BUBBLE CHAMBER FILM ANALYSIS (BBC)

Revision 2000.1 January 2000

First watch the video on this experiment in the Physics Library. There are two parts to this experiment; first, you will study low-energy K^- induced reactions. In the second part, high-energy photon-proton interactions will be investigated. You should spend roughly equal amounts of time on each part.

Student's Name____

Partner's Name____

Pre-lab Discussion Questions

It is your responsibility to discuss this lab with a professor or T.A. on the first day of your scheduled laboratory period. This signed sheet must be included as the first page of your report. Without it you will lose 1/3 of a letter grade. You should think about and be prepared to discuss at least the following before you come to lab:

for the K^- component

1. What is a bubble chamber?
2. How is the K^- beam used in this experiment produced?
3. Sketch the tracks of the six most frequent decay modes of the K^- .
4. How can charge conservation be applied to distinguish between decays and interactions in flight?

for the Photon-Proton interaction component

5. How is the high energy photon beam produced in this experiment?
6. How does the photon interact with matter? Which processes are the most important in this experiment?
7. How can you distinguish inelastic photon-proton interactions from the elastic processes?
8. What is an electromagnetic shower?

for both machines

9. Demonstrate to the Staff that you can load the film (refer to appendix on film-loading, Appendix D).
   Staff member: As the preservation of the film is very important to the future use of this experiment, please initial below to indicate that the student can load the film without damaging it: Staff initials: __________

Staff Signature ____ Date ____________

Completed on the *first* day of lab? (circle) Yes / No

OVER FOR MIDLAB QUESTIONS

Mid-lab Questions

for the K^- component

On day 5 of this lab, you should have an estimate for the value of the K^- mean lifetime. Show it to a GSI and ask for a signature.

Staff Signature ______________________________ Date __________

Completed on the *fifth* day of lab? (circle) Yes / No

for the Photon-Proton interaction component

On day 8 of this lab, you should have an estimate for the value of the cross-section of strange particle production. Show it to a GSI and ask for a signature.

Staff Signature ______________________________ Date __________

Completed on the *eighth* day of lab? (circle) Yes / No

INCLUDE THIS SHEET AS THE FIRST PAGE OF YOUR REPORT

Physics 111 Advanced Lab Student Evaluation of Experiment

Now that you have completed this experiment, we would appreciate your comments. Please take a few moments to answer the questions below, and feel free to add any other comments. Since you have just finished the experiment it is *your* critique that will be the most helpful. Your thoughts and suggestions will help to change the lab and improve the experiments.

Please be as specific as possible, using both sides of the paper as needed, and turn this in with your report. Thank you!

Experiment name: ____ Date: ________

How was the write-up for this experiment? How could it be improved?

How easily did you get started with the experiment? What sources of information were most/least helpful in getting started? Were the reprints appropriate? Did the Pre-lab discussion help? Did you need to go outside the course materials for assistance? What additional materials could you have used?

What did you like and/or dislike about the experiment?

Would you recommend this lab to fellow student? Why or why not?

What advice would you give to a friend just starting this experiment?

If the course materials were available over the internet (WWW, FTP, etc), would you (a) have access to them and (b) would you prefer to use them this way?

Please circle the abbreviations of the other labs you have done. ATM BBC BRA COM CO_2 GMA HAL HOL JOS LLS LIF MNO MOS MUO NLD NMR OPT RUT XRA	Overall quality of this experiment? 1 2 3 4 5 Poor Average Good

BUBBLE CHAMBER FILM ANALYSIS

Laboratory Staff Revision 3.4 January 1998

Part 1: K^- induced reactions.

I. References

1. D. Griffiths, *Introduction to Particle Physics*
2. D.H. Perkins, *Introduction to High Energy Physics,* 2nd edition (Addison-Wesley, 1982). Chapters 1,3 and parts of 6 are especially relevant.
3. W.T. Eadie, et al, Statistical Methods in Experimental Physics, (North-Holland 1971)
4. For K^-p total cross sections, CERN/HERA Report No. 70-6 (in Physics Library); R. L. Cool et al., Phy. Rev. Letters 16, 1228 (1966).
5. For general elementary particle data, *Review of Particle Properties*, Phys. Rev. D50, 1173 (1994) (in Physics 111 files).
6. For information on the experimental hardware, *Alvarez Group Scanning Training Memo,* available both on film and in book form in the Physics Library; Lawrence Radiation Laboratory publications 2A, *The Bevatron*, and 31, *The 72-in Bubble Chamber*. Note that both of these bubble chamber publications apply to the 72-in device, although you will probably be working with film from the 25-inch version which is of better quality.

II. Introduction

This experiment differs from others in Physics 111 in that your data have already been collected, in the form of photographs on 70 mm film, by one of the hydrogen bubble chambers operating at the Berkeley Bevatron in the 1960's. The film is a library of examples of real fundamental-particle physics events. The incident particles are K- mesons, the lowest-mass “strange” particle, with a momentum of 1.5GeV/c.

K^- mesons incident on hydrogen nuclei (protons) in this momentum range produce a rich spectrum of final states including both long-lived ($>10^{-10}$ sec) particles and short-lived "resonances" which are also called particles. Since the latter can be identified only by careful measurement of a large statistical sample, this laboratory instead concentrates on the long-lived final states, which can be identified by *scanning* rather than quantitative momentum measurement of the tracks. Scanning the film is the experimental work of this laboratory, and it produces immediate dramatic evidence of the underlying physics. Selection rules that require weak decays of strange final states —both mesons and nucleon-like baryons— cause long strange particle lifetimes. These correspond to observable short charged tracks, or short gaps due to neutrals followed by the "vee" from their two-body decay. Many particles or processes have a visual signature. For example, "knocked-on" electrons are revealed by their lazy spirals, while the decay sequence $\pi^+ \to \mu^+ \nu_\mu$; $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ has a bizarre series of connected track segments.

To proceed, you need an introduction to the elementary particles and the conservation laws that govern their interactions and decays. The mesons and baryons that you will see in this film in fact are composed of still more elementary quarks, while the lighter leptons like the electrons and muons are as elementary as the quarks, as far as we know.

Some conservation laws are as familiar as those of (angular) momentum and charge, while others involve totally new quantum numbers like strangeness and charm. Consult Tipler, Chapter 12 for a start.

You also need a working introduction to the principles of the bubble chamber and to the techniques of film scanning. An excellent source is the training manual that was used by scanners working on the 72-in chamber operated by the Alvarez group at LBL. However, you will do your experiment on film from the 25-in chamber, which is somewhat clearer and easier to scan, so please ignore the Alvarez training manual information that is specific to the larger chamber. You will not need the training for measuring, as opposed to scanning, since you will be doing only the latter, but this information will give you a clearer idea of what was really happening in the chamber. The physical parameters of the 25-in bubble chamber are given in the appendices to this write-up.

III. Experiment

1. Scan 250 frames of film, recording the roll and frame number for each event found. The detailed procedure of how to do this is given in **IV**. **Procedure** below. Organize how you are going to proceed, to minimize how often you need to back up and look for something you should have been recording. Each partner scans the same 250 frames by herself or himself. In the end you will compare your scanning efficiencies - see the last paragraph in **V. Error Analysis.**

2. As you proceed through the scan, sketch eight different kinds of events found; include the roll and the frame number on your sketch.

