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NOTES ON SOME EXPERIMENTAL TECHNIQUES FOR 200-GeV PHYSICS: WIDE-GAP SPARK CHAMBERS AND GAS PROPORTIONAL COUNTERS

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ABSTRACT

The utility of wide-gap spark chambers at NAL is discussed on the basis of experience with this technique in current cosmic-ray experiments. The potentiality of spatial resolution superior to that obtainable with other spark-chamber systems is emphasized. Secondly, the utility of a system of gas proportional counters for particle identification through the relativistic rise is explored, and the results of an earlier study are discussed.

I. INTRODUCTION

In 1967 a proposal was submitted to the NSF for a cosmic-ray mountaintop facility for studying strong-interaction physics in the 100-1000-GeV energy region. In the preparation of this proposal some studies were carried out on experimental techniques which have not been reproduced elsewhere. In the following I have transcribed bodily portions of that proposal with annotations and deletions appropriate to the interests of NAL and to subsequent developments.

The two topics considered here are wide-gap optical spark chambers as a means for achieving very high resolution and gas proportional counters as a means of differentiating between particle types (e.g., protons and pions) at high energies (100 GeV).

II. THE WIDE GAP SPARK CHAMBER

Optical spark chambers using gaps of 5 to 8 inches are simple to construct, show excellent multi-particle detection efficiency, and may be photographed with small-aperture optics permitting very precise digitization of spark location. Such chambers are not useful for tracks inclined more than 45° to the normal (E field direction), and they display marked inefficiency for tracks greater than 25-30° to the normal when several other, smaller angle tracks are also present. However, within a ±20-25° cone multiplicities of over 20 tracks have been photographed.

When using conventional spark chambers, the center of each spark is carefully digitized and the best particle trajectory is found by fitting a curve to the separate spark coordinates. Several investigators find that each spark fits the trajectory to $\pm 250\mu$ or better, so that a best fit to 25 sparks would give a track coordinate precise to $\pm 50\mu$. This limit is probably set by the transverse range of delta rays in neon at NTP. Correspondingly, by digitizing many points on a single spark in a wide-gap chamber photograph, a best fit to the trajectory can be found where each point fits the trajectory to a comparable precision. We find that $\pm 100\mu$ is typical of deviations from a best fit to a single wide-gap chamber spark (excluding the curved ends of the spark).

Experimental Studies

We have studied the properties of a chamber of two 8-inch gaps located between smaller chambers each having a pair of 2-inch gaps and triggered on cosmic-ray muons as shown in Fig. 1. Photography employed a 300-mm Dallmeyer f/4.5 lens stopped to f/16, and 35 mm Tri-X film. About 60 tracks of cosmic-ray muons of at least 200 MeV were photographed and digitized. Assuming that the two smaller chambers correctly defined a straight line particle trajectory, the wide-gap spark digitizations gave a fit to the track angle of ± 1.1 mrad and to the position of the track intersection with the midplane of the chamber of $\pm 150\mu$. Each spark was digitized at 40 points. It was necessary to digitize the sparks separately and to allow for a displacement of each spark toward the chamber anode just as in conventional narrow-gap chambers. For this reason, precise measurements require chambers with two gaps symmetrical about the driven electrode.

We found it necessary to make corrections for the pin-cushion distortion of the lens by digitizing extremely carefully plumb lines of glowing 0.006-in. tungsten wires. Best fitted curvilinear coordinates were then stored in a computer and each digitized spark coordinate was corrected accordingly. Results of angular and position resolutions of the wide-gap chamber are summarized in Figs. 2 through 4. These figures are clearly upper limits, as the multiple scattering of muons of several hundred MeV already would give comparable figures for angle and displacement errors. Note that a 300 MeV/c particle would multiple-scatter in 0.001-in. of aluminum by 0.9 milliradians (rms). In these tests a one-inch wooden table top was the primary source of scattering between the lower small chamber and the wide-gap chamber. This introduced errors of ± 2.6 mrad in $\Delta\theta$ and of ± 0.25 mm in ΔX for 300 MeV/c muons. Thus we believe that the precision obtainable with two wide gaps is definitely better than that possible using the same space occupied by one cm gaps, independent of whether the recording is optical, magnetostrictive, or otherwise. A typical rms value of the deviation of individual digitized points from the best fit line is approximately 0.10 mm. In Fig. 5, the deviations of the digitized points are plotted for a typical spark. Therefore, with 40 measured points along a 20-cm spark an estimate of the probable angular error that can result from such a fit is under 0.1 mrad. At energies above several GeV, where multiple scattering may be neglected, we believe that such an estimate may be representative of the ultimate intrinsic precision of the chamber.

