentum distributions, and specific channels vary with energy up to 500 GeV/c. This kind of survey should go far in answering questions raised by the models discussed above. We emphasize once more that the bubble chamber has no intrinsic high-energy cutoff for these studies. Valuable information will be provided from unfitted data up to 500 GeV/c; moreover, studies in specific channels should be possible with a track-sensitive target configuration to detect neutrals if conventional fits are not satisfactory.

3. Conventional Bubble-Chamber Studies

The bread-and-butter type of bubble-chamber strong-interaction physics will be interesting to extend to NAL energies. This will involve the use of rf-separated beams and will probably be most fruitful in the $\lesssim 100$ GeV/c range where unambiguous four-constraint kinematic fits should be most easily obtained.

It will be of interest to pursue searches for new particles or resonances at higher masses and determine their quantum numbers where possible. Production mechanisms will be very interesting to test and energy-dependent studies of two-body channels will be important for testing Regge behavior. High-energy $\bar{p}$, $K^{\pm}$ beams will provide a new and rich variety of channels to study in detail. It hardly needs further mentioning that the extended range of energies provided by NAL will provide an exciting list of experiments to perform by the bubble-chamber technique which has proven so effective in the past.

III. SUMMARY OF PROPOSALS

A. The strong-interactions bubble-chamber proposals, as of July 22, 1970, are summarized in Table I

B. The salient facts are

1. There are 16 proposals from 22 groups
2. About 9×10^6 pictures are requested
   - $\sim4.4\times10^6$ for 15-foot (NAL)
   - $\sim1.5\times10^6$ for 15-foot (NAL) of smaller chamber
   - $\sim3.2\times10^6$ for a smaller chamber, in most cases with downstream detectors
3. Most groups want to do energy-dependent exploratory studies up to the highest energies with unseparated beams
4. There are only two rf beam proposals, which most likely reflect the user's pessimism as to the availability of these beams
5. There is a strong demand for a second chamber

IV. TECHNICAL REQUIREMENTS

A. Bubble Chamber and Beams

The 15-ft NAL bubble chamber is considered to be the basic instrument, and beams must be provided for it to satisfy the fundamental physics requirements. We suggest the following types of beams in Area 1:

1. A high-energy unseparated hadron beam for protons and π^- in the range of $100 \leq p \leq 500$ GeV/c,

2. A medium-energy, rf-separated π^+, K^+, K^-, and $\bar{p}$ beam in the range of $30 \leq p \leq 100$ GeV/c,

3. A neutrino beam (to be discussed elsewhere).

For reasons of beam and budget economy we add the following requirements, the first of which is compulsory, the others optional.

- The ν beam should exist together with one or both hadron beams;

- The ν beam should operate in its counter mode together with any of the above bubble-chamber beams;

- The hadron beams are low-intensity proton users.

Therefore, the major portion of the accelerator protons should be used by the neutrino target.

B. Area Layout

We suggest the installation of a low-intensity target (~1 cm beryllium) in a location 100 m upstream from the neutrino target. (See Fig. 1.) The rms multiple scattering angle of this target on the transmitted proton beam is $< 10^{-5}$ radians.

The target produces a secondary beam which is accepted at a nominal production angle of 1 mrad with a solid angle of 10^{-7} sterad. The beam is deflected away from the proton beam by a septum magnet, positioned 50 m downstream, where the beams have a 5 cm distance, and the secondary dimensions of 1.5×1.5 cm^2. By the deflection of 10 mrad the beam passes the neutrino target box.

The flux of diffracted protons at the angles given above is $\sim 10^9$ for 10^{13} incident protons (Appendix B). This high flux requires the controlled reduction of intensity by, at least, seven orders of magnitude. There are four independent parameters for flux control: primary proton flux, target thickness, production angle, and vertical acceptance (the horizontal acceptance provides a spread of the beam in the bubble chamber and should not be cut). Under the same conditions a flux of secondary particles can be obtained which is sufficient for unseparated and separated bubble-chamber beams (Appendix B).