   These events should include the following types:

   a. $K^- \to \mu^- \bar{\nu}_\mu$
   b. $\pi^+ \to \mu^+ \nu_\mu$
   c. $K^- p \to \pi^+ \pi^- \Lambda^o; \quad \Lambda^o \to p\pi^-$
   d. $K^- p \to n\bar{K}^o; \quad \bar{K}^o \to \pi^+ \pi^-$

Count the number of *decays* in flight on these 250 frames, and measure the length of the track from the beginning of the fiducial region (see section **IV Procedure** for instructions on how to choose a fiducial region) to the decay vertex. Then determine the branching ratio of the "tau" (τ) mode of decay $K^- \to \pi^+ \pi^- \pi^-$

$$BR \equiv \frac{Rate(K^- \to \pi^+ \pi^- \pi^-)}{Rate(K^- \to all)}$$

Please note that "all" in the formula does not include *interactions* of K$^-$ with protons in the bubble chamber. Your analysis of the branching ratio should not include particles that have interacted in the chamber.

4. Count the number of $K^- p \to anything$ interactions. This includes $K^- p \to K^- p$, $K^- p \to strange\_particles$, etc. Also, as above, measure the length of the track from the beginning of the fiducial region to the interaction vertex.

IV. Procedure

Select a fiducial region within which you will accept good events. This should be defined by fixed marks visible in each frame and should allow for a big enough visible track area outside the region to guarantee that the incoming tracks are beam tracks. See figure 1 for a suggested fiducial region. Once you have selected this region, ignore events outside of it.

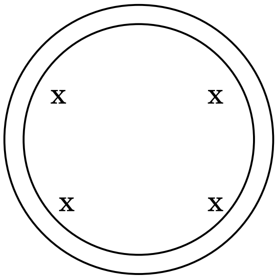


Figure 1: Use the four outermost x's as a fiducial region. This allows enough space for all beam tracks to enter the fiducial region.

Record all events found in the fiducial region. For this purpose an event is any beam track that does not traverse the fiducial region in a smooth arc. (Can you think of any reactions that would result in a final state that is different from the beam track only by a small kink or change in curvature?) Ignore any incoming beam tracks that are not parallel to the "standard," as these probably have scattered and lost energy upstream of the chamber. Record the frame number, rough location within the chamber, the length of the beam track within the fiducial region up to the event and the event type – "elastic interaction," interactions, decays in flight, and/or 3 prongs, "two prong," "four prong," "two prong with vee," etc. (Even or oddness of the prong count usually classifies the events into interactions or decays. Why?) [all decays are odd]

Every tenth frame, record the number of good beam tracks that enter the fiducial region. Since this information is to be used to obtain the total number of incoming tracks, you must also record the total number of frames scanned. Any biases that are introduced should be the same in the track count and the frame count. For example, if a particular frame cannot be scanned because of bad film, do not include it in the frame count or the track count.

A major source of systematic error is scanning inefficiency. To correct for such inefficiency, you and your partner will scan completely independently, keeping different lists.

V. Error Analysis

The errors in your results can be divided into two sources, systematic error and statistical (random) error. Both are important for this experiment.

Systematic Error: These errors are subject to the usual problem: if you knew exactly how big they were, you would correct for them and they would no longer be errors. Thus it is necessary to estimate. To stimulate your thinking, here is a non-inclusive list of possibilities:

In small-angle elastic scatters the recoil proton sometimes is invisible or hard to see. If it is missed, the event may be classified as a decay or overlooked entirely. (See problem #1 below)

Some K decays will be missed for decays occurring near zero degrees to the beam if the momentum change is small. (See problem #2 below)

If a Σ or Λ hyperon decays very early, its decay products will look like directly produced particles, usually π mesons. It will appear that the strangeness of the initial K^- is not conserved in its strong interaction!

Decays in flight remove K^- from the sample that could possibly interact, and vice versa. If your analysis does not take such effects into account (see discussion below), it will have introduced its own systematic error.

You probably do not have a uniform efficiency for finding all types of events. To determine your scanning efficiency from two independent scans that found N_1 and N_2 events, respectively, do the following. Partition the events into the set of events found by both scanners, or N_{12} ; the events found by scanner 1 but not by scanner 2 , or $N_1 - N_{12}$; etc. From these subtotals you can determine the efficiencies of each scanner and estimate the number of events missed by both. Also estimate the uncertainty in the efficiencies by using the article Exact Treatment of Search Statistics included in this writeup and include that uncertainty in your error analysis. .

Random Error: It may help to start with a few basic facts:

1. You could determine the random error in this experiment just by repeating it 10 times. For each quantity determined, you would take the square root of the sum of the squares of the differences of each measurement from its average value, and then divide by 3. But this is a lot of unnecessary work if you already know that the source of random error is just random counting. In this case the standard deviation is given by Poisson statistics to be $n^{1/2}$, where n is the average number of counts. It is usually good enough to approximate the average number of counts by the number actually observed. So if you observe 100 random counts, the random error on that observation is 10.

2. In the case of a result that is a function of several independent random counts, the usual laws of error propagation using partial derivatives apply. For example, if you measure $n_1 = 100$ and $n_2 = 100$ random counts, their ratio has a 14% random error.

3. If you take the ratio of two counts that are not statistically independent, point 2 does not apply. For example, if you toss a loaded coin and get $n_1 = 91$ heads out of $n_1+n_2 = 100$ throws, the random error on $\frac{n_1}{n_1+n_2}$ is $\sqrt{\frac{n_1 n_2}{(n_1+n_2)^3}}$, or about 3% rather than about 14%.

VI. Problems To Do

1. Think about an elastic scattering:

a. Consider the difficulty in observing and identifying a small angle of K^- p elastic scattering. See diagram. Determine the angle of deflection of the kaon below which the proton-recoil becomes invisibly small. To do this note that the bubble size is about 0.3 mm and that for recoil lengths greater than 1 cm you probably have a good scanning efficiency at all azimuth angles. To convert this to momentum, use the range-momentum graph which can be found in Review of Particle Properties (RPP).

b. We would like to correct the total cross section for events lost due to missed small angle elastic scattering. This differential cross section at small angles has been measured to be approximately $d\sigma/dt \cong 70$ mb/(GeV/c)^2 where t is the square of the invariant 4-momentum transfer. (See Perkins pg 167 or RPP pg S40 for a brief discussion of this Mandelstam variable)

At small angles $t = (p\theta)^2$. Decide at what angle your scattering efficiency drops below 50% and make an approximate correction to your cross section.

2. a. For a kaon of 1.5 GeV/c , calculate the maximum muon momentum from K_{u2} decay for a decay angle of zero degrees . It is simplest to show that the neutrino momentum in this case is $P_\nu = (m_k^2 - m_\mu^2) / 2(E_k + P_k)$ and proceed from there. Would this momentum change be sufficient to reveal the kaon decay despite the absence of a kink?

b. Since the kaon is spinless, its decay will be isotropic in the center of mass. The relationship between the lab angle θ and CM angle θ' is

$$\tan\theta = \frac{\sin\theta'}{\gamma_k (1 + \frac{\beta_k}{\beta_\mu}\cos\theta')} ,$$

which for our purposes can be approximated by θ=θ'/2 for small angles. Use your judgment as to the minimum lab decay angle at which good scanning efficiency can be realized. From this, estimate what fraction of kaon decays are missed as a result of invisibly small kinks. Remember that the solid angle subtended by a cone with opening angle α is 2π(1-cos(α/2)).