Chamber Construction

Our chamber construction employs half-inch thick plate glass walls for economy and optical quality, hardened aluminum foil of 0.001 in. or 0.002 in. for electrodes, and mylar of 0.005 in. or greater for gas sealing. The chambers employ a 2-inch "dummy gap" between the ground electrodes and outer shield electrode and gas seal. Atmospheric pressure variations only affect the gas seal foils, and the electrical noise is greatly reduced by the outer, passive ground electrode. Wires are stretched around the glass side walls with 0.5 inch spacing and connected to 8 strings of resistor dividers at four corners, each string consisting of sixteen 4.7 kilo-ohm resistors in series, to produce a uniform electric field along the dielectric surface. The capacitance of the test chamber was 95 pf, giving a time constant of about 1 μsec. We have successfully spliced thin aluminum foils together with mylar strips and used them in chambers, so that we foresee no essential problems in building and operating chambers of very large sizes ($2 \times 4.5\ m^2$ to $3 \times 7.5\ m^2$). We would operate such chambers by connecting two or more pulsers to the central driven electrode, one pulser for each 1 to 2.5 m of chamber length.

The pulsing of wide-gap chambers requires Marx generators of fast rise time, reliable pulsing, and large capacity. We have developed a very satisfactory generator of 8 stages, 3900 pf/stage, and 240 kV.

Wire-Chamber Arrays vs Wide-Gap Chambers

Inevitably a discussion of these chambers leads to questions concerning the alternatives of wire chambers using direct data readout into a computer. In order to obtain the same precision with wire chambers we would require at least 24 gaps (with alternate electrodes orthogonally) and using wire spacings of 0.3 mm with corresponding complexities in data readout. The chamber construction would be vastly more complex, and the multiple scattering worse, even with the thinnest available wires. Although the spark coordinate data could be immediately available, in fact the time required to process the spark coordinates to produce a kinematical reconstruction of the event through non-uniform magnetic fields in general requires a second stage in data processing. It is our experience that the logical steps in reducing spark information to space coordinates are equivalent, whether using wire-chamber readout or using flying-spot digitization of film. The subsequent kinematical and dynamical analysis is identical.

In a cosmic-ray experiment at Echo Lake operated over the past year, we have incorporated two wide-gap chambers of 80×80 in.^{2} sensitive area, each with two 8-inch gaps. With crude corrections for optical distortions, the apparent "scattering angle" of 100-GeV hadrons (the lack of collinearity of tracks in the two chambers) is about one milliradian.

Precise optical corrections are currently in progress, which should significantly improve this figure. The resolution is, of course, over the 4 m^2 area of each chamber, photographed in 90° stereo by two cameras, each viewing a 2 m chamber edge with a 2 m depth of field. Film digitization of single tracks is being carried out successfully using the 4000-line resolution automatic digitizing system (MASS[1]). Although limited to 10μ least count on the film plane, the recording of 13 points per spark, distortion correction, and line fitting, permits the milliradian fits mentioned earlier.

Summary

As a consequence of our experience with large wide-gap chambers, I believe that they are the ideal detector for downstream (very high momentum) particles. The constraints of photography are the same as apply to the streamer chambers. Direct video tape recording might be more easily applied to the wide-gap chamber in view of the greater light levels as compared with the streamer chamber. With care it should be possible to record angles (vectors of straight tracks outside magnets) to much less than a milliradian, and coordinates (intersections of tracks with the mid-plane of a chamber) to $\pm 50\mu$.

Pairs of wide-gap chambers spaced by two meters would then define the angles of tracks to $\delta\theta = \pm 2 \times (50/2) \times 10^{-6} = \pm 35$ microradians. Two such chamber pairs on each side of a 4 tesla-meter magnet would determine momenta to $\delta p = 4 \times 10^{-5}\, p^2$, or 1% at 250 GeV/c.

In the context of very high resolution, it should not be forgotten that all sorts of effects normally ignored become important when such precision is required. For example, steel and glass have coefficients of thermal expansion of 10^{-5} per degree. Hence, recording chamber coordinates precise to 10^{-5} requires a thermal stability and homogeneity of 1° over the apparatus. In photography, air turbulence, etc., become factors; other examples can be cited. However, the lesson to be learned is that there is more to high precision than the facility to digitize coordinates to 10^{-4} meters.

In conclusion, serious efforts should be made to explore the ultimate resolution of wide-gap chambers. Their incorporation into NAL experiments could permit significant savings in magnets and other analysis systems for experiments where their use is appropriate.

III. GAS PROPORTIONAL COUNTERS FOR PARTICLE IDENTIFICATION

In a situation where various particles traverse a region of space within a large phase-space volume (a large range of momenta, angles, and coordinates), such as following a magnet that analyzes products of a reaction, the identification of particles as pions, kaons, nucleons, etc., by means of Cerenkov counters becomes very awkward. The relativistic rise in ionization may permit such an identification of particles by means of gas proportional counters, provided that the particle momenta are known and that many samples of ionization of each particle are taken. This problem was considered in the context of separating > 100 GeV/c positive pions from protons in the incident cosmic-ray hadron flux. The result of that study is reported below.

It is well known that the energy loss of a particle increases logarithmically with its energy, at energies $> 2\ mc^2$. The relativistic rise is partly due to increase in the value of maximum transferable energy and partly due to the relativistic expansion of the zone of electrical influence of the incident particle. It is with the latter effect we are concerned here. Since the energy loss is a function of only the Lorentz factor, γ, of the incident particle, a measure of energy, $\gamma\ mc^2$, in a calorimeter, or of momentum, $\sqrt{\gamma^2 - 1}\ mc$, in a magnetic field and the energy loss, $f(\gamma)$, determines the mass, m, of the particle.

