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**PSEUDO CLOUD-CHAMBER TRACKS
AND THEIR USES**

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Abstract

Pseudo cloud-chamber tracks are artificial tracks superimposed by double exposure on otherwise normal photographs of real cloud-chamber tracks. We originally developed the pseudo tracks as a means of training our scanners to look for low-density (quark) tracks; since then, many other uses have arisen. Such uses include 1) checking the model we use in generating the pseudo tracks, 2) investigating the effects of using different gases

in the model, 3) training our scanners to hand-count tracks under a microscope, 4) normalizing the hand-counted data, 5) keeping the scanners alert by using the pseudo tracks as "carrots," 6) determining how efficient our scanners are in finding quark tracks (and in the process proving that we can find such tracks), 7) analyzing our automatic scanning system, and 8) studying the feasibility of new approaches to the search for quarks.

Introduction

The quark is a theoretical subatomic particle that has enabled physicists to construct a mathematical model explaining the existence of many other subatomic particles.¹ In the model, quarks have either positive or negative charges that are either one-third or two-thirds the charge of an electron (i. e., quarks have charges of $\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$). Ever since Gell-Mann proposed the quark in 1964,² experimentalists have been searching for it without success.^{3,4} A possible exception is McCusker and Cairns^{5,6}; it was their report that triggered the quark hunt here at the Lawrence Livermore Laboratory.

The tool we are using in our search is the Wilson cloud chamber.⁷ A charged particle passing through the gas-filled chamber at a high velocity strips electrons from the gas atoms in or near its path,

Water vapor then collects on the now-ionized gas atoms, forming a visible trail of droplets. The density of this track (i. e., the number of droplets per centimeter) is a function of the speeding particle's charge. The more highly charged the particle is, the more droplets it creates per centimeter. In comparison with a particle having a charge of $1e$ or more, the quark, being a fractionally charged particle ($\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$), creates fewer droplets per centimeter ($1/9$ and $4/9$ as many, respectively). In our cloud chamber, this is equivalent to 7 droplets/cm for the $1/9$ track and 29 droplets/cm for the $4/9$ track.

Since quark tracks occur infrequently (1 out of 10,000 tracks according to McCusker and Cairns, less than 1 out of 500,000 tracks according to our work), and since we had little idea of what a quark track looks like in a cloud

chamber, our search was like hunting for a needle in a haystack without knowing what the needle looked like. This re-

port describes our development of the needle (artificial, or pseudo, cloud-chamber tracks).

Development of the Pseudo Tracks

Pseudo cloud-chamber tracks are superimposed by double exposure on otherwise normal photographs of real cloud-chamber tracks. To ensure that pseudo tracks have the same appearance as normal tracks, we have examined many aspects of pseudo tracks. Such aspects include droplet size and brightness, tracks appearing to be outside the cloud chamber (i. e., stereoscopic reconstruction), tracks appearing to go in and out of illuminated regions, characteristics of "blobs" in the tracks, apparent age of the tracks, turbulence and temperature gradients in the cloud chamber, placement of the tracks in the chamber, and double-exposure techniques for superimposing the tracks.

DROPLET SIZE AND BRIGHTNESS

The size of the droplets in the pseudo tracks was measured with a microscope (see Fig. 1), and the brightness of the droplets was measured with a densitometer. The size and brightness were adjusted by means of light diffusers, neutral-density filters, and different camera apertures. In addition, the size of the droplets in normal tracks was compared with the size of the droplets in the pseudo tracks via a programmable film reader (see Fig. 2). The size of the pseudo droplets was within 10% of the size of normal droplets, and the exposure of the pseudo droplets on the camera film was correct to within 25%.

Fig. 1. Comparison of the droplet sizes in normal and pseudo tracks under a microscope (35X). The late cosmic-ray track did not have time to separate and diffuse before the cloud chamber became sensitive. (Compare this figure with Fig. 5.)

TRACKS APPEARING TO BE OUTSIDE THE CHAMBER

The fact that some pseudo tracks appeared to be outside the cloud chamber was not a problem at first, for the scanners did not notice this. With training and experience, however, the scanners saw that the pseudo tracks appeared to move too much across the top glass of the cloud

Cosmic-ray track

HH613 TRACK 113

08 0223 0435 *2 02

719 DROPS READ IN, 1333 CREATED IN 18.79 CM, GIVING 70.95 DROPS/CM.
LFLV = 18.80

LAS VEGAS MODE
5.23 MICRONS

38 OF 38 SECTIONS USED IN PARABOLA FIT
RMS θ IS 0.0593 CM FIT θ IS 0.4586 CM
BLOB TEST OF 40 / 0.20 CM EXTENDED TO 0.25 CM
RMS θ IS 0.0467 CM FIT θ IS 0.0511 CM
RMS θ IS 1.59/CM FIT θ IS 0.19/CM
784 GOOD DROPS (49.1 % SINGLES)
IN 14.56 CM GIVES 53.85/CM
(SUBTRACT B_{avg} AND GET 52.96 /CM)
AVERAGE OF 15 GROUPS IS 53.9 $\pm$ 13.9
WITHOUT GROUP 13 WE GET 51.9 $\pm$ 12.1

Pseudo track

HH613 TRACK 90

40 0000 0000 *0 01

223 DROPS READ IN, 389 CREATED IN 4.82 CM, GIVING 80.68 DROPS/CM.
LFLV = 4.82

LAS VEGAS MODE
5.22 MICRONS

10 OF 10 SECTIONS USED IN PARABOLA FIT
RMS θ IS 0.0634 CM FIT θ IS 0.0691 CM
BLOB TEST OF 43 / 0.20 CM EXTENDED TO 0.35 CM
RMS θ IS 0.0613 CM FIT θ IS 0.0721 CM
RMS θ IS 0.46/CM FIT θ IS -1.01/CM
338 GOOD DROPS (46.7 % SINGLES)
IN 4.45 CM GIVES 76.03/CM
(SUBTRACT B_{avg} AND GET 76.03 /CM)
AVERAGE OF 4 GROUPS IS 78.2 $\pm$ 17.1
WITHOUT GROUP 3 WE GET 85.3 $\pm$ 13.8