3. Starting from a differential equation expressing the attenuation of beams as a function of x due to decays and interactions, derive the following relation for the number of K$^-$ as a function of x :

$$N = N_o \exp(-x / \gamma\beta c\tau) \exp(-x N_A \sigma\rho / A) \qquad \text{(Eq. ✶)}.$$

Here $\gamma\beta = p/m$, N_A = Avogadro's number, A = atomic weight, and σ = total cross section.

4. Determine

a) the total cross section σ for the interaction of 1.5 GeV/c K$^-$ with protons and

b) the K$^-$ lifetime τ (or cτ).

To do this, obtain the average quantity, ΔN/Δx, for a) ΔN_I = total number of interactions and b) ΔN_D = total number of decays where Δx is the average K$^-$ path length within the fiducial volume. Relate this to dN/dx used to derive the equation in step 3 above (Eq. ✶).

5. Show that to a very good approximation, the effective number of K$^-$ averaged over the target length, to be employed in the above calculation, may conveniently be taken as $N = N_0 - \frac{\Delta N_I + \Delta N_D}{2}$. Explain how to arrive at this formula for N. (Hint: first calculate ΔN_D and ΔN_I as a function of flight distance. does you answer make sense inthe limit of very long flight distance?)

VII. Analysis and Questions

1. Compare the value for the K$^-$ mean life with the published value (from the Particle Data Table in the library). The published value is based on experiments with K$^+$ mesons at rest.

   (a) Why is it not feasible to measure the K$^-$ lifetime at rest ?

(b) What conclusions can you draw about the special theory of relativity?

(c) What conclusions can you draw about the relation between a particle and its corresponding antiparticle?

2. Compare the cross-section you have measured with published values at this beam momentum.

(a) Based on your measured cross-section and classical "geometrical" model in which a K^- sees a proton "effective radius," estimate that radius.

(b) The total cross-section as a function of beam momentum exhibits "bumps" that are attributed to the formation of a short-lived "resonance" particle. If we assume that the K meson and the proton were to combine to form a single resonant particle at the beam momentum for your data, what would be the rest mass of the resonance?

(c) What would the quantum numbers of the resonance be? Quantum numbers like leptons and baryon number and strangeness can be simply written down from conservation laws, but those such as spin, isospin, and parity in general can take on more than one value and can depend on the relationship between spin and statistics.

Part 2 Photon-Proton interactions.

I. References

1. D. H. Perkins, *Introduction to High Energy Physics*, 3rd edition, Addison-Wesley, 1987. Chapter 1, Section 2.1, 2.3-2.5, 4.1, 4.11-4.12, 5.1-5.6, Appendix A. Good coverage of basic concepts relevant to this experiment.
2. B. R. Martin and G. Shaw, *Particle Physics*, John Wiley & Sons, 1992. Chapter 1, 2, 3, Appendix A, B. Good coverage of basic concepts relevant to this experiment.
3. F. V. Murphy and D. E. Yount, *Photons as Hadrons*, Sci. Am. July, 94 (1971). An elementary discussion of the 'weird' behavior of photon that can be studied in this experiment.
4. T. H. Bauer et al., *The Hadronic properties of the Photon in High-Energy Interactions*, Rev. Mod. Phys. **50**, 261 (1978). An advanced review article.
5. J. C. Kent, *Charmed-Particle Photoproduction Cross Section at 20 GeV/c*, Ph.D. thesis, UC Berkeley (1983). Chapter 1, 2, 3. A detailed document containing valuable information of this experiment.
6. S. A. Wolbers, *Inclusive Photoproduction of Strange Baryons at 20 GeV*, Ph.D. thesis, UC Berkeley (1984). Chapter I, II A.1, II A.2a, III A.1-3, III B.1, VI A.1. It has discussions that are useful to this experiment.
7. J. D. Jackson, *Classical Electrodynamics*, 2nd edition, John Wiley & Sons, 1975. Section 15.2-15.5. Although the discussion is on bremsstrahlung, part of the formulation can be applied to pair-production.
8. J.E. Brau et al., *Photo Production Of Charmed Particles At 19.5 GeV*, Stanford 1981, Proceedings, The Strong Interactions, Stanford, CA (1981), p. 441. It has a good introduction to the BC 72/73 experiment.
9. K. Abe et al., *Lifetimes, Cross-sections And Production Mechanisms Of Charmed Particles Produced By 20 GeV Photons*, Phys.Rev **D33**: 1, 1985. This is an article summarizing some details of the charm production in this SLAC experiment.
10. W.T. Eadie, et al, *Statistical Methods in Experimental Physics*, North Holland, 1971.
11. David Griffiths, *Introduction to Particle Physics,*

II. Introduction

In the second part of the Bubble chamber laboratory, you will look at 70mm pictures taken with the 40" bubble chamber filled with liquid hydrogen at SLAC. Some parameters of the bubble chamber and the cameras are given at the end of this component of the write-up. The events stored on film come from the BC 72/73 experiment which ran in the summer of 1980 through spring of 1982. In this experiment, the incident particle is a photon beam. For energies less than 100 MeV, photons interact with matter primarily through quantum-electrodynamical processes. At higher energies, photoproduction can occur and the photon is considered as a hadronic particle. The description of this hadronic behavior of the photon is still an active subject in contemporary particle physics. Through an intricate method of detection, you will observe many different types of photon interaction with matter in this lab. All the scanning techniques you learned in the first bubble chamber experiment will be applicable to this experiment.

III. Experimental Procedure

1. Follow the loading procedure as described in Appendix D.
2. Define and record the fiducial region for your scanning of good events.
3. You will need to scan at least 500 events (a few of them will have nothing in the picture) in order to accumulate enough statistics for further data analysis.
4 For each picture, record the frame number and the event type: electromagnetic process or photoproduction (do you remember how to distinguish the two?). If you have a photoproduction, record the number of prongs, examine the event carefully to see whether there is any decay (for example, a 'Vee' downstream of the interaction point) associated with the interaction. If you are lucky enough, you may run into a charmed particle decay!

Sketch

- a gamma-electron collision;
- a low energy pair production;
- an electromagnetic shower;
- a photoproduction event with three prongs;
- a photoproduction event with five prongs;
- a photoproduction event with seven prongs;
- all photoproduction events with a 2-prong decay involved;
- any photoproduction of charmed particle (explain why you think so).

IV. Problems

1. Quantitatively derive the incident energy of the photon beam at the bubble chamber. The high energy photons are prepared by scattering a photon of a few eV from a 20 GeV electron. Read the reference material provided, especially the extracts from the Ph.D. theses. Is it possible for pair-production to occur in a vacuum?

2. Using the Uncertainty Principle, estimate the size of an object that a photon can probe for photon energies of
   (a) 2 eV,
   (b) 20 MeV, and
   (c) 20 GeV.

   Then discuss why we need to use different models to describe the photon interaction with matter at different energy regime.

3. From your scan, estimate the production cross section of strange particles in 20 GeV photon-proton reaction. Is your result reasonable?