We shall first consider the possibility of identifying protons and pions at energies of about 100 BeV.

In Fig. 6, we have shown the calculated most probable energy loss as a function of the Lorentz factor, γ, based on the formula given by Rossi.[2] This particular curve is for 15 cm of argon at 760 Torr pressure. Correction due to the density effect, which becomes applicable at $\gamma > 100$ in the present case, is also shown in the figure. This correction is calculated on the basis of formulae given by Sternheimer.[3] It is seen that the most probable energy losses for a proton and a pion both of 100-BeV energy are 33.1 and 36.7 keV respectively. In Fig. 7, we have shown the so-called Landau fluctuations in the energy losses suffered in a gas counter by pions and protons both of 100-GeV energy. These curves are drawn from the tabulated values given by Seltzer and Berger[4] on the basis of theory of Vavilov.[5] It is seen that there is a considerable amount of overlap, and a single measurement would seldom distinguish a proton from a pion. The situation cannot be improved just by increasing the pathlength using but a single counter.

Determination of the Energy-Loss Distribution

The way out seems to be to employ an array of N_0 counters where N_0 is a large enough number and apply a likelihood ratio test to distinguish the particles. Here one computes the ratio

$$\prod_{i=1}^{N_0} (Y_{i,\ \mathrm{proton}}) \Big/ \prod_{i=1}^{N_0} (Y_{i,\ \mathrm{pion}}),$$

where $Y_{i,\ \mathrm{proton}}$ is the value of the ordinate of the Landau curve for protons at the pulse height Δ_i and $Y_{i,\ \mathrm{pion}}$ the corresponding quantity for pions. If this ratio L is $>>1$, the incident particle is a proton, and if $L << 1$, it is a pion. If L happens to be ≈ 1, there will be some ambiguity and the degree of ambiguity depends on how well the L values for the assumed incidence of a pure proton beam and for a pure pion beam separate.

Experimentally, it is found that the distributions of energy losses in a gas proportional counter are in reality about twice as wide as those given by Landau's theory and shown in Fig. 7. Experiments leading to this conclusion are described elsewhere.[6] While the theoretical calculations of Landau straggling are valid for thicker detectors, they do not apply to counters wherein the most probable energy loss is not orders of magnitude greater than the atomic binding energies. Blunck and Liesegang[7] have modified the energy loss expressions including atomic binding effects and find a significantly broader width to the Landau curve for very thin detectors. Our gas proportional counters fall in the regime of these calculations. As an example, we have shown in Fig. 8 an experimentally obtained pulse height distribution (from the experiments discussed in Ref. 5) together with the expected distributions on the basis of theories due to Landau and due to Blunck and Liesegang. In general, the latter theory gave a slightly broader pulse height distribution on the smaller pulse side than the experimental data. If the theory is indeed in error in predicting too great a probability for small pulses, our ability to separate pions from protons would be improved. More experimental data with accelerator beams are needed to finally fix the exact ionization curve.

Monte Carlo Test

To test the efficacy of the likelihood ratio test, the following was done: An empirical formula to fit the energy loss distribution curve by the Blunck-Liesegang theory for our experimental conditions was found and is given below:

$$F(\Lambda)d\Lambda = 0.088 \exp(-\Lambda^2/26) \text{ for } \Lambda < 0 \tag{2a}$$

$$= 0.145 \exp\{-0.5 [\Lambda/2 + \exp(-\Lambda/2)]\} \quad \text{for } 0 < \Lambda < 12. \tag{2b}$$

Here Λ is a dimensionless parameter, and any arbitrary energy loss, Δ, in the counter is expressed by

$$\Delta = \Delta_{\text{most probable}} + \Lambda \left(0.300\, mc^2 \frac{Z}{A} x\right), \tag{3}$$

where m = rest mass of the electron,

Z = atomic number of the medium,

A = atomic weight of the medium,

and

x = thickness of the gaseous medium measured in g cm^{-2}.

Assuming that the incident particle is a proton and using Eq. (2) as the reference curve, a set of N_0 random pulse heights (called here as one proton event) were generated on the computer according to the method suggested by Von Neumann.[8] For this study we have chosen an array of 6 and 12 counters (i.e., $N_0 = 6, 12$). A totalof 10,000 proton and 10,000 pion events with $N_0 = 6$, and 5000 proton and 5000 pion events with $N_0 = 12$ were generated on the computer and analyzed with the likelihood method ratio discussed above.

In Table I, obtained on the basis of this calculation, we give the separability of protons and pions with an array of 12 counters, using the likelihood ratio method. The separability is given in the form of efficiencies for detection of the two kinds of particles. The separability is asymmetric between pions and protons both because the positive pions are less numerous than protons in cosmic rays and because of the asymmetry of the ionization (Landau) curves.