Fig. 2. Computer-calculated comparison of a normal track with a pseudo track. The upper graph for each track shows the droplet sizes, and the lower graphs show the track widths. (Compare this figure with Fig. 11.)

chamber from one half of a stereoscopic view to the other. Therefore, when the scanners were not sure whether a track was real, they would note the apparent movement across the top glass and thereby determine if it were a pseudo track. This is one of the reasons why some of the higher density pseudo tracks (53 to 65 droplets/cm) were found, realized to be abnormal, and labeled pseudo tracks. Another reason was that some pseudo tracks were exposed in only one half of a stereoscopic view. The apparent mis-

location of the pseudo tracks is not a problem with the low-density tracks because the scanner has to find the tracks first, and it is the ability to discover the track that is important to the quark search.

To correct the apparent mislocation, the mirrors on the refocus lenses were turned slightly inward, moving the images of the pseudo tracks on the film. The tracks then appeared to be inside the cloud chamber. Out of a sample of 35 tracks, 70% appeared to be inside the chamber.

TRACKS APPEARING TO GO IN AND OUT OF FOCUS AND IN AND OUT OF REGIONS OF GOOD ILLUMINATION

Attached to the cloud chamber were four 35-mm Nikon F^{*} cameras⁸ whose apertures were set at $f/16$, giving a depth of field of 3 in. The cameras were set to focus at the center of the cylindrical chamber, which is 8 in. deep and has good illumination up to 1.5 in. on either side of the center.

The tracks coming into the chamber crossed the region of good illumination and good focus as well as the region of poor illumination and poor focus around the good region. This changed the appearance of the droplets. It was this appearance that had to be correct for a pseudo track that was simulating a track slanting through these regions. This was accomplished by placing neutral-density (ND) filters over the ends of the pseudo tracks. These filters are typically graded 0.1ND, 0.2ND, 0.3ND, and 0.4ND. A 0.3ND filter, for example, reduces the light by a factor of 2. The filters gave the pseudo tracks the appearance of going out of the region of good illumination and focus. The filters were also an excellent guide in determining the correct exposure of each track.

To simulate the steepness of real tracks in the chamber, the pseudo tracks were shortened or lengthened and the proper grades and lengths of ND filters were placed over the ends of the tracks.

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Atomic Energy Commission to the exclusion of other products that may also be suitable.

In the course of adding the pseudo tracks to the chamber, we noted that when one or more of the lights became weak, the ND filters had to be changed to ensure the correct exposure of the pseudo tracks.

BLOB CHARACTERISTICS

A 65-droplet/cm track was generated by a computer using the Rutherford cross section for the size and frequency of "blobs."^{4,9,10} (When a track has more than 30 droplets in a length of 0.25 cm, the result is termed a blob.) The computer produced individual droplets and variously sized blobs with the aid of a mathematical model of the diffusion process. The track was then superimposed on photographs of cosmic-ray tracks in several different cloud chambers to investigate the "blobbiness" of the pseudo track in comparison with that of the cosmic-ray tracks. For cosmic-ray tracks in nitrogen-filled chambers, there are about 3 blobs in a 20-cm track. In the 65-droplet/cm pseudo track, there were 5 blobs (see Fig. 3). Thus, the model appeared to be too blobby and was therefore made less so. In the new model, the production of single ions is four times as probable as it was in the old model, so the number of blobs is decreased by a factor of about 2. Because of statistical fluctuations in the model, the portions of the computer-generated tracks that are used to make the double exposures are still being selected according to their blobbiness (i. e., sections that are too blobby are not used, for such tracks would be easy to find).

At first, the pseudo tracks were made so that the blobs in the positive and

Fig. 3. Histograms comparing the blobbiness of computer-generated pseudo tracks with the blobbiness of cosmic-ray tracks in nitrogen. The effect of the old and new models for generating pseudo tracks is also shown. The 1/9 and 4/9 histograms are derived from the 9/9 histograms based on 100 tracks. The asterisks indicate how the number of blobs in the 65-droplet/cm pseudo track compare with the number of blobs in the real and the 9/9 pseudo tracks.

negative columns of the tracks were horizontally separated from each other. In photographs of real tracks, we noted that this is true only of tracks that come into the cloud chamber vertically, for the separating field in our chamber is horizontal. The model now being used has the blobs displaced as if they were in a track coming in at 20 deg from the vertical. This is a good enough model for tracks coming in at 10 to 30 deg from the vertical (see Fig. 4).

APPARENT TRACK AGE

The age of a cosmic-ray track can be measured in two ways: 1) by determining the width of the positive and/or negative columns, which is the result of a diffusion

process and is proportional to the square root of the time, and 2) by determining the separation between the two columns, which is the result of the ion mobilities in the separating field. Because the latter method is proportional to time, it is the most accurate measurement of age. Both factors had to be correct for the pseudo tracks, and they were changed until the correct relationship was obtained.

A comparison of the widths of the positive columns of a standard track and a pseudo track showed that the pseudo track was narrower than the standard track (see Fig. 2). Two things have been done to correct this: 1) Boot valves have been installed in the chambers to decrease the expansion times and thereby decrease the width of real tracks, and 2) the code for

generating pseudo tracks has been changed to increase the width of pseudo tracks by 17% (see Fig. 11).