4. a) Look up the total interaction cross sections for γ_p and γ_d. Estimate $\sigma_{\gamma n}$ and compare to $\sigma_{\gamma p}$. Is your result surprising in view of the lack of charge of the neutron?

   b) Look up the total interaction cross sections for γ_p and $\pi^{\pm}p$ collisions at high momenta (E/c > 10GeV) (e.g. Phys. Rev. D 45, III 86-89 (1992)). Estimate $\sigma_{\pi\pm p}/\sigma_{\gamma p}$. Qualitatively explain your result in terms of the expected amplitude of the hadronic component of the photon (Bauer et al, Rev. Mod. Phys. 50, 261 (1978) p. 274)

5. Discuss the feasibility of distinguishing $\gamma\rightarrow\mu^+\mu^-$ or $\gamma\rightarrow\tau^+\tau^-$ from $\gamma\rightarrow e^+e^-$. Estimate the relative cross sections.

SLAC Bubble Chamber Information

The primary detector of the BC 72/73 experiment was a 40-inch diameter bubble chamber filled with liquid hydrogen. The bubble chamber was operated at a temperature of 29° k, 3 degrees warmer than normal in order to obtain a higher linear-density of bubbles (60/cm) and a smaller size bubble (55 microns). It was immersed in a 2.6 tesla magnetic field which was parallel to the bubble chamber cylinder axis. The expansion of the chamber occurred at a frequency between 10 and 12 Hz, which was matched to the repetition rate of the laser beam.

The optics included three stereoscopic cameras, each with an f/22 125mm lens, which took three of the four pictures taken at each trigger signal. The fourth was taken by a high resolution optics camera (HRO), with a single lens of focal length 360 or 610mm. These large focal lengths provided the spatial resolution needed for the study of charm decays. A down-stream trigger in a secondary detector activated the cameras.

V. Appendices

Appendix A

Training Film

The first part of the roll is a training film used by beginning scanners employed at Lawrence Berkeley Laboratory and elsewhere. Spend the first few hours reading through the film. (You can check out the same material in book form and read it over in advance, in order to use your lab time efficiently.)

You will have neither the time nor the inclination to look at all 451 frames. Some of the material is meant for professional scanners and is unnecessary for the purposes of this experiment. You may skip:

II(c). Scanning Technique, frames 10-57.
IV. Analyzing Bubble Chamber Interactions, Part II, frames 73-151.
V(b) through V(g). Sample Events (other than K^-p), frames 192-451.

You should examine:

- Introduction sections, frames 2-9.
- A Brief (and dated) Summary of Particle Physics, frames 58-72.
- Some sample events like the ones you later will scan: K^-p Interactions, frames 152-191. In this section View 1 will describe the event, View 3 will show the actual film, and View 2 can be superimposed on View 3 to help find and identify the tracks of interest.

Appendix B

Experimental Film

You will be using film from the 25" bubble chamber at the Bevatron, as it is clearer than film from the 72" chamber. Vital data about this film:

- Beam: K^- mesons with momentum 1.5 GeV/c.
- Chamber: 25" Bubble Chamber (data collected in 1968).
- Chamber fluid: liquid hydrogen, density approximately 0.06 gm/cm^3. The exact density may be determined from the film itself. The range of a positive muon arising from the decay of a π^+ at rest is 0.0646 gm/cm^2, or approximately 1 cm on the film. Measurement (in three dimensions!) of the track length (in real space, not on the table!) of such muons fixes the hydrogen density.

- Magnet field (inferred by Physics 111 students' measurements of the beam track curvature): 1.667 Tesla.

Appendix C

25-inch Bubble Chamber Optics

Despite its smaller size this device was designed to compete with the larger chambers at Berkeley, Brookhaven and CERN by virtue of its "precision" optics and uniform dark field illumination.

The chamber had two precision windows. The cameras were located on 3 corners of a 19.62-inch square and looked at the chamber through a 4.62-inch thick flat glass window (n=1.59), Fig. C-1. The far window was a spherical lens that focused the single flash tube, located on the side opposite to the cameras, on a spot between the cameras. To optimize the illumination it was necessary to put the convex surface of the far window inside the chamber. This makes it more difficult to determine whether a track exits in the chamber through the far window.

Figure C-2 shows a sketch of a typical event including the prominent features of the chamber. There are three sets of fiducials on the hydrogen (inside) surface of the near (plane) window. One is in the center, four are on a 12.00-inch square (Fig. C-3), and four more are on a 9.90-inch square rotated 45^o from the first (Fig. C-3). There are five fiducials on the convex surface of the far window, one in the center and four on a 13.10-inch square (Fig. C-4). Finally, there are 2 fiducials on tabs fixed to the side of the chamber near the beam entrance window in a plane containing the center of the chamber. Their separation (9.75 inches) determines the magnification in the beam plane and thereby calibrates the fiducial volume.

Appendix D

Operation of the Film Scanning Machine SP-V(A)

- Turn the machine on. Make sure the main AC power circuit breaker located on the wall in (the bubble chamber) Room 238 LeConte is on (up).
- Go to the back of the SP-V(A). Located the 3 pole black circuit breaker(bottom center below the printed circuit cards) and turn it on.
- Push the button marked START located on the top right corner of the lower left back panel (next to the printed circuit card panel).
- On the same panel the three lower lights marked (-30v) (+6V) (-24V) should all be lit. If not, recheck your execution of the above instructions. If any of the lights still refuses to go on, get help.
- Now return from the back of the SP-V(A) and sit at the end of its table where the controls are located. The panel at the right (as Fig. D-1) has the projection lamp and speed/direction controls for the film. Push in the #4 button while leaving all others out.
- Check the identity of the film already on the SPV(A). It is probably the data film (25-inch chamber).
- If necessary, load the film using the film path sketched in Fig. D-2. When loading film, the FILM LOAD switch located to the left of the operator should be up. When scanning film, the switch should be down.
- Locate the FILM POSITION OVERLAY controls to the left of the operator. The x and y coordinates are controlled by three large knobs (x) and three small concentric knobs (y). From right to left, the first set of knobs controls the grid (which we do not use), the second controls View 1, and the third controls View 3. View 2 is fixed. These controls may be used to fine tune the superposition of the three views on the scan table.
- Locate the large "lever arm" to the left of the operator. It moves all three views in concert along the axis of the table. This is useful, for example, when the film is positioned so that the frame number is immediately in front of the operator but the actual picture is further away. In this case, push the lever down and then slide it all the way toward you.
- With the correct film loaded and the above controls identified, use the levers to the operator's right to put the View 3 lamp only in the "hold on" position. Then move the film slow forward to find the frame number (example: 0007). Caution: the SPV(A) has no mechanism for detecting the end of film! If you advance the film too far it will come unloaded!
- With View 3 on the table, direct your attention to the frame number on the right-hand side of the film (ignore other numbers). Use the slow forward/backward controls to position that number close to the operator. If you are using the 72-inch training film, no further movement along the long table axis will be necessary. However, if you are scanning the 25-inch data film, it will now be necessary to use the "lever arm" described above to move the center picture (of the three pictures visible on the table) close to the operator. The other pictures do not correspond to this frame number and should be disregarded.

- You are now ready to start scanning the film. From this position you can now overlay Views 1,2, and 3 in any combination. Remember that the frame number is correct only in View 3, and that (on 25-inch film) the center picture of the three pictures visible together with the frame number is the viewing picture.

- To turn off the SP-V(A), just stop the film and turn off the circuit breaker on the back of the unit.