The detailed layout of the two hadron beams will depend on the configuration of the neutrino area, which is unknown at this moment. The unseparated beam should consist of two stages, for momentum analysis, possibly good for $\Delta p/p = \pm 0.001$, and for momentum recombination. It should operate up to 500 GeV/c. The rf-separated beam will follow the design by J. Lach.[6]

Special problems have to be studied before the decision on the final layout:

- It is planned to place the 15-ft chamber at the distance of 20 meters from the end of the neutrino shield. Depending on the width of this shield, the charged beams must be brought to the bubble chamber either by a sharp bend or by a hole in the neutrino shield.

- Special effort should be made to spread the beam horizontally in the bubble chamber to avoid superposition of tracks.

- Space should be foreseen to place a threshold Cerenkov counter in the beam line and a set of wire chambers in front and behind the chamber. The equipment will be installed at a later stage for tagging purposes.

- Tagging of tracks leaving the bubble chamber requires a reasonably thin exit window.

V. "SMALL" BUBBLE-CHAMBER PROGRAM

The unique properties of bubble chambers for hadron physics (i.e., visibility of vertex, 4π solid-angle detection, lack of bias, accuracy of slow-particle measurement and discrimination, excellent detection efficiency for high-multiplicity events, availability of working analysis programs and analysis equipment, and ability to observe and analyze the unexpected "new particle") clearly apply to any existing smaller bubble chamber. We believe that the interesting physics program related to hadronic interactionsabove ~100 GeV/c described in Section I, combined with the great interest in this kind of physics already reflected in the proposals (22 university and laboratory groups), and with some special advantages that a second, small bubble chamber offers to NAL, justifies a serious effort to set up such a device in a high-energy, unseparated, proton or π^- meson beam at NAL. Of the class of bubble chambers with high field and length $\geq$ 30 inches in the U. S., at least one, the ANL-MURA 30-in. chamber may be available together with trained and expert operating crew living within commuting distance.

A. Arguments in Favor of a Second Bubble Chamber at NAL

1. While the 15-foot bubble chamber should prove an excellent instrument for hadronic physics, its function as a neutrino detector fixes its location at 0° behind a drift space and muon shield. This may limit to some extent the beams available to it, and/or its compatibility with other counter experiments, particularly in the first year or two of its operation. A second bubble chamber, in a second location, may accommodate a high-energy hadron beam not easily accessible to the 15-foot chamber, and in a manner well adjusted to parasitic operation with counter experiments in Area 1.

2. A second bubble chamber will ensure that more pictures will be taken, e.g., the ANL 30-inch could easily average 4×10^6 pictures per year (the chamber can easily take 2 pictures/pulse). More pictures distributed to more high-energy physics groups will ensure that more brains are at work trying to unravel the mysteries of hadronic interactions above ~100 GeV/c.

3. A second bubble chamber, such as the ANL 30-inch, or the SLAC 40-inch, or BNL 80-inch, will allow for the possibility of adding secondary-particle tagging apparatus downstream of the bubble chamber. This can be used in several ways, e.g., to measure momenta of particles in the forward jet more accurately; to detect (or anti out) high energy π^0's or neutrons in the forward cone. The assumption here is that two bubble-chamber pictures, one before and one after the long spill, will be

taken on every machine pulse, and that the downstream tagging apparatus (wire chambers in one proposal, wide-gap chambers in another) would give information on a subset of the events in the bubble chamber.

4. Finally, a second bubble chamber, such as the ANL 30-inch, could be installed and ready for picture taking by January, 1972 (one year earlier than the 15-ft chamber). In addition, entire data-analysis systems, including measuring machines, analysis programs and people are available now. If an unseparated hadron beam were available, high-energy proton runs in the bubble chamber could complement counters in doing particle survey work useful for the design of future experimental areas.