IV. EXPERIMENTAL TESTS OF PARTICLE IDENTIFICATION BY ENERGY LOSS

During 1966 and 1967, an extensive experimental program was carried out to study the properties of gas proportional counters in the context of the particle separation problem. Proportional counters of cylindrical, hexagonal, and square cross section with anode wires of 0.005 in. to 0.010 in. were made, as well as flat boxes with parallel anode wires in the mid plane. Counter diameters and heights of 3 to 6 inches were used, and several different filling gas mixtures were employed. With a mixture of 93% argon and 7% CH_4, excellent results were obtained with all of the counter geometries. The pulse height distributions from monoenergetic γ sources and α sources agreed with the widths calculated from the statistics of the numbers of ion pairs produced, and the counters were shown to be accurately linear in their response over the entire range investigated. The response of the square box and of parallel anode wire flat box counters were studied in a proton beam of 800 MeV and a pion beam of 1.5 and 4 BeV/c. The resulting pulse height distribution curves were in reasonable agreement with the Blunck-Liesegang theory. The response to cosmic-ray muons at sea level was broadened due to the range of velocities present in the muon flux; however, again the experimental distribution agreed well with a folding of the theoretical energy loss curves and the muon spectrum.

Cosmic-Ray Test

In the 1966-67 Mount Evans-Echo Lake experiment, two proportional counters were used, each containing three layers of 36×80 in.^{2} counters. One counter, the "multibox," contained an array of 6×6 in.^{2} cells with an anode wire along the center of each cell. Anodes of each horizontal layer of 6 cells were tied together into a common preamplifier. The other counter, the "multiwire," employed parallel anode wires spaced by 2 in. horizontally and located between two horizontal aluminum ground planes 6 in. apart. In all counters the horizontal ground planes were 0.001 inch aluminum. The 6 counter layers were separately digitized so that the ionization of an incident vertical particle was recorded in six independent channels. If a hadron, its energy was determined by the ionization calorimeter below the counters. The counters were calibrated with muons and gave good agreement with the resolutions computed and measured with the smaller prototype counters.

A sample of 150 hadrons unaccompanied by showers and of energies between 70 and 150 BeV was studied in an attempt to test the maximum likelihood method outlined above. Each of the events was treated as in the Monte Carlo program to determine a value of L, and a distribution of the resulting L values was formed. From this distribution and the corresponding 6 counter Monte Carlo distributions, a pion-to-proton ratio was computed. It was found that the computed value for the pion-to-proton ratio was a strong function of the value in channel number assigned to the position of the peak in the muon calibration runs. This sensitivity arises partly due to smaller number ($N_0 = 6$) of the counters employed in the experiment and partly due to the broad nature of the pulse-height distribution. Our lack of precise normalization of our counters and the extreme sensitivity of this method to the normalization precluded any meaningful π/p separation. A recent study by Soviet physicists[9] with ten counters has obtained comparable results.

Our experimental program also included a study of wall effects in the counters, and from 0.00025 in. mylar to 0.25 in. copper no wall effects were observed. We also did not observe a deleterious effect of delta rays penetrating from one counter to the other, although this may occur rarely. In other words, our six-counter system behaved statistically like six completely independent counters.

One technical achievement which was crucial to our recent experimental program and to this proposal was the compatible operation of the gas proportional counters and the wide-gap spark chambers. The gas counters collect 10^5 electrons on a 400 pf capacitance over 3 μsec rise time. The spark chamber, on the other hand, is pulsed at 100 kV about 400 nsec following the particle passage. When suitable care was exercised in shielding, the pickup from the spark-chamber pulse in the gas-counter circuitry was at worst 5% of the pulse height of a minimum ionizing particle and was at best undetectable.

Conclusions

As a result of this theoretical, experimental, and computational program, we can state several conclusions. We can build counters of performance consistent with theoretical predictions, and these construction techniques can be extended from 2 m^2, already operated, to larger areas. We have an operational understanding of the resolution and ionization theory. With an array of 22 counters, we think that we can separate pions and protons of above 100 BeV using the maximum likelihood computation. For each given event we can know the certainty in particle type assignment. While this method of separation deteriorates above 300-500 BeV, due to the density effect, the use of as many as 22 separate horizontal layers should permit over half of the protons to be identified even above 500 BeV. We have not carried out the Monte Carlo computations for other energies and other numbers of counters beyond those discussed above, (Table IV), although extending the calculated example from 6 to 12 counters made a significant improvement, and at least as great an improvement would come on expanding from 12 to 22 separate samplings of ionization.

In order to consider this separation scheme at NAL, extension of the Monte Carlo calculations to larger numbers of counters should be carried out, and kaons should be included in the maximum likelihood calculations. The counter size should also be varied from 15 cm to 1 cm (where the width of each Landau curve becomes broader but the number of independent samples of ionization increases. It is possible that 100 separate counters are necessary for reasonable π-K separation. One might imagine a drift space of $5 \times 2 \times 2\,m^3$ (5 m along the dominant particle direction), filled by a 100×40 matrix of gas counters, each $5 \times 5\,cm^2 \times 2$ m long. The long dimension should be parallel to the magnetic field. The counters could be enclosed in independent $2 \times 2m^2$ 5 cm thick gas volumes. In each, a plane of 150 wires spaced by 1.3 cm would be connected in pairs or threes to separate linear amplifiers. The proportional (e.g., 7 bit) readout of about 10^4 channels might be formidable. The consequent analysis might permit the simultaneous identification of several high-momentum final state particles. No other solution to this problem has been suggested to our knowledge.