Fig. 4. Histograms showing the space-versus-angle distribution of extensive air showers¹⁰ having densities of more than about 20 m^{-2} at sea level, based on 350 showers observed by Bassi, Clark and Rossi.^{11,12} The solid curve shows the variation with altitude of the number of showers having densities of more than about 50 m^{-2} . The dashed curve shows the number of showers versus the solid angle in our experiments. We used the latter curve as a guide for determining at what angle pseudo tracks should be added to cloud-chamber photographs.

TURBULENCE AND TEMPERATURE GRADIENTS IN THE CLOUD CHAMBER

Because of turbulence inside the cloud chamber, the tracks are not absolutely straight. This is especially true near the edges of the chamber. The pseudo tracks were therefore given a large radius of curvature (128 in.). The tracks were also placed in such a way that they would fade out before they got into the most turbulent regions.

Cloud chambers also have temperature gradients in which the tops of the chambers

are warmer and the vapor is less saturated. Thus, the negative columns in these regions are less developed (i. e., they have fewer droplets per centimeter) than the positive columns, which still have 100% of the ions developing droplets. The pseudo tracks were made with the negative columns 35% developed at the upper end and gradually increasing to 65% developed at the lower end over a 20-cm length of track. The portions of the track to be used were then selected according to 1) the temperature gradient, and 2) the apparent position of the pseudo track in the chamber (top or bottom).

PLACEMENT OF THE TRACKS IN THE CLOUD CHAMBER

In placing the pseudo tracks in the cloud chamber, many things had to be taken into account: 1) the kind of gas—only N_2 was used for the sake of scanner efficiency, 2) the lighting problems in the chamber—different ND filters were used to ensure the correct exposure, 3) the temperature gradient in the chamber—this determined how high or low a track could be placed in the chamber, and 4) the camera geometry—this determined the limits of the placement that would still show in both cameras. About 5% of the tracks were placed to represent tracks coming in on the edge of the field of view (i. e., showing in only one of the two stereoscopic views).

The pseudo tracks were placed in the chamber with both controlled and random methods. The controlled method allowed us to achieve the proper angular relationship with respect to the triggered shower.^{9,11} This was accomplished by first taking a Polaroid picture of the triggered shower,

then placing the pseudo track in the chamber at the same angle as the shower tracks. In the random method, the pseudo tracks were placed in the chamber without knowing the angle at which the shower tracks had come into the chamber. With this method, about 40% of the pseudo tracks had about the same angle as the shower tracks. The scanner criteria were also taken into account: no tracks at more than 45 deg from the vertical or shorter than 4 in. were used. The average track length was 5 in., and most of the tracks were between 10 and 25 deg from the vertical (see Fig. 4).

DOUBLE-EXPOSURE TECHNIQUES

Setting the cameras for double exposures was difficult since the cameras had no built-in mechanism for registering double exposures. Thus, at first the pseudo tracks appeared simultaneously in each pair of cameras only 20% of the time. By developing a frame counter, we later increased this to 92%.

The procedure we used to superimpose pseudo tracks was as follows:

1. Frame counters were installed on *the cameras and the unexposed film* was wound backwards for, say, 10 frames.

2. Refocus lenses were installed on the cameras and the cameras were set for normal operation.
3. A template with the pseudo track (see below) was placed on the top glass of the cloud chamber.
4. Flash lamps were triggered and the image of the pseudo track was recorded on the film.
5. The refocus lenses were removed and normal lenses were installed.
6. The film was rewound to its original position.
7. The template was removed.
8. The cameras and the cloud chamber were set for normal operation.
9. Images of real tracks were recorded on the film.

SUMMARY

The development of the pseudo track was designed to ensure consideration of the most important aspects of making such tracks. Continuous upgrading has resulted in pseudo tracks that fit our nitrogen cloud chambers (operating at 1000 Torr and 20°C). If it is correctly exposed, a 65-droplet/cm pseudo track will be perceived by the scanners as a "normal" track. Further upgrading will be done as needed.

Development of the Template

The first template we used consisted of 0.005-in.-thick Mylar painted black with 0.003-in.-diam holes drilled through it by hand. The present templates, which are also made of Mylar, were developed with the aid of a computer code.¹⁰ The code uses random-number tables to calculate

ion locations in three dimensions according to a mathematical model that appears to reproduce the characteristics of real tracks. The ion locations are then projected onto an x-y plane and put on magnetic tape. Next, the tape is put into a Gerber automatic drafting machine, which

Fig. 5. Test track used to select the proper droplet size for the pseudo-track template. The numbers on the left indicate the diameters (in inches) of the corresponding droplets on the template. The test track was compared with a real track. (Compare this figure with Fig. 1.)

develops a droplet pattern according to the x-y coordinates. The drafting machine goes to the x and y coordinates with an accuracy of ± 0.0002 in. With this accuracy, we can simulate real droplet-overlap problems.

The drafting machine produces droplets by exposing film to a beam of light 0.0031 in. in diameter. The film is contact-printed to make a positive template with white dots on a black background. The proper droplet size was chosen by making a test template that contained variously sized droplets ranging from 0.002 to 0.005 in. in diameter in six steps (see Fig. 5). The template was then superimposed on normal cloud-chamber photographs for comparison with real droplets.

Checking of the Computer Model

The computer model was described on p. 4. During the early phases of the program, the pseudo tracks were fairly uniform with few or no blobs. During the later phases, however, the pseudo tracks appeared to be too blobby. After more knowledge was gained, the pseudo tracks were selected with blobbiness being taken into account. Also, we developed

a new model^{4, 9, 10} in which four times as many single ions were created as in the previous model (see Fig. 3). This made the track less blobby. The new model fits cloud chambers filled with N_2 .

The apparent age of the pseudo tracks (i. e., the width of the positive and negative columns) has a considerable influence

on how the new model appears on film. If the tracks are too narrow, they appear to be more blobby, and if they are too wide, they appear to be more uniform (see the center of Fig. 13).