B. Limitations in the Physics That Can Be Done at High Energies With A "Small" Bubble Chamber

The physics that can be studied with unfitted events with p or π^- on H_2 in the 100 to 500 GeV/c region has been spelled out in some detail in Section 1. Surprisingly enough, almost all of the physics can also be done in a small bubble chamber like the ANL 30-inch. Some limitations are:

1. The interaction region is 0.3 m instead of 3 m; nevertheless, a 100,000 picture exposure yields one event per μb cross section.

2. Events involving complex chains of decays or interaction downstream over distances $\gtrsim$ 1 m are lost to the small chamber.

3. The momentum measurement accuracy in the small chamber by itself precludes the possibility of extracting unique 4c events from the total. This may still be possible in the big chamber below full machine energy. The quality of information about the downstream jet particles should be much better in the big chamber.

Some compensations:

4. Downstream tagging with a second magnet can make up to some extent for difficulty (3) above. It may add extra information not available in a 15-ft bubble-chamber exposure without its own downstream tagging.

5. The visibility close to the vertex of each event should be somewhat better in a smaller chamber.

C. Beams, Possible Sites, Chambers

In this section we summarize our ideas on these three subjects.

1. Beams: A good quality unseparated beam of positive and negative particles of variable momenta from 100 GeV/c up to 500 GeV/c is desired. It is believed that a simple two-stage beam will be required to control the particle intensity for the bubble chamber, reduce beam halo, and allow one or two incident proton beam momenta to produce secondary particle beams with several different momenta. A cruder simpler

beam may only work for diffracted protons at the energy of the incident protons. A momentum resolution of ~ 0.1%, plus some feedback control (such as moving a wire target, or kicking a magnet current) to limit the number of particles entering the bubble chamber is needed.

2. Possible Sites: The desirability of having beams above 200 BeV/c argues strongly for a site in Area 1. The exact location for a second bubble chamber will depend on the final configuration adopted for Area 1. A diffracted proton beam arising either from a thin target upstream of the main neutrino target box, or from a second target box if the two-target solution is adopted, could serve as a good source of low-intensity high-energy hadron beams for the second bubble chamber. It should be placed in a position so as to minimize extra shielding. Because of the low intensities, the shielding problem for hadron experiments are substantially simpler than for neutrino physics, and it is closely coupled to the target configuration.

3. Bubble Chambers: The committee agrees that a ranking of bubble chambers in order of worthwhileness for NAL would be: BNL 80-inch > SLAC 40-inch > ANL 30-inch > any smaller chamber. We are under the impression that the ANL 30-inch may be much more available than the 40-inch or the 80-inch chambers. In addition, an experienced operating crew within commuting distance to NAL is available for the 30-inch.

4. Triggering of Bubble Chambers in a Hybrid Mode of Operation.

A rapid-cycling bubble chamber could be used as a hydrogen target and a low-energy vertex particle detector in a triggered mode for several interesting physics problems. The availability of a high-energy beam to a second bubble chamber, together with the experience gained in operating a bubble chamber in the tagging mode will facilitate the possibilities for triggered-mode operation. The triggered mode of operation would probably not be feasible in Area 2 because the muon flux is probably too large to allow a bubble chamber to operate throughout the long spill. No such background problem would exist if either only two bursts per machine pulse, one before and one after the flattop, feed a bubble chamber, or a more massive shield is installed, as contemplated in Area 1.

VI. CONCLUSIONS

1. There are a variety of important strong-interaction studies that can be done with a bubble chamber at NAL. Valuable data will be obtained up to the highest NAL energy.

2. There is obviously a strong interest on the part of users for strong-interaction studies as exhibited by 15 proposals including 23 groups.

3. To provide the required physics, it will be necessary to have both a high-

energy (up to 500 GeV/c) unseparated beam and an rf-separated beam as well as a neutrino beam for the 15-ft chamber.

4. To provide an adequate flexibility and scope for the strong-interaction program, we strongly urge that a second bubble chamber be moved to NAL.

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Table I. Summary of Bubble-Chamber Proposals for Strong Interactions (As of 7/22/70).