Table I. Proportional Counter Study: Separability of Protons and Pions in an Array of 12 Proportional Counters by the Likelihood Ratio Method With Enhanced Widths. ϵ is the Fraction of Particles for Which the L Range Specified is Found.

	To Select Proton Beam			
L	> 1.0	> 3.0	> 5.0	> 8.0
ϵ_p	85%	60.7%	50.3%	40.7%
ϵ_π	19.2%	6.0%	3.4%	1.8%
Contamination	6.5%	2.9%	2.0%	1.3%
	To Select Positive Pion Beam			
L	< 1.0	< 0.5	< 0.3	< 0.1
ϵ_p	14.1%	6.9%	3.7%	0.5%
ϵ_π	78.4%	60.1%	48.1%	19.1%
Contamination	37.4%	27.8%	20.6%	8.3%

These efficiencies and the π^+/p ratio (≈ 0.3) in the cosmic radiation would imply a certain amount of contamination by the wrong kind of particles whose values are given in the fourth column.

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[8] See, for example, A Practical Manual on the Monte Carlo Method, by E. D. Cashwell and C. J. Everette (Pergamon Press, 1959), p. 9.

[9] G. L. Bashindzhagyan et al., On the Use of Multi-Layer Proportional Counters for Identification of Protons and PL-Mesons in Cosmic Rays, paper presented at 11th International Conference on Cosmic Rays, Budapest, Aug. 1969, (to be published).

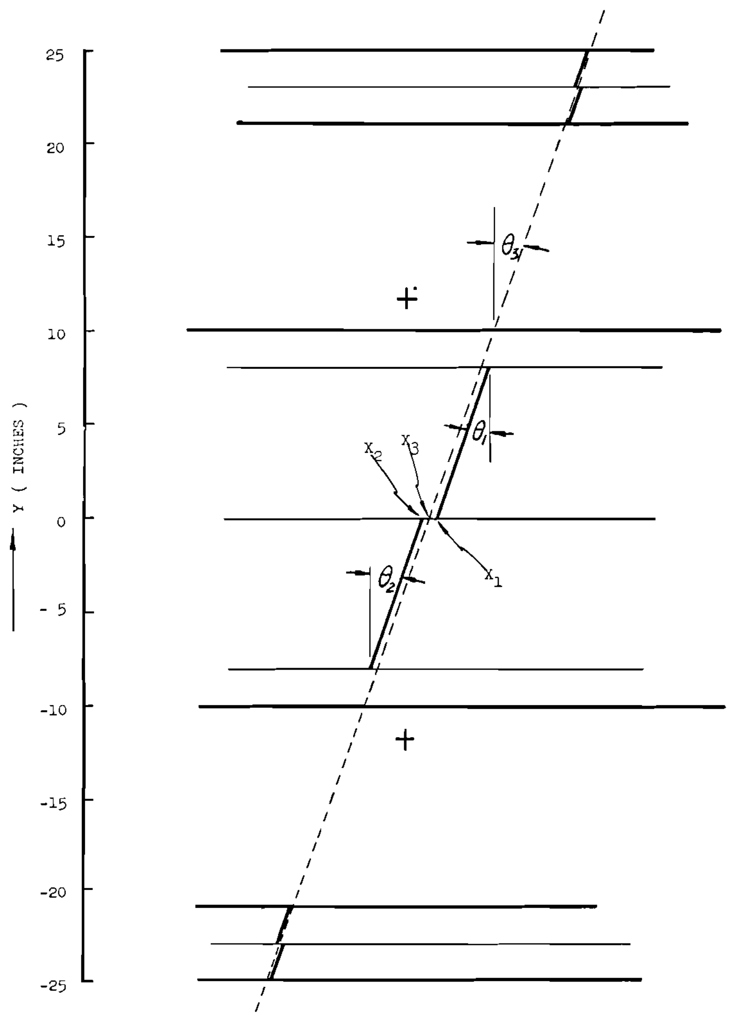

Fig. 1. Method for measuring precision of tracks in a wide-gap chamber.