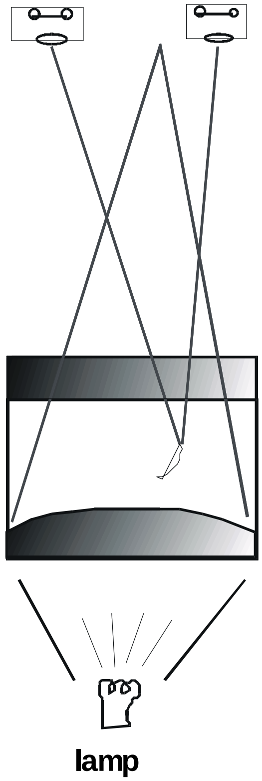
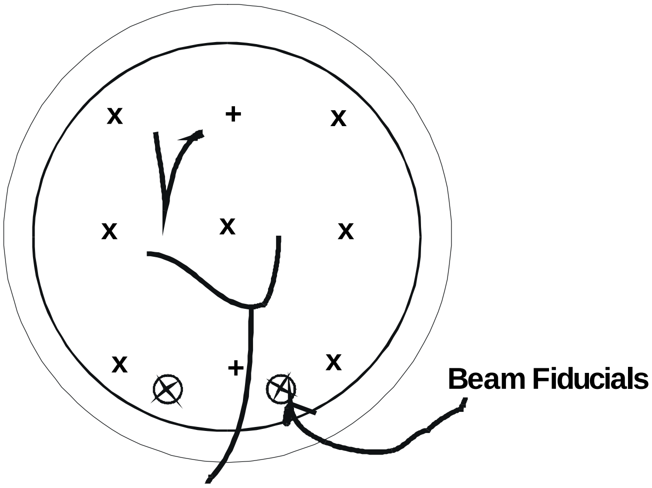


Fig. C-1



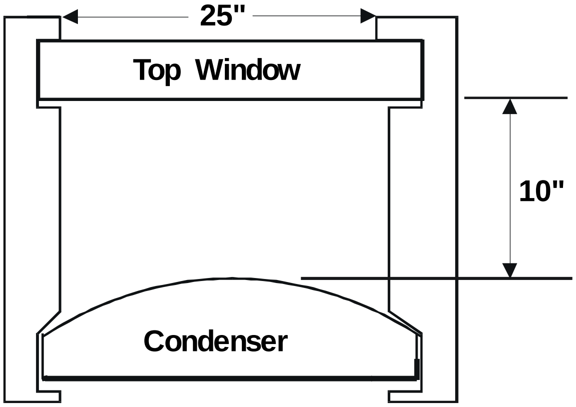


Fig. C-2

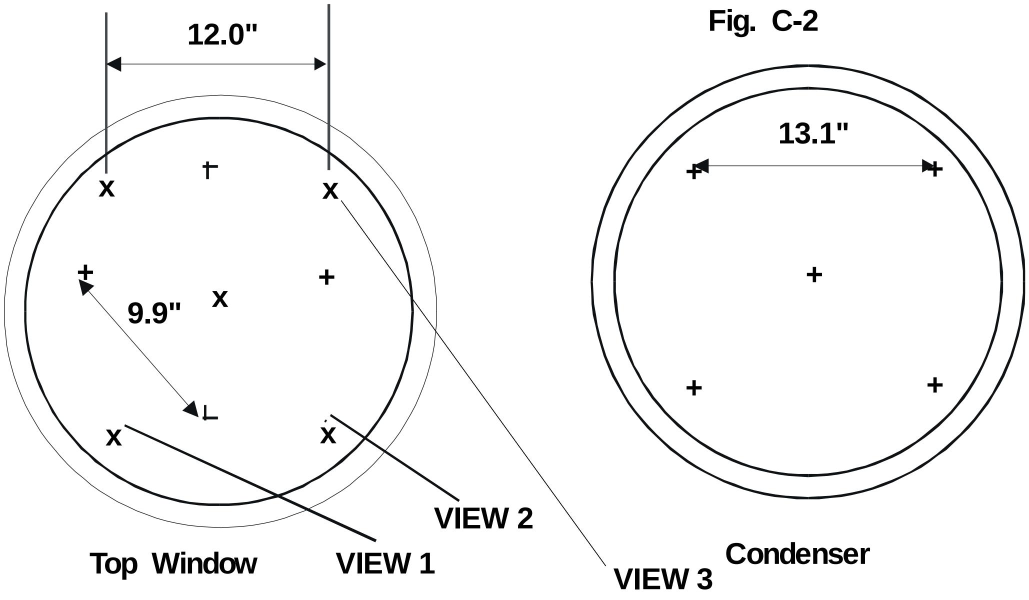
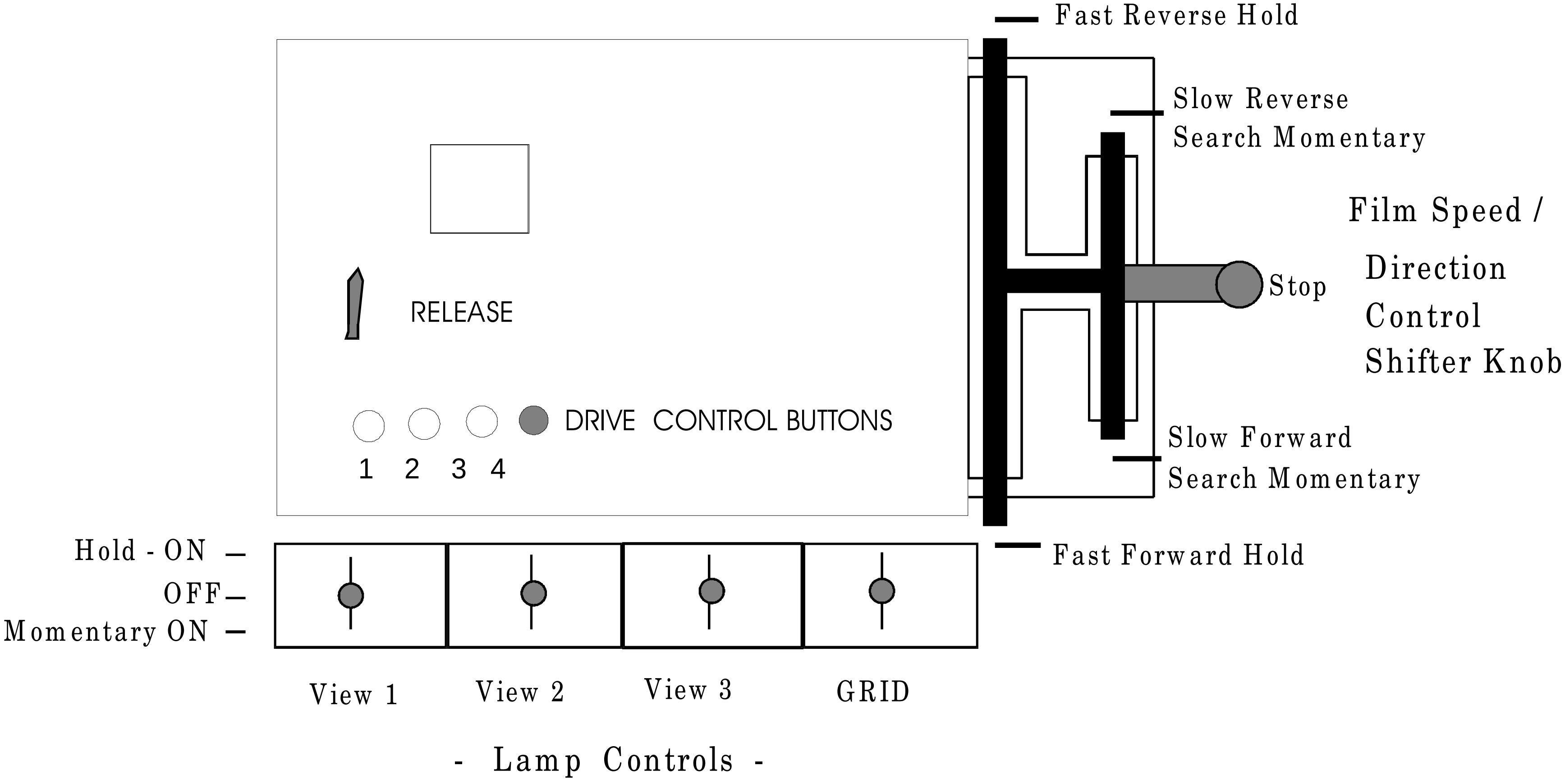