Number	Group	Spokesman	Beam	Momentum GeV/c	Chamber	Pictures ($\times 10^3$)	Physics
2	Maryland, MSU, ISU, ANL	Snow	π^-, p	70-200 and up	30-in. + spec.	1000	"multiparticle study" $pp \rightarrow p(p\pi\pi)$ slow, high mass resonance, new particle
17	Ohio	Reynolds	$\bar{p}$	20, 40, 60	80-in. or 15-ft (D_2)	1000	$\bar{p}n \rightarrow pp\pi^-\bar{p}$ (4c)
37	NAL-UCLA	Malamud	p	up to 500	15-ft	250	"multiparticle study" at 5 energies
39	Wisc.-Toronto-Duke	Walker	π^-, p	100, 200	rap. cycl. BC		tagged beam, diff. dissoc. of the target
40	Purdue	Willman	π^-	100	15-ft	500	$pp \rightarrow pp2\pi$, $pp4\pi$
41	BNL-Purdue	Barnes	p	high	15-ft	100	"multiparticle study"
46	NAL	Huson	π^-	≥ 150	15-ft	250	survey $\Delta p/p \sim 0.1\%$, $\Delta\theta \approx 0.1$ mrad track-sensitive target in H_2Ne
47	MIT	Pless	π^-, p	200	BC-WC	10^6 pulses	diff. dissoc. and elastic scatt.
58	BNL-Vand.-Wisc.	Panvini	π, p	200-400	15-ft	1400	"multiparticle study" ($\Delta p/p \approx 0.1\%$, good beam angle tagging)
62	Michigan	VanderVelde	π^-, p	100, 200	small BC	200	"multiparticle study"
65	BNL-Vand.-FSU	Lai	K^o	20-60	15-ft	1000	$K_Lp \rightarrow K_Sp$, $K^*\Delta$, etc.
66	Michigan	VanderVelde	π, p	>100	small BC + spec.	1000	$A + p \rightarrow A + M$ slow study internal structure of M; $\Delta p/p \lesssim 0.2\%$
77	Colorado	Libby	p	high	15-ft	250	produce hyperons from heavy plates in BC study; hyperon-nucleon interaction
78	IIT	Burnstein	π, p	> 50	small BC		multiparticle study
80	JHU, Roch., Yale	Ferbel	π^-	60, 150	small BC or 15-ft	500	"multiparticle," inclusive reaction with Δ, diffraction mass spectra, new particle
83	Tohoku	Kitagaki	$\bar{p}$	40-140	15-ft	600	$\bar{p}$-p
16 proposals	22 groups		π^-, p, $\bar{p}$, K^o	8 for 15-ft 2 for small 15-ft 6 for hybrid		9 M pictures	

Note: "multiparticle study": study all reactions to compare with predictions from Yang, parton, quark, and Regge models.

APPENDIX A. BEAM TOLERANCE: MOMENTUM AND ANGULAR RESOLUTION

This note discusses and estimates, in a rough way, the beam momentum and angular resolution ($\Delta p/p$ and $\Delta\theta$) desired for the NAL 15-foot bubble chamber. We recommend that the reader consult the attached bibliography of NAL summer-study reports. From these articles one can deduce values for $\Delta p/p$ and $\Delta\theta$ assuming various models based on which measurements of physical quantities are of interest. Rather than accept the limitations of this approach, we suggest that the beam tolerances be determined from the multiple scattering and setting error limits imposed by the bubble chamber. These requirements set a natural floor on $\Delta p/p$ and $\Delta\theta$.

$$\frac{\Delta p}{p}_{\text{m.s.}} = \frac{0.13\alpha}{H^2\ell} \approx 0.3\% \text{ for } \begin{array}{l} \alpha \approx 20 \\ H = 30 \text{ kG} \\ \ell = 300 \text{ m} \\ \epsilon = 250 \text{ microns} \end{array}$$

For the beam tolerance on momentum, we suggest that it be lower than this limiting value due to multiple scattering in the bubble-chamber liquid, that is

$$\frac{\Delta p}{p}_{\text{beam}} \leq 0.2\%.$$

In the same way, one can calculate, $\Delta\theta$ due to the setting-error limitations of the bubble chamber.