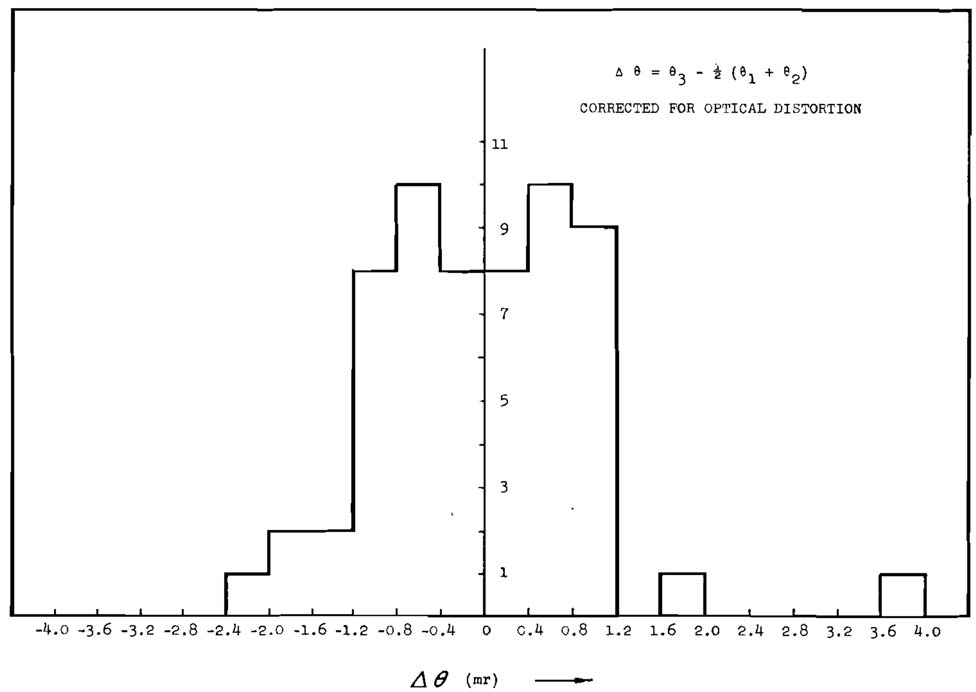

Fig. 2. Angular precision of tracks in a wide-gap chamber.

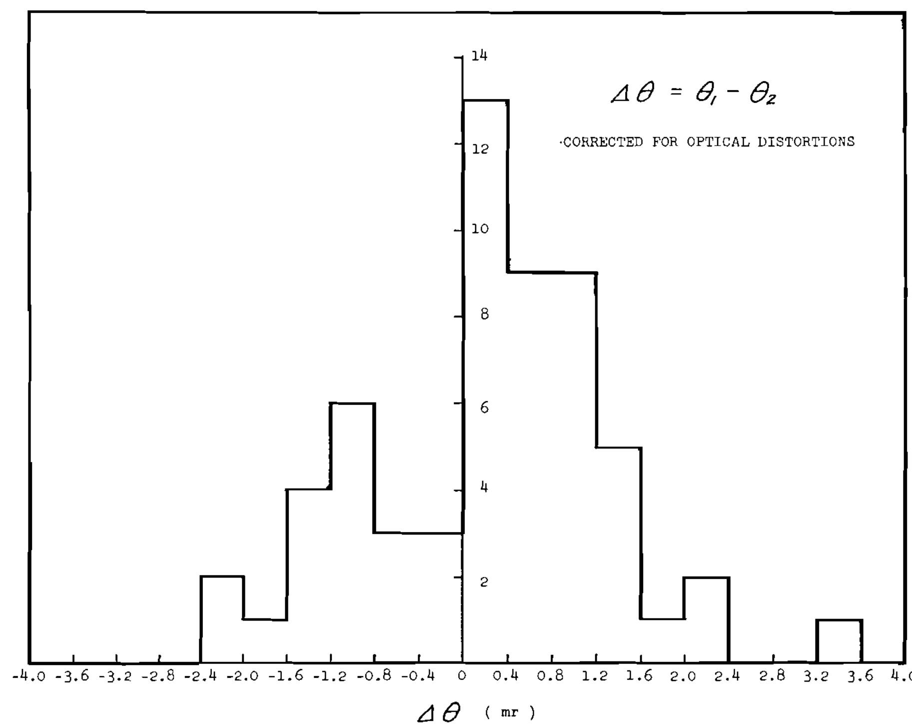

Fig. 3. Difference in apparent angle of a track measured independently in two separate gaps.

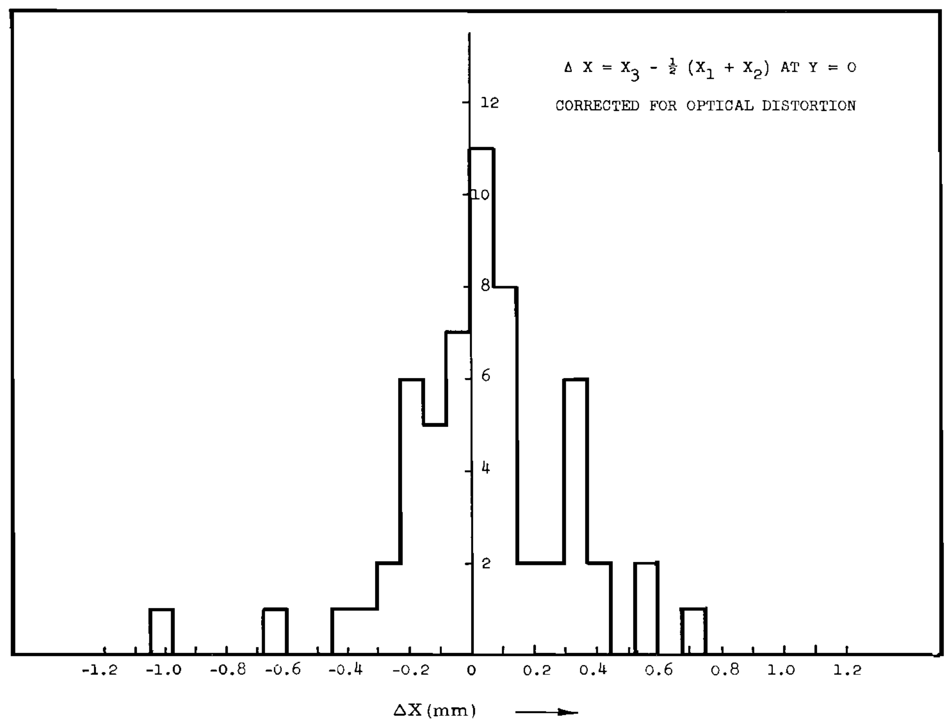

Fig. 4. Apparent displacement of a point on the trajectory as located by wide-gap chambers from the trajectory determined by auxiliary chambers.