The main tool we used to check the new model was a computer coupled with an automatic drafting machine. This system enabled us to vary the parameters efficiently.

Effects of Using the Model with Different Gases

Little has been done about making pseudo tracks in gases other than nitrogen, although some pseudo tracks have been placed in chambers filled with argon or carbon dioxide. The model^{4,9,10} used for nitrogen-filled chambers can be changed to fit argon-filled chambers by 1) decreasing the width and separation by about 50%, 2) selecting more blobby tracks, and 3) increasing the

droplet density. With the small number of tracks made to date, it appears that the older, more blobby model is fairly good for argon.

All that can be said for carbon dioxide is that we can develop such a model when necessary. The nitrogen model seems to be about right, but the droplet density needs to be increased to about 110 droplets/cm.

Training of the Scanners

The training of the scanners to search for light-density (quark) tracks developed into a three-phase program in which the knowledge of each phase was applied to the succeeding phases. Communication with the scanners was the key to the success of the program.

PHASE 1

Prior to the development of the pseudo tracks, the scanners were trained via a double-exposure technique in which light-density tracks were superimposed on previously exposed normal-density tracks. This was accomplished by rewinding the exposed film in one camera only, under-expanding the chamber so that the positive column was not fully developed, and double-exposing the one view. The view that was not double-exposed had the posi-

tion and the droplet count of the light-density tracks.

The scanners looked first at the double-exposed view and marked all of the light-density tracks they found. Then they scanned both views to find the light-density tracks they had missed. This was the start of training our scanners to find light-density tracks, so it was labeled phase 1. At this time, the efficiency of the scanners in finding 4/9 quark tracks was about 60%, with some ability in finding tracks with droplet counts as low as 17 droplets/cm (see Fig. 6).

This training method was satisfactory only at the start of the program. Upgrading of the method was necessary for obvious reasons: 1) The use of only one double-exposed view gave the scanners a clue that there were interesting tracks in that picture, 2) the use of a single

Fig. 6. Improvements in scanner efficiency since the start of the training program. Note that the two abnormally high points were not considered in drawing the connecting lines. This is because some of the pseudo tracks looked obviously artificial and thus attracted attention to themselves.

underdeveloped positive column did not correctly simulate real tracks, and 3) the lower limit of 17 droplets/cm was too high for 1/9 quark tracks. However, this method did point out the need for developing a better model in order to more realistically assess our ability to find quark tracks, and it pointed out the importance of having a running account of the scanners' efficiency.

PHASE 2

The idea of superimposing pseudo tracks on both views was tested a few times. The tests were performed with a piece of black-painted Mylar having 0.0011-, 0.0032-, and 0.0055-in.-diam holes drilled through it (see Fig. 7). The tests were successful, so phase 2 of the scanner training was started. Three pseudo tracks (9, 13, and 32 droplets/cm)

were drilled, using a print from the double-exposed film as a template. In each case, a single column was drilled twice, side by side, to make a positive and negative column. A fourth pseudo

Fig. 7. Mylar template used to prove the feasibility of superimposing pseudo tracks on both views of normal cloud-chamber tracks. The template is taped to the top glass of the cloud chamber.

track (25 droplets/cm) was also drilled, using a 2X enlargement of a normal late cosmic-ray track that was narrow enough for the enlargement to make it the normal width. Each pseudo track was then placed on the top glass of the cloud chamber and refocus lenses were installed on the cameras. Pictures were then taken, and the film was rewound for normal operation.

This technique superimposed the pseudo tracks on normally exposed film.

The exposure of the pseudo tracks was critical in determining the resultant droplet size. Photometric comparisons of the droplets in the pseudo tracks and the droplets in normal cosmic-ray tracks showed that 74% of the pseudo tracks were correctly exposed. The remaining pseudo tracks were underexposed by more than 25% and were not used to obtain scanner efficiencies. Because the cameras have no built-in mechanism for making double exposures, only 20% of the pseudo tracks were correctly exposed in the corresponding views.

A rating system was devised to weight the pseudo tracks according to:

1. The exposure. For example, a 25% underexposed track was weighted 1.5 if found or 0.5 if missed. On the other hand, a 25% overexposed track was weighted 0.5 if found or 1.5 if missed.
2. The specific film frame in which the track appeared. For example, if the track was the only one in the picture, it was weighted 0.5 if found or 1.5 if missed.
3. The overall appearance of the track. For example, if the track was in only one view, if it was in the center of the cloud chamber, and if it had a high density (more than 25 droplets/cm), it was weighted 0.5 if found or 1.5 if missed. On the other hand, if the track was in only one view, if it was in the right- or left-hand portions of the cloud chamber, and if it had a low density (less than 25 droplets/cm), it was weighted 1.5 if found or 0.5 if missed.

During this phase of the training program, 50% of the pseudo tracks had weightings other than 1.0.

As is noted in Fig. 6, the scanner efficiency for 4/9 quark tracks increased from 60 to 80%, with the lower limit approaching the efficiency needed to detect 1/9 quark tracks (7 droplets/cm).

PHASE 3

Phase 3 brought further improvements in the training program. This phase used the computer-generated tracks described earlier (see p. 4). The first few tracks were hand-drilled, using the computer printout as the template. We then developed a method that could take the computer data and, via an automatic drafting machine, transfer it to a film negative. The negative was then processed onto a Mylar film positive with 0.003-in.-diam transparent dots on a black background. As before, the correct droplet size and brightness were obtained with the aid of the appropriate ND filters, diffusers and exposures.