Fig. C-3

LOCATION OF "3"
CAMERA VIEWS

Fig C-4



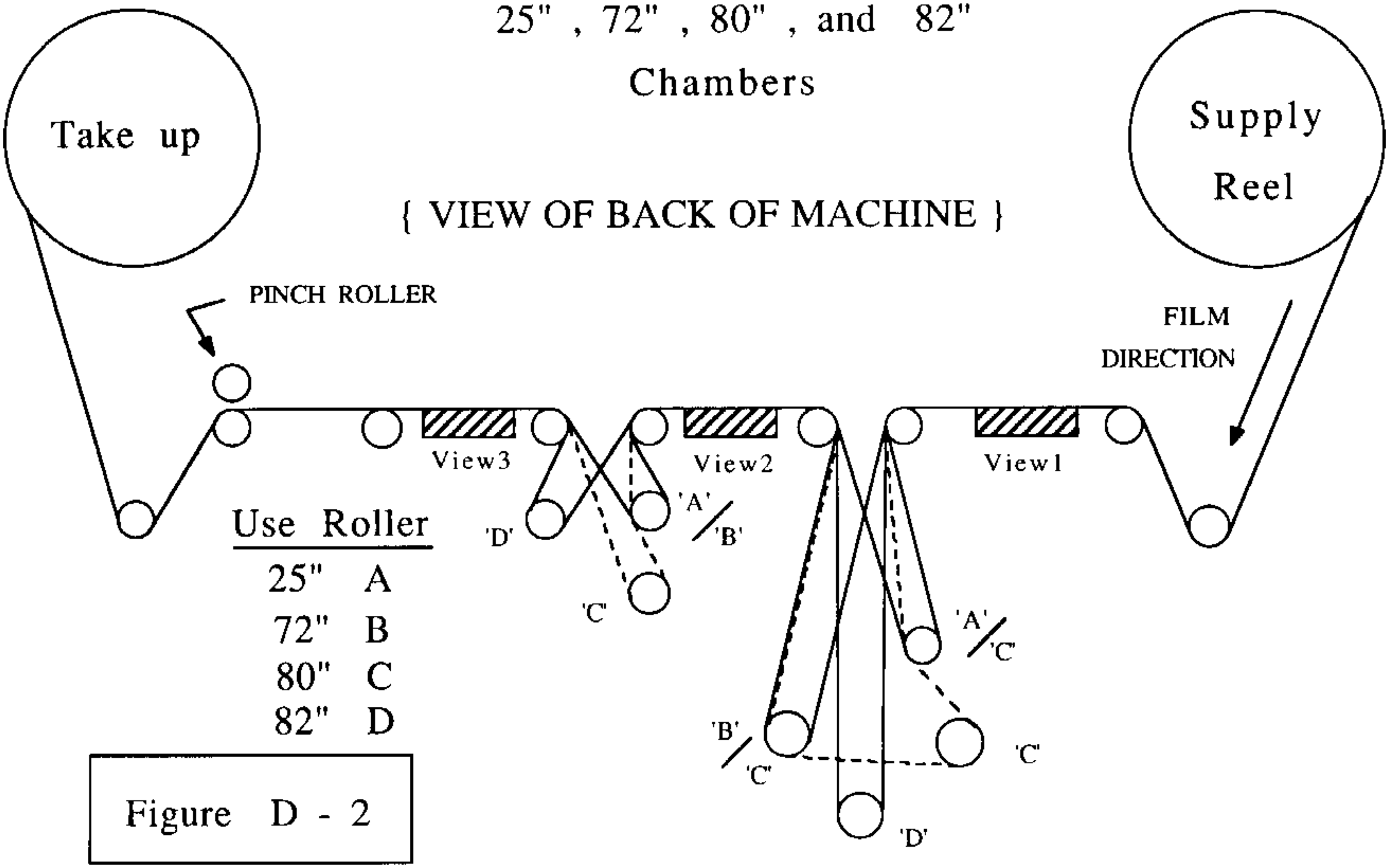
SP-VA OPERATOR FILM CONTROLS

Figure D-1

FILM LOADING

SP-VA (Machine #1)