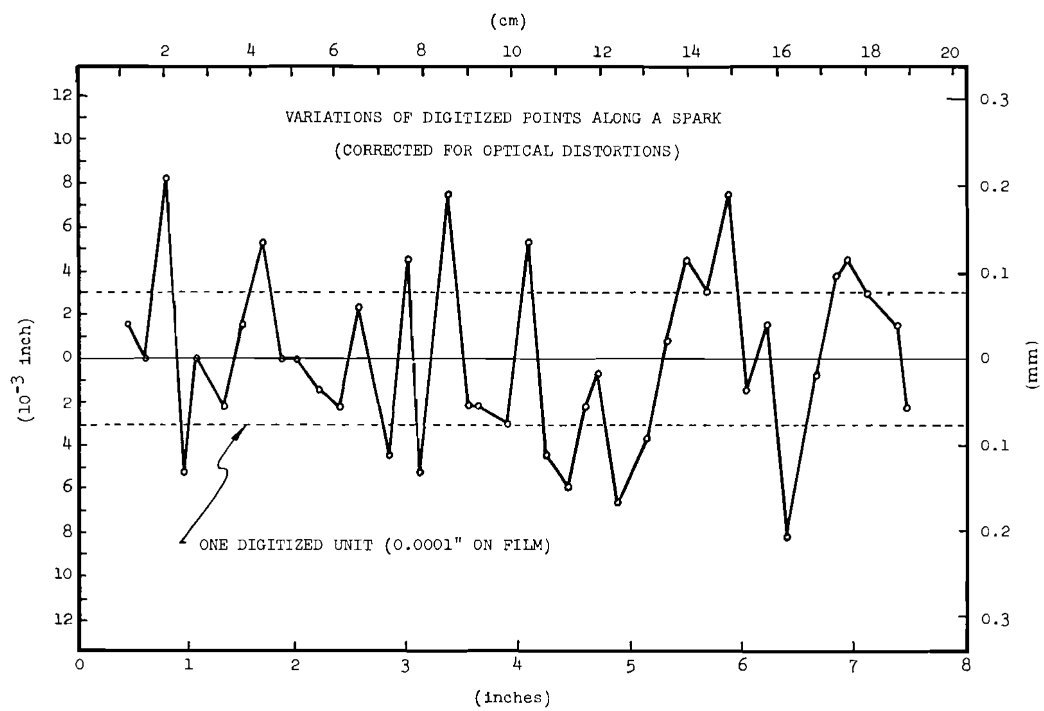

Fig. 5. Scatter of individual digitizations on a single wide-gap spark track.

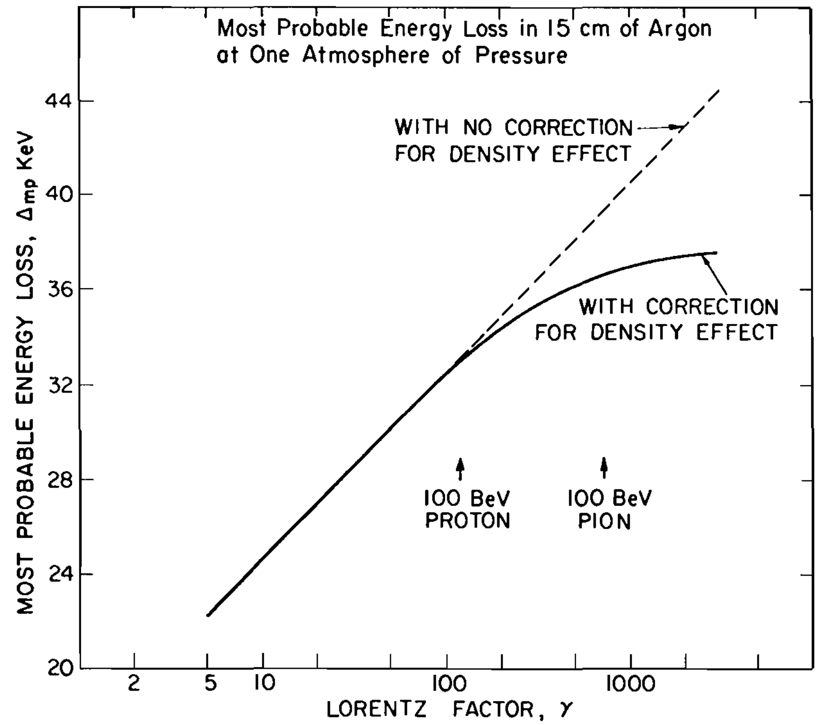

Fig. 6. The most probable energy loss (Landau distribution) in 15 cm of Argon gas at one atmospheric pressure, suffered by an incident singly charged particle with Lorentz factor, γ, is shown as a function of γ.