$$\Delta\theta = \left[\frac{2\times 10^{-3}\alpha\ell}{p^2} + 3.8\times 10^{-6}\epsilon^2\right]^{\frac{1}{2}} \approx 0.1 \text{ mrad.}$$

For the beam tolerance on angular resolution, we suggest that it be lower than the above-limiting value, that is,

$$\Delta\epsilon \leq 0.1 \text{ mrad.}$$

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APPENDIX B. PARTICLE YIELDS

1. We compute the yield for incoherent diffraction scattering of protons on a beryllium-target of 1 cm (~30 cm of liquid hydrogen)

$$P_{in} = 500 \text{ GeV}$$

$$n_{in} = 10^{13} \text{ protons}$$

$$\theta_{sc} = 1 \text{ mrad } (-t = 0.25 \text{ GeV}^2)$$

$$d\Omega = 10^{-7} \text{ sterad}$$

$$n_{diff} = 0.65\times10^{9} \text{ protons.}$$

2. We compute the yields of secondary particles produced by protons on a beryllium target of 1 cm ≈ 1/30 interaction length (according to NAL flux calculations by Awschalom and White, National Accelerator Laboratory Report FN-191).

$$p_{in} = 500 \text{ GeV}$$

$$n_{in} = 10^{13} \text{ protons}$$

$$\theta_{prod} = 1 \text{ mrad}$$

$$d\Omega = 10^{-7} \text{ sterad}$$

$$\left|\frac{\Delta p}{p}\right| = 1\%.$$

particle/ momentum	p	$\bar{p}$	π^+	π^-	K^+	K^-
50	1.2×10^5	2.5×10^4	1.2×10^6	1.2×10^6	2×10^5	1.3×10^5
100	5×10^5	2.7×10^4	2×10^6	1.7×10^6	2.3×10^5	1×10^5
200	4.7×10^6	7.3×10^3	2.7×10^6	1.3×10^6	2.7×10^5	3.3×10^4
300	1.5×10^7	1×10^3	1×10^6	4.5×10^5	1.2×10^5	6×10^3
400	2.1×10^7	1.1×10^1	1.1×10^5	4×10^4	2.7×10^4	1.3×10^2

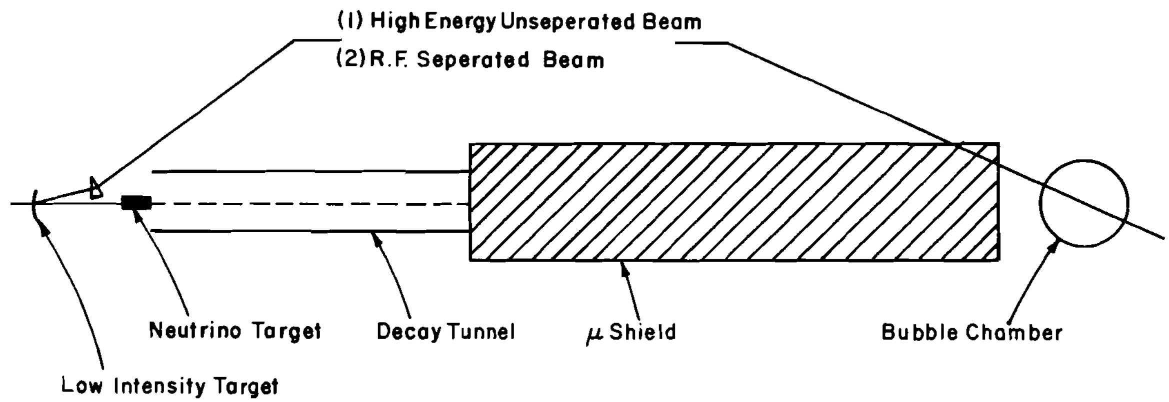

Fig. 1 Area I layout (schematic).