This procedure gave us much more flexibility because it had a fast turnaround time (an order of magnitude better than the hand-drilling), it freed personnel to do other work, and it allowed us to vary the parameters of the model. The width, separation, track density, and blobbiness were changed to fit the N_2 chamber by 1) developing a normal-density pseudo track, 2) trying it in the chamber, 3) changing the necessary parameters until the track looked real, and 4) programming low-density tracks for use in training scanners and determining their efficiency.

The new procedure also allowed us to change the tracks often enough so that the scanners could not remember the appearance of any one track. With this capability, we were able to obtain a measure of scanner efficiency versus track density (see Fig. 6 and Table 1). (The densities in this phase ranged from 4 to 65 droplets/cm, with an efficiency of 86% for the 4/9 tracks and 40% for the 1/9 tracks.) In addition, the development of a good double-exposure technique (via the frame counter) increased the percentage of correctly exposed pseudo tracks in both views to 92%.

The phase-3 procedure allowed a smooth flow of pseudo tracks through the system. Also, only 28% of the tracks were weighted as being too bright or too dim, etc.

SUMMARY

As in the development of the pseudo tracks, the training of the scanners went through an evolution in which the development was kept ahead of the scanners' knowledge. We were very careful in defining the goals we wanted the scanners to achieve. The emphasis was on finding light-density tracks, not normal-density pseudo tracks, for the idea was to train the scanners to

Table 1. Number of tracks used to obtain scanner efficiencies during phases 1, 2, and 3 (compare with Fig. 6).

Track density (droplets/cm)	Number of different tracks used ^a	Number of tracks found/ number of tracks made ^b
4	2	3/9
6	4	12.5/27.5
7	4	9/15
12	8	13.5/23
20	3	7/7
24	6	32/57
32	4	11/13
48	2	3/3
53	3	11/11
65	6	4/16.5

^aSome tracks were used more than once.

^bThe numbers in this column are actually weighted values that were derived as described on p. 11.

find 1/9 and 4/9 quark tracks. This has been accomplished by continually changing both the tracks and the track density (see Table 1) and by putting the tracks in different cloud chambers at different times. The rate at which we put pseudo tracks on film was about one every three weeks of cloud-chamber operation, or about one pseudo track in every 400 exposures.

Training Scanners to Hand-Count Under a Microscope

The problem in hand-counting is the overlapping of the droplets. It is difficult to know when to count an apparent single droplet as actually being two or more droplets. With the aid of pseudo tracks, however, one can count a track

having a known density and obtain a feel for the number of droplets that should be generated in a hand count.

Three different pseudo-track templates were made. The templates used the same track, but the droplet sizes and the scales

were different. The droplet sizes were 0.002, 0.005, and 0.010 in. We then made a template with 0.002-in. droplets and enlarged it three times. This was the master template, which we used to obtain the true count (to within 1%).

The tracks were about 9 cm long and were partitioned into nine different sections. The tracks were counted by hand, using the 0.010-in. droplet size first. We then analyzed the data with regard to droplet overlapping versus droplet size. We found that with the 0.010-in. droplets about 8% more droplets were lost because of overlapping than with the 0.005-in. droplets (see Fig. 8.).

Fig. 8. Error in counting droplets as a function of the density of a 1X pseudo-track template. The graph also shows how changes in the droplet size change the number of droplets counted because of droplet overlapping.

Normalizing the Hand-Counted Data

A pseudo track having a density of 65 droplets/cm was superimposed on a normal cloud-chamber photograph in order to compare the actual and hand-counted number of droplets in the track. The track was counted by 10 different people, only two of whom were experienced hand counters (N. G. and W. P.; see Fig. 9). The track was hand-counted between points A and B, excluding the blob and the crossing track. A positive, 3X enlargement of the track was also hand-counted and comparisons were made. The 3X enlargement indicated that there were 510 droplets, whereas the two experienced hand counters averaged 420 (18% low).

The template itself was then counted by

the same people, and comparisons were made. The overall group average was much better, but the experienced counters still stood out (see Fig. 9).

To investigate where the droplets were being lost, the track was partitioned into 11 countable sections and hand-counted by one person (D. E.) with the aid of a microscope. The results are shown in Fig. 10, which indicates some of the problems with droplet overlapping.

A pseudo track was made up and superimposed on six frames, then hand-counted by the experienced hand counters. Comparison of this count with the template count shows that the two hand counters were counting about 20% low.

Fig. 9. Pseudo track used to train scanners to hand-count cloud-chamber tracks with the aid of a microscope. The actual number of droplets in the track (510) was found by enlarging the track to three times its original size. The histogram shows the counts obtained by 10 different hand counters (only two of whom—N.G. and W.P.—were experienced) when they counted both the pseudo track and the template from which the track was made.

Drops lost	Blob size	% of blob	% of track
0	10	0	0
3	16	18.8	0.6
5	23	21.8	1.0
9	34	26.5	1.8
17	44	38.6	3.5

Fig. 10. Number of droplets lost and percent of blob lost as a function of the number of droplets in blobs. Blobs containing more than 30 droplets are not included in the count. These data were obtained by one person (D. E.) counting the pseudo track shown in Fig. 9.

Using the Pseudo Tracks as "Carrots"

To date, more than 500,000 cosmic-ray tracks from extensive air showers have been scanned. One scanner has looked at about 80% of these tracks. The

use of pseudo tracks as "carrots"^{4,9} has helped prevent our scanners from becoming bored and inefficient. This is an important function that should not be ignored.

Efficiency for Finding 1/9 and 4/9 Quark Tracks

The efficiency of the scanners in finding 1/9 and 4/9 quark tracks is closely tied to the scanners' training. To determine the efficiency, we edited and weighted cloud-chamber photographs as described on p. 11). In phase 2, only 35% of the pseudo tracks on the photographs were useful for obtaining the efficiency of the scanners. In phase 3, 65% were useful, even though more selective criteria were used in this phase. Thus, 65% reflects more of a change than would otherwise be suggested.