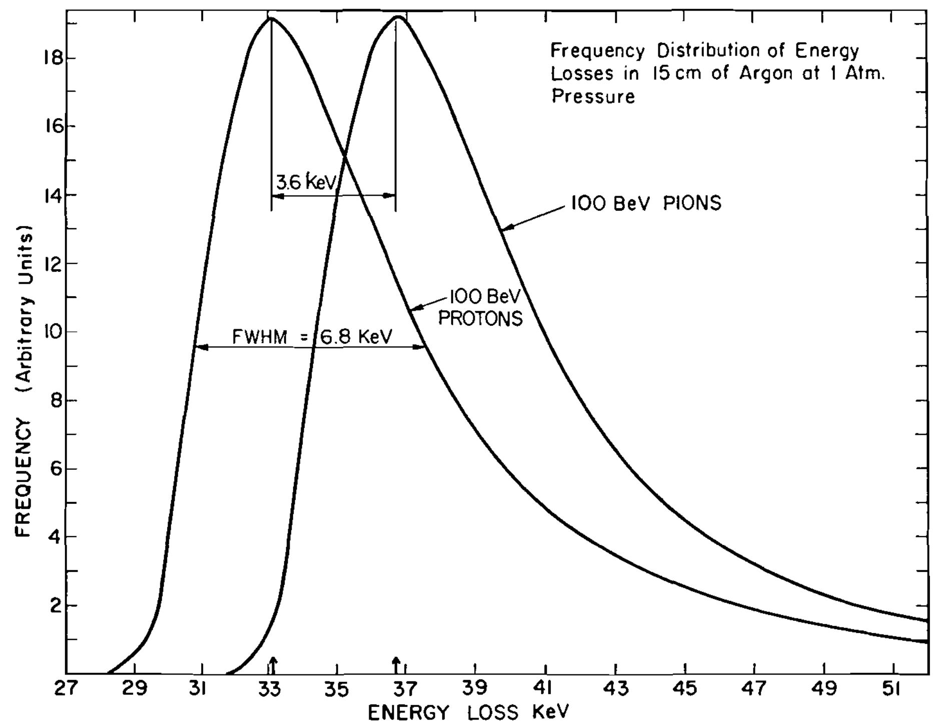

Fig. 7. Landau distributions of energy loss in 15 cm Argon (1 atm pressure) suffered by 100-BeV protons and 100-BeV pions.

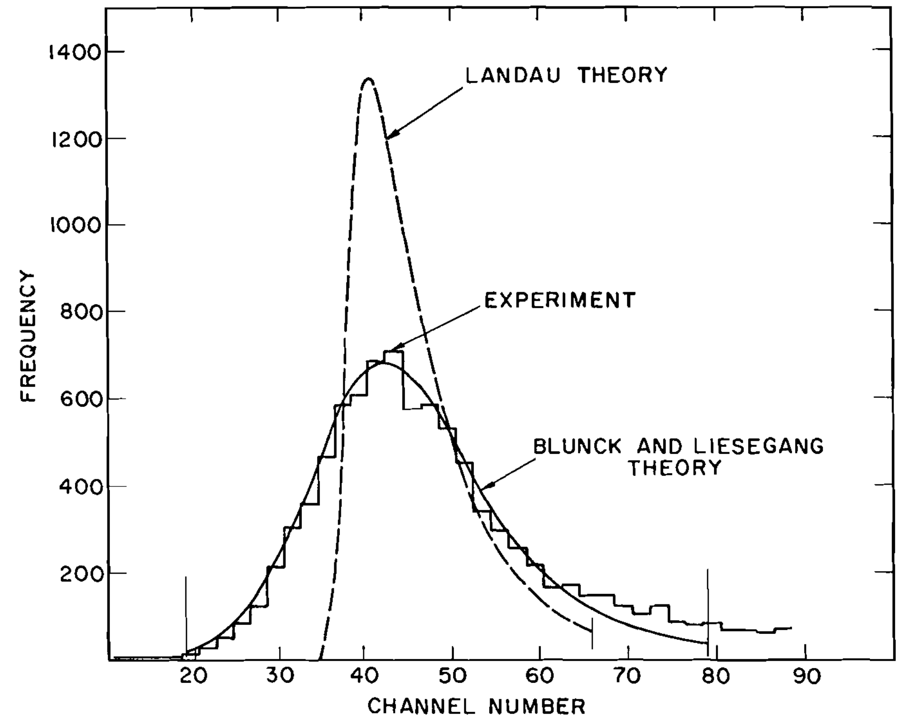

Fig. 8. Experimental frequency distribution of energy losses suffered by 4.0 BeV/c negative pions in a pathlength of 15 cm in the proportional counter; smooth curves are the normalized theoretical distributions based on the theories of Landau and of Blunck and Liesegang.