46 mm Single Reel Setup
25" , 72" , 80" , and 82"
Chambers



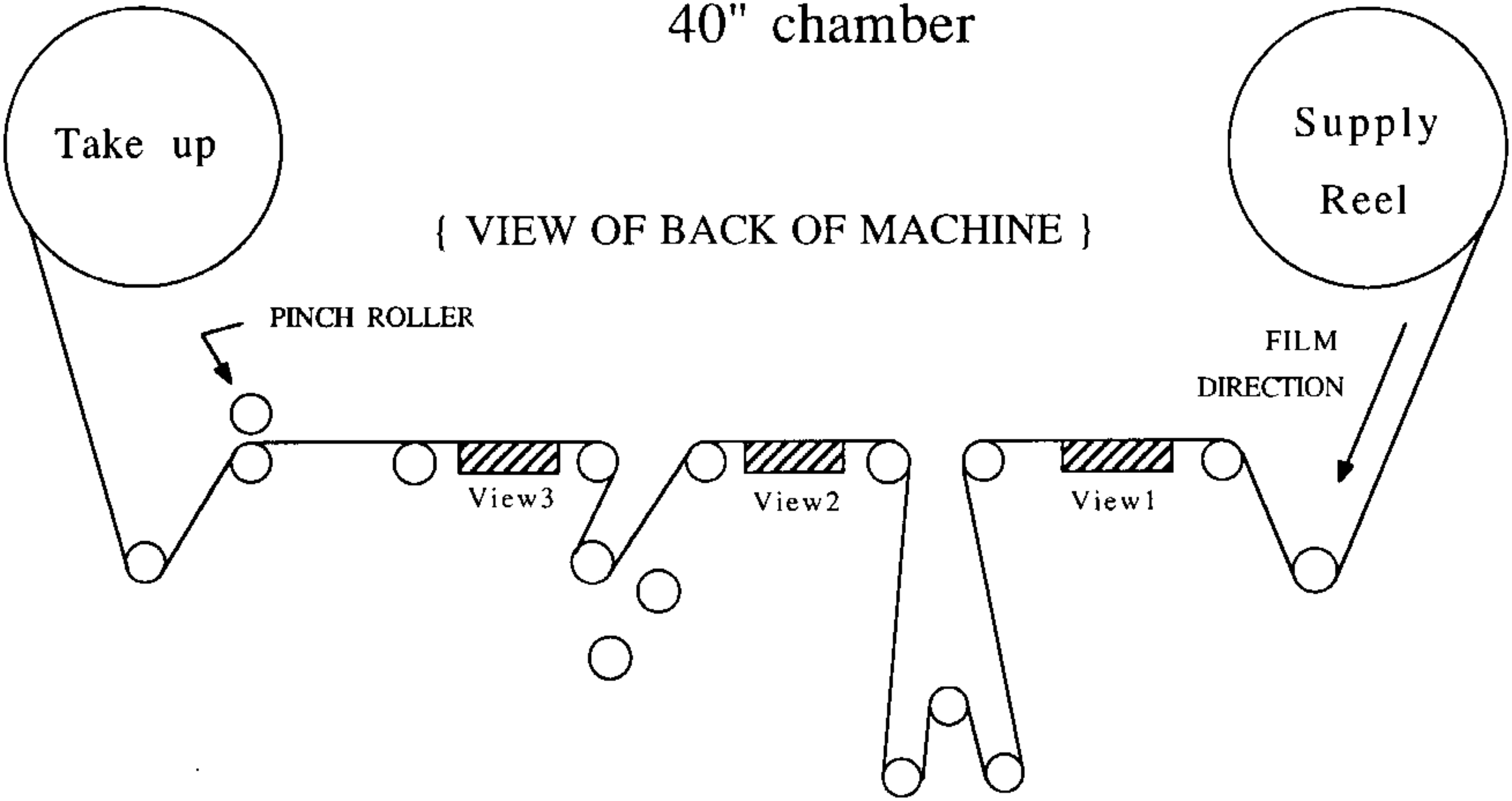
Use Roller	
25"	A
72"	B
80"	C
82"	D

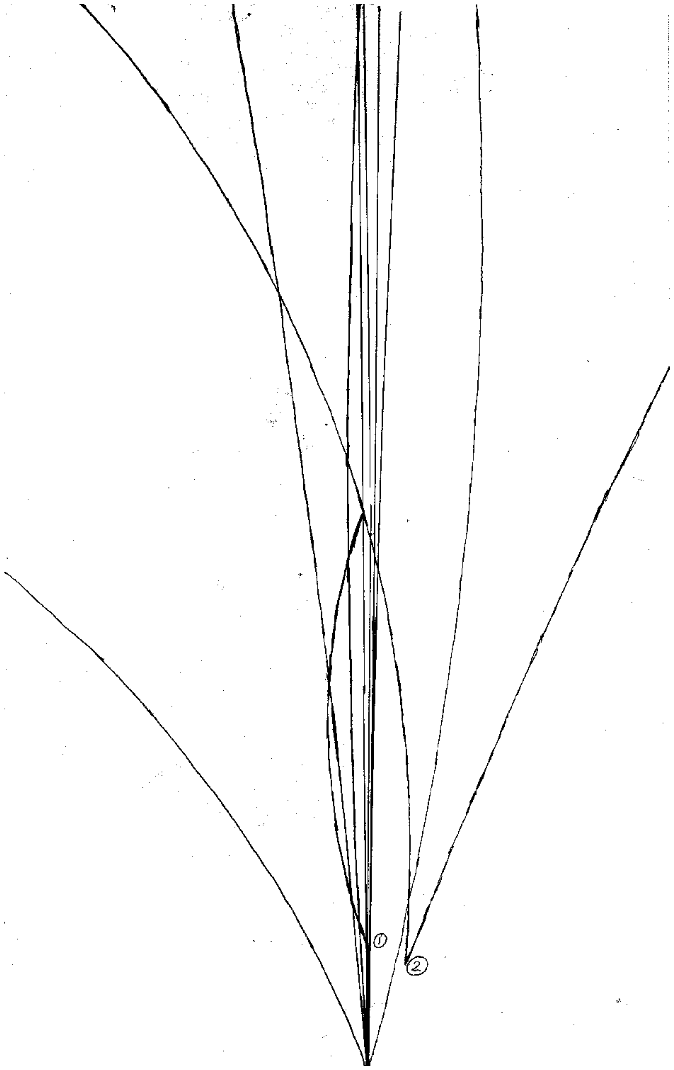
Figure D - 2

FILM LOADING

SP-ⅤA (machine #2)

70mm single film loading
40" chamber



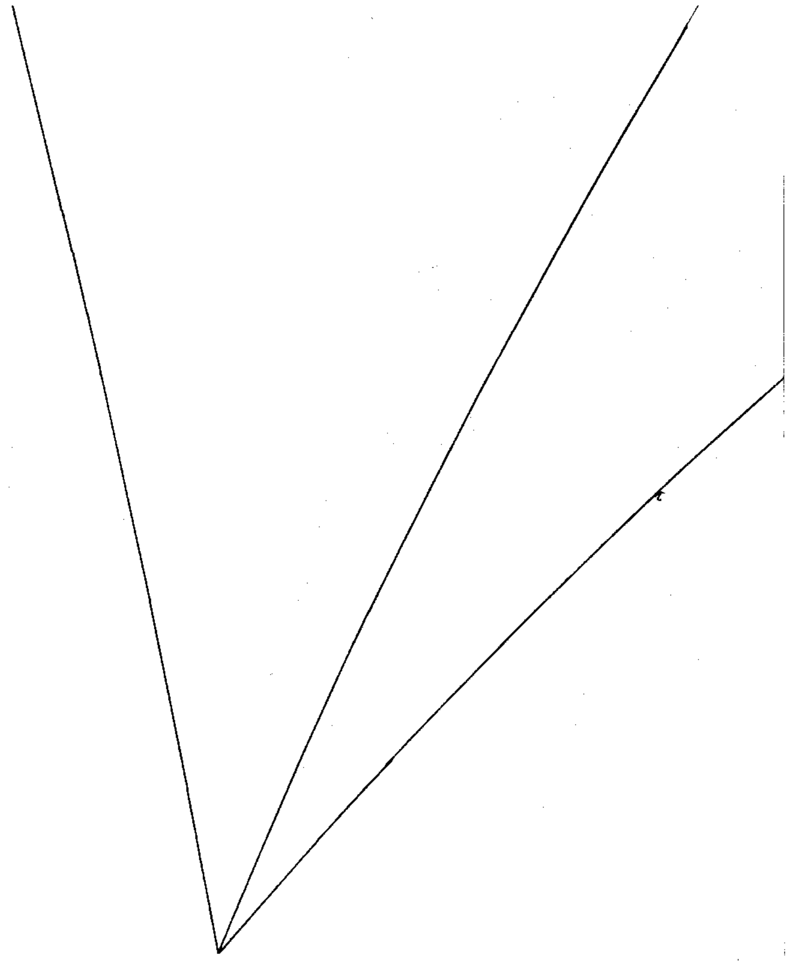


Example of a γp interaction giving 9 prongs.
One decayed at ①.
A neutral strange particle decayed at ②.