The criteria the pseudo tracks had to meet in order to be useful for determining the scanners' efficiency were:

1. The exposure of the pseudo-track droplets had to be correct to within 25% of the exposure of the other droplets in the photograph.
2. The angle of the track in the chamber had to be within 45 deg from the vertical.
3. The track could not appear to be too close to the edge of the chamber so as to appear too straight for

- that region of the chamber (phase 3 only).
4. The ends of the tracks had to fade and could not appear to stop too abruptly inside the chamber (phase 3 only).
  5. The track could not be given away by any camera malfunctions.
  6. The photograph had to have at least one triggered event along with the pseudo track.

7. The track had to appear in both views (phase 3 only).
8. The track had to appear to be inside the chamber (phase 3 only).

From the start of the project to date, the scanners' efficiency for finding 4/9 quark tracks changed from 60 to 90%, and their efficiency for finding 1/9 quark tracks increased from zero to 40%.

Analyzing Our Automatic Scanning System

We have developed an automatic method for measuring the ionization created by charged particles passing through cloud chambers. In this method, film images of individual droplets are located, identified, and counted. The key apparatus is a programmable film reader⁹ (PFR), which consists of a precision cathode-ray tube (CRT) and an optical system for focusing the CRT spot on film and measuring the light transmitted. The CRT spot is about $6\ \mu$ in diameter at the film plane; droplet diameters average $20\ \mu$. Film densities are recorded for a rectangular array of points $5\ \mu$ apart along the track. The net output of the PFR is 25 tracks/hour. The data are then processed by two sophisticated computer codes to give the number of droplets per centimeter in real space.

Three different pseudo tracks were made up and put in three different cloud chambers having two camera geometries (24.5 and 28.5 in. between the camera lenses and the centers of the chambers). The densities of these tracks were 7, 32, and 65 droplets/cm. The tracks were put

in the chambers at various angles and in numerous views.

A 3X enlargement of each pseudo track was made for use as a master. The computer codes¹⁰ that analyze the PFR output were then modified to print their results at the same scale as the master (see Fig. 11). In this way, the template could be slid across the printout and individual droplets located, thereby providing a complete comparison with the computer codes. Such things as grid-wire effects, backgrounds, crossing tracks, blob cut-off, blob generation, and droplet generation were investigated (see Tables 2 and 3).

There are two ways of analyzing the track-analysis codes: 1) looking at each droplet on the template and comparing it with the information printed by the codes (the comparison is made only in the countable sections of the track), and 2) looking at the final average number of droplets per centimeter as determined by the codes and comparing that with the results from the template. These two methods separate the different functions of the codes (see Tables 2 and 3).

HH613 TRACK 109

331 DROPS READ IN, 1946 CREATED IN 25.65 CM. GIVING 75.86 DROPS/CM.
 LFB = 17.33 LFLV = 17.30 LF/LS = 0.0675
 # = 109.6 # = 98.9 Z = 21.6

X1 = 60.1
 Y1 = 50.1
 Z1 = 37.7
 X2 = 36.3
 Y2 = 46.4
 Z2 = 29.1
 CT = 0.9422
 R = -1320.8
 RCST = -1111.5

15 0223 16:13 *2 02

51 OF 52 SECTIONS USED IN PARABOLA FIT
 RMS # IS 0.0632 CM ANALIZ NON-CONVNG
 BLOB TEST OF 39 / 0.20 CM EXTENDED TO 0.30 CM
 RMS # IS 0.0579 CM FIT # IS 0.0623 CM
 RMS # IS 0.37/CM FIT # IS 0.11/CM
 965 GOOD DROPS (46.0 % SINGLES)
 IN 21.60 CM GIVES 44.68/CM
 (SUBTRACT BLOB AND GET 44.45 /CM)
 AVERAGE OF 22 GROUPS IS 44.0 ± 16.3
 WITHOUT GROUP 1 WE GET 42.4 ± 14.9

Fig. 11. Example of the computer printout that was modified to print at the same size as the 3X enlargement of the pseudo track. The numbers of droplets per 0.05 cm are expressed as numbers from 0 to 9 and as letters from 10 to 35 (A = 10, B = 11, etc.). (Compare this figure with Fig. 2. For further information on the data shown in this printout, see Ref. 10.)

Table 2. Data obtained by superimposing a nominal 65-droplet/cm pseudo track on 16 frames of normal cloud-chamber photographs. The table shows the results obtained with both methods of analyzing the tracks. The reason for the difference between the two sets of results is mainly because of the error in the blob-cutoff portion of the track-analysis code.