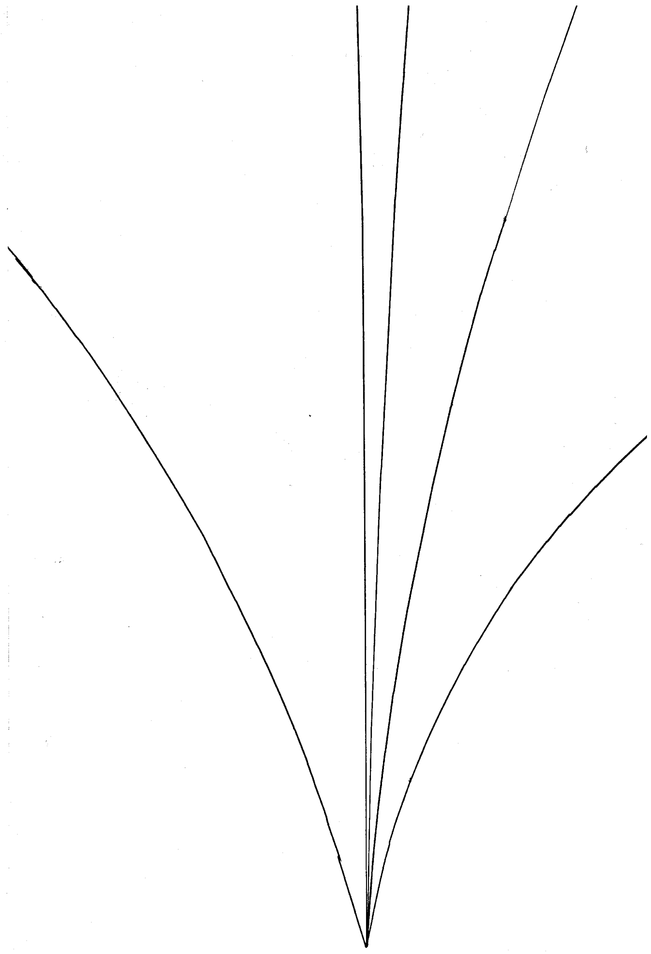
γp→ 7 prongs with

$p + p \rightarrow p + p$ at ①

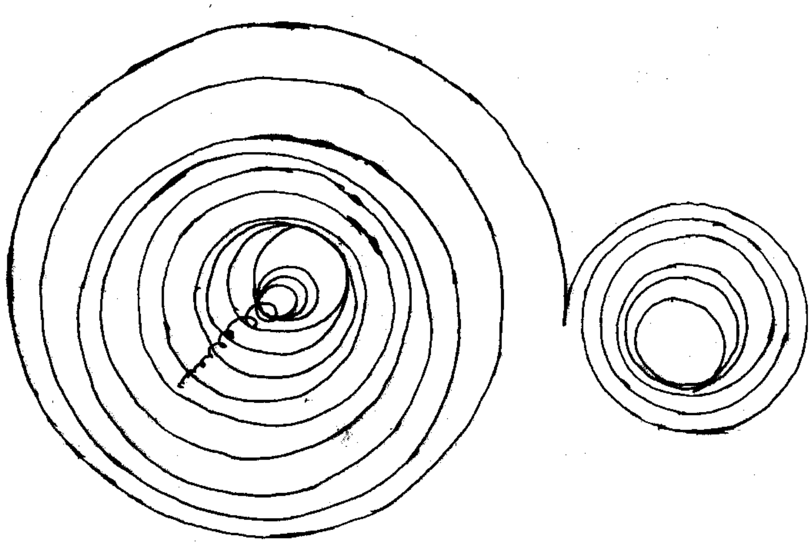
and $\pi^+ + p \rightarrow \pi^+ + p$ at ②



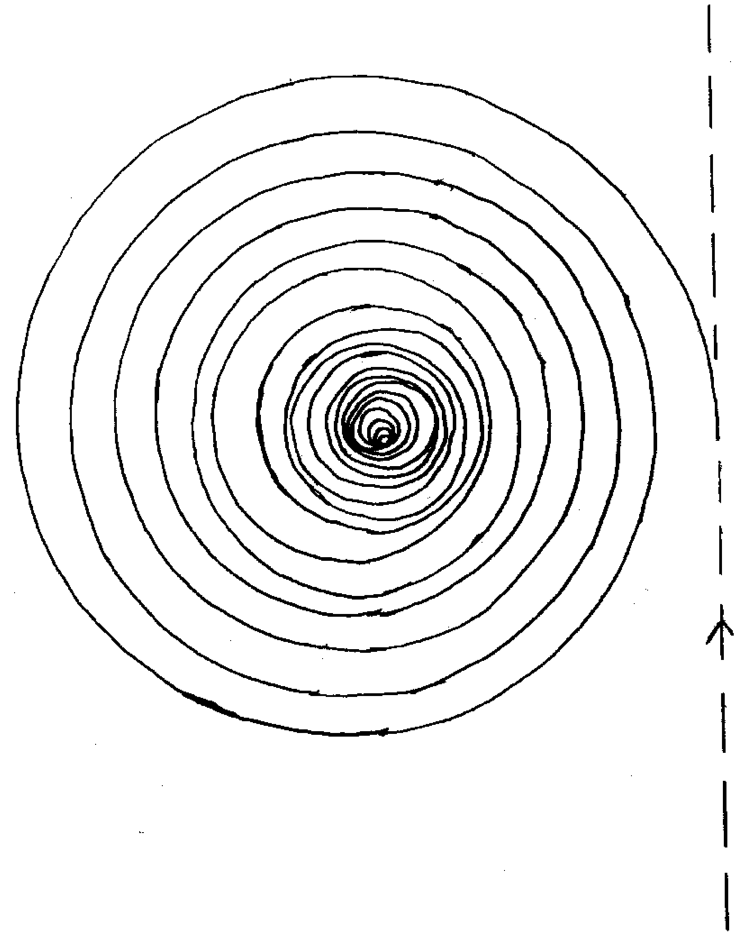
$\gamma\, p \rightarrow p\, \pi^+ \pi^-$



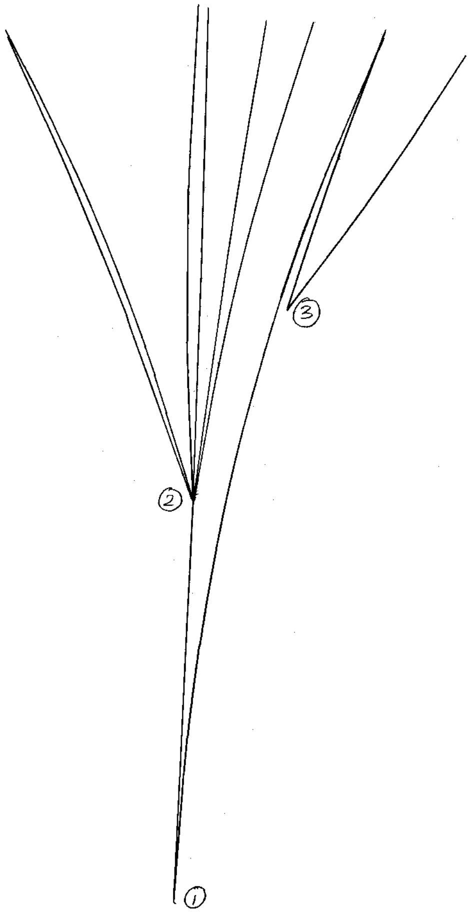
$\gamma\, p \rightarrow$ 5 prongs



$\gamma \rightarrow e^{+}\, e^{-}$



$\gamma\, e^{-} \rightarrow \gamma\, e^{-}$



① $\gamma \rightarrow e^{+} e^{-}$

② $e^{-} p \rightarrow 6\ prongs + 1\ neutral$

③ neutral particle decays into 2 daughters