Method 1										Method 2				
Track number	Number of droplets per centimeter		Difference (%)	Grid effect (%)	Background effect (%)	Net effect (%)	Droplets generated (%)	Single ions (%)	Number of droplets per centimeter		Difference (%)	Total droplets in blobs ^a		
	3X template minus background	Printout minus background							Adjusted 3X template	Printout minus background		3X template	Printout	
15-89	67.61	64.05	5.3 low	0.1 low	0.2 low	0.3 low	5.0 low	41	62.6	64.05	2.3 high	271	251	
8-91	50.86	47.23	7.1 low	3.4 low	3.5 high	0.1 high	7.2 low	46	50.0	47.23	5.5 low	110	96	
8-98	51.81	45.73	11.7 low	4.9 low	0.6 low	5.5 low	6.2 low	50	49.0	45.73	6.7 low	183	154	
15-103	49.71	55.32	12.3 high	1.2 high	4.2 high	5.4 high	6.9 high	39	45.8	55.82	21.9 high	107	101	
15-106	53.19	54.31	2.5 high	0.2 low	1.3 low	1.1 high	1.4 high	41	53.1	54.51	2.7 high	262	27	
15-109	43.67	46.25	5.9 high	1.0 high	1.1 low	0.1 low	5.0 high	45	43.5	46.25	6.3 high	263	279	
15-110	48.74	53.08	10.5 high	1.4 low	9.7 high	8.3 high	2.2 high	46	48.0	53.88	12.3 high	130	127	
15-111	48.60	46.00	3.5 low	1.0 low	1.8 high	0.8 high	4.3 low	35	45.2	46.90	3.8 high	34	25	
8-113	52.66	52.04	0.5 high	3.0 low	0.1 low	3.1 low	3.6 high	49	56.0	52.94	5.5 low	237	232	
8-120	57.93	50.60	12.7 low	0.6 low	0.6 low	1.2 low	11.5 low	45	55.6	50.60	9.0 low	266	234	
8-126	66.68	67.05	0.6 high	5.7 low	6.1 high	0.4 high	0.2 high	48	56.2	67.05	19.3 high	91	94	
15-129 ^b	72.87	68.56	5.9 low	1.0 low	0.9 high	0.1 low	5.8 low	35	62.0	68.56	10.6 high	34	25	
15-132	73.12	64.38	12.0 low	2.3 low	0.4 high	1.9 low	10.1 low	41	61.8	64.38	4.2 high	151	120	
15-186	66.40	69.83	5.2 high	0.3 high	4.6 high	4.3 high	0.9 high	45	70.5	70.5	1.0 high	54	46	
15-189	69.05	66.04	4.4 high	6.7 low	1.5 low	0.5 high	4.9 low	37	62.9	66.04	0.2 high	130	118	
15-190 ^c	66.51	66.05	0.7 low	3.0 low	5.2 high	2.2 high	2.9 high	40	71.6	66.05	7.8 low	57	68	
Average	58.71	—	1.0 low	1.9 high	2.1 high	0.7 high	1.6 low	43	55.8	—	3.0 high	—	—	
rms	5.85	—	7.5	2.3	3.1	3.2	5.5	4.6	8.5	—	9.0	—	—	
rms/ $\sqrt{n-1}$	±2.55	—	±1.9	±0.6	±0.8	±0.8	±1.4	—	—	—	2.3	—	—	
Totals: 2453												2286	(6.8% low)	

^aBlob = 34 to 73 droplets.

^bSame track as 15-103 but treated differently.

^cRepeat of track 15-189.

Table 3. Data obtained by superimposing a nominal 32-droplet/cm pseudo track on six frames of normal cloud-chamber photographs. This particular pseudo track illustrates the problems with the blob-cutoff and crossing-track criteria used in the track-analysis code: 1) the track is relatively blobby, and 2) the blobs are on the borderline of being classed as blobs. The latter depends on the blob criteria used: blob = 30 droplets, or blob = 30 + (number of droplets per centimeter $\times$ track width); e.g., $30 + (32 \times 0.25) = 38$ droplets.^a The method-1 data were taken before the blob-cutoff and crossing-track portions of the code were changed, whereas the method-2 data were taken after the corrections were made. Thus, comparisons are difficult. The table is meant to show some of the problems in analyzing the data.

The data from sixteen 65-droplets/cm tracks were analyzed first, and we found that the code correctly counted only about 75% of the droplets in each track (25% low). This error was primarily caused by improper handling of blobs containing more than three droplets. We made the necessary corrections to the codes and reran the data. With the corrected codes, and using the two methods of analyzing them, we found an error of about $1 \pm 2\%$ low for method 1 and $3 \pm 2\%$ high for method 2, with an rms spread of 7.5 and 9% per track respectively. By dividing the total number of droplets in all of the tracks (13,628) by the corresponding total length (232.1 cm), we obtained 58.72 ± 0.15 droplets/cm. This number was then compared with the computer printout, which gave 12,739 droplets in 225.8 cm, or 56.41 ± 0.56 droplets/cm. The reason for the

Track number	Method 1										Method 2										Total droplets in blobs	Printout	
	Number of droplets per centimeter					Number of droplets per centimeter in printout					Number of droplets per centimeter in printout					Difference (%)							
	3X	template	minuz	background	background	3X	template	minuz	background	background	3X	template	minuz	background	background	Difference (%)							
																Difference (%)							
8-92	48.56	48.00	10.7 low	0	4.3 high	4.0 high	3.5 low	34	33.2	13 high	40.1	40.7	6 high	47	46								
8-95	35.03	35.03	10.5 high	0	12.5 high	12.5 high	6.0 high	51	34.6	19 high	32.4	32.4	7 high	71	66								
8-101	25.41	25.41	12.3 high	1.0 high	0.5 high	1.3 high	11.0 high	39	31.0	18 high	30.8	30.8	4 low	71	68								
15-107	23.39	22.47	3.0 low	0.5 low	0.6 low	1.1 low	2.0 low	44	21.5	2 high	22.6	23.4	15 low	157	132								
8-119	29.11	29.11	1.3 high	1.2 high	0.0 high	0.0 high	48	30.3	5 high	27.6	27.6	4 low	10	10	134								
8-121	27.56	27.46	20.2 high	3.1 high	0.1 high	1.2 high	0.0 high	48	30.3	5 high	27.6	30.3	2 low	134	134								
Average	31.77	—	7.8 high	0.3 high	4.0 high	4.5 high	3.2 high	44	—	10 high	—	—	1.4 high	—	—								
rms	6.0	—	0.9	1.5	5.0	5.6	6.0	—	—	3	—	—	2.3 low	—	—								
rms/wt ²	—	—	4.4	40.7	22.5	22.7	—	—	—	—	—	—	2.3	—	—								
Total: 556											Total: 556											470	

^aThe pseudo track was made with the old model and thus has blob criteria that are different from the criteria that would occur in a track made with the new model. Some of the blobs are on the borderline.

^bBlob = 20 to 32 droplets.

Fig. 12. Counting error produced by the automatic track-analysis system. The error was obtained with pseudo tracks that were sent through the system at various times and that were put in several different cloud chambers having two different camera geometries. The numbers of droplets on the templates are known to within 3% in the old model and to within 1% in the new model (see p. 4).

computer's shorter track length is the grid-wire effect. Comparing the two numbers gives an error of $(58.72 - 56.41)/58.72 = 3.9 \pm 1\%$ low.

The computer codes' error is generally $1 \pm 2\%$ low, but with certain blob

criteria, it can be $3 \pm 2\%$ high. This shows up more in the lower density tracks (see Table 3, where the error in the blob cutoff is 18% low and the corresponding error in the track count is 10% high).

The data from six 32-droplet/cm tracks were then analyzed. The two methods of analyzing the data gave an error of 8% high and 20% high respectively. Reexamination of the data showed that the light-density parts of the tracks were being cut out as crossing tracks and that the blob cutoff needed adjustment.¹⁰ This was reflected by the 20%-high number. The codes were corrected, and new analyses found errors ranging from 1% low to 10% high. The 10%-high number was greatly dependent on the criteria used for blobs (see Table 3). By adding the length of the six tracks, dividing by the total droplets counted, and comparing the result with the total length and droplets on the template, we found that the droplet density for the six tracks was correct.

The 65-droplet/cm tracks were then rerun and examined. We found that the corrections in the crossing-track and blob-cutoff portions of the code were in the right direction. The new errors ranged from $3 \pm 2.3\%$ high with a spread of 9% per track to $1 \pm 2.5\%$ high with a spread of 10% per track. Only method 2 was used to make this comparison.

The codes would not handle the one 7-droplet/cm track because there were too few droplets for normalization.¹⁰ The data indicate that the various low-count tracks were not counted properly because the droplets were so infrequent that the running minimum-contrast level was governed by the graininess of the film rather than by the droplets themselves. The con-

sequence was that the film grains were transformed into droplets, and then when the normal droplets were measured the result was large blobs. This has also been corrected (see Fig. 12).

In summary, the automatic system for scanning cloud-chamber tracks is a complex and sophisticated system. We have normalized the computer codes by running one 65-droplet/cm pseudo track through the system 16 times and one 32-droplet/cm pseudo track six times (see Fig. 12). With this process, and because the tracks were counted in different sections (the densities of the two tracks ranged from 27 to 71 droplets/cm), we are able to obtain a good indication of how the system handles cosmic-ray tracks. At present, it appears that the codes handle cosmic-ray tracks with an error of $2 \pm 5\%$ low and that the main problems are determining crossing tracks and blob cutoffs. These problems, however, are taken care of in the editing of the output. One editorial criterion throws out any track that appears to have an error of 5% or more because of crossing-track and/or blob problems.

After the necessary corrections to the code were made, pseudo tracks ranging from 7 to 65 droplets/cm were put in various cloud chambers and run through the normal channels. These tracks were edited, and 42% of them passed the editing criteria (see Fig. 12). Also shown in Fig. 12 are the edited 65-droplet/cm and 32-droplet/cm pseudo tracks that are mentioned above.

Fig. 13. Photograph of many different kinds of pseudo cloud-chamber tracks superimposed on a typical cloud-chamber picture. The pseudo tracks are indicated by arrows, and the nominal number of droplets per centimeter in each track is indicated by the numbers with the arrows. All of the pseudo tracks were made with the model that fits the nitrogen-filled cloud chamber. The unmarked tracks are normally triggered cosmic-ray tracks. Note the $1/9$ tracks in the upper left-hand corner of the photograph. These tracks show what $1/9$ quarks would look like in a horizontal cloud-chamber geometry. An amusing sidelight on the training of our scanners can be seen on the left-hand side of the photograph. The trail of footprints has the same track density as a $4/9$ quark track. The track was made in the form of footprints to keep the scanners alert.

Studying the Feasibility of New Approaches to the Search for Quarks

The pseudo tracks were first used to determine the scanners' efficiency in searching for $4/9$ quarks. Scanner training and efficiency tests were started. Next, a $1/9$ pseudo track was put in several cloud chambers, and it was found that the general background in the chambers was too high. If the background could be reduced, it would be feasible to search for $1/9$ quarks in the present geometry.

We made a pseudo track in which the negative column varied from 20% developed to 80% developed. We used this as a guide for determining the expansion ratios of the chambers. It was found that in general the chambers were being over-expanded and that the general chamber background was dependent on the expansion ratio. The necessary adjustments were made, and the backgrounds went down to 0.1 to 0.5 droplets/cm³. The $1/9$ pseudo was put in the chambers again, and it was discovered against the new low background. The chambers were then officially "on the air" for $1/9$ quarks.

At this point, a new concept for searching for $1/9$ quarks was suggested. This

was to change the orientation of the chamber from vertical to horizontal. The horizontal geometry has many advantages:

1) there is less overlapping of separate tracks, 2) low-density tracks can be seen more easily because they are shorter (due to foreshortening) and are therefore denser, 3) there are more catalogable tracks per frame (an average of 7 as opposed to the previous 1.5), and 4) the chamber cross section is larger by a factor of about 4.

In order to test the feasibility of this geometry, we turned one of the chambers on its side. The appropriate pseudo track was made and put in the chamber for evaluation (see Fig. 13 in the upper left-hand corner). The problem here was in the length-to-density ratio. This was a completely new concept, so the scanners had to be retrained. After the pseudo track was evaluated, it appeared to be feasible to make the change. A quick scanner-training film and a rough scanner-efficiency test were then made. The efficiency in looking for $1/9$ quarks in the new geometry was about 50%, but this is expected to improve with training.

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