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ON THE ANALYSIS OF BUBBLE CHAMBER TRACKS

Hugh Bradner and Frank Solmitz

INTRODUCTION

Since its invention by Glaser in 1953, the bubble chamber has become a most valuable tool in high-energy physics. It combines a number of advantages of various older methods of particle detection: it offers high spatial resolution, rapid accumulation of data, some time resolution, and some choice of the nucleus whose interaction one wants to study (bubble chambers have been made to operate with a large number of different liquids, including H_2, D_2, He, Xe, and several hydrocarbons). In order to exploit the advantages of spatial resolution and rapid data accumulation, high-speed high-precision analysis procedures must be developed. In this article we discuss some of the problems posed by such analysis. The discussion is based largely on experience gained in performing hydrogen bubble chamber experiments with the University of California's "Bevatron" (6-Bev proton synchrotron).

Let us first summarize the observational data obtained with the bubble chamber. A charged particle passing through superheated liquid produces a string of bubbles; stereophotography by two (or sometimes more) camera lenses makes it possible to reconstruct the path of the particle in three dimensions. The curvature of the track—in the presence of a magnetic field—is a measure of the momentum divided by the charge; the direction of the curvature indicates the sign of the charge; the number of bubbles per unit track length is a function of the velocity of the particle and its charge; range of a particle stopping in the liquid gives the momentum if the particle mass is known; change of curvature with distance can establish the mass if measurements are sufficiently accurate. Energetic delta rays give some information on the velocity of a particle. Multiple Coulomb scattering can be used in high-atomic-number liquids to give a measure of momentum times velocity. In low-atomic-number liquids, the effect is too small to be useful and merely sets a limit on the accuracy of curvature measurements.

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In addition to observing tracks of charged particles leaving a nuclear interaction, one can also detect neutral particles, either through observation of charged particles coming out of secondary interactions, or through charged decay fragments (in the case of unstable neutral particles).

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(British) gigavolt = bev

barn = 10^{-24} sq. cm

10^{-27} sq. cm

millibarns

THE NEED FOR RAPID ANALYSIS

In many respects the problems of bubble chamber analysis are similar to those encountered in cloud chamber physics, but the relatively high density of liquids makes interactions so much more common that one must learn to deal with a much larger volume of events. Take, for example, an experiment in which 30 π mesons of 1 Gev are passed through a 25-cm-diameter hydrogen bubble chamber at each Bevatron pulse. If the total interaction cross-section were 35 mb, there would be about one interaction per pulse, or 14,000 interactions in 24 hours' operation. About 200 of these interactions would produce "strange particles,"--Λ hyperons, Σ hyperons, and K mesons--decaying in the volume of the chamber. The complete analysis of such an event by standard cloud chamber techniques would require on the order of a day. Thus the analysis of only the strange particles produced in 24 hours of bubble chamber operation would keep one physicist, using standard analysis techniques, busy for the better part of a year.

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NEED FOR ACCURATE MEASUREMENTS

In many bubble chamber experiments one observes several competing reactions, which must be separated on the basis of energy balance and momentum balance between the various particles taking part in the interaction. The more accurately the momenta and the directions of tracks are measured, the more clearly the various types of reactions can be separated. Consider, for instance, the three π-meson-induced processes:

$$\pi^- + p \rightarrow \pi^- + p, \qquad \text{(a)}$$

$$\pi^- + p \rightarrow \pi^- + p + \pi^0, \qquad \text{(b)}$$

$$\pi^- + p \rightarrow \pi^- + n + \pi^+ . \qquad \text{(c)}$$

In all three cases a positive and a negative track leave the point of interaction of the incident π^- meson. The elastic scattering, case (a), can be identified by direction measurements alone: momentum conservation requires the incident π^- meson to be in the plane defined by the outgoing two particles. The momentum of the incident π meson imposes an additional condition on the directions. The charged reaction products in the inelastic processes (b) and (c) may occasionally come close to fulfilling the direction conditions for elastic scattering. In order to get a clean separation one must determine space angles of tracks to about 1° or less. Reactions (b) and (c) may often be distinguished by identification of the positive track (by ionization or by delta rays). When such identification is not possible one may still be able to tell (b) from (c): by energy conservation one can determine the energy of the "missing neutral" and by momentum conservation its momentum and hence its mass. In this way one can determine whether the observed reaction fits (b) or (c). For a clean separation one must be able to measure momenta to within about 10% or less.

ULTIMATE LIMITS ON ACCURACY

The ultimate limit in attainable accuracy of curvature measurements is set by the statistical nature of multiple Coulomb scattering (mCs) on charged particles passing through the liquid. The ultimate accuracy in range measurements is similarly set by the statistical nature of the energy transfers that cause straggling. Thus mCs leads to an rms curvature

$$K_{sc} = \sqrt{2/3}\ \ (21/p\beta)\ \ \sqrt{L/X}\ \ \text{cm}^{-1},$$

where p = momentum in Mev/c,
β = velocity divided by velocity of light,
L = length of track,
X = radiation length.

The magnetic curvature in a field of H kilogauss for a singly charged particle is $K_H = 0.3H/p\ \text{cm}^{-1}$. Thus the fractional uncertainty in magnetic field curvature (and hence in momentum determination) is

$$K_{sc}/K_H = \sqrt{2/3}\ \ (21/0.3\beta H)\ \ \sqrt{1/LX}.$$

In a liquid hydrogen bubble chamber we have X = 15.6 m, and thus

$$K_{sc}/K_H = 1.45/\beta H\sqrt{L}.$$

PRESENT LIMITS
ON ACCURACY OF MEASUREMENT AND ANALYSIS

Although mCs sets an ultimate limit on attainable analysis accuracy, there are many other factors, such as turbulence or optical distortions, which may be more severely limiting in a particular experimental arrangement. For purposes of comparing the various factors, let us consider a "standard" track with momentum 1.0 Gev/c and length 25 cm in a 10-kilogauss magnetic field. ? The sagitta would be 0.23 cm in the absence of mCs, but mCs will make the sagitta unreliable to ± 3%, i.e., ± 70 microns in space. If the image is demagnified in photography by a factor of 15, this corresponds to an uncertainty of ± 5.7 microns on the film. Bubbles are characteristically about 0.3 mm at the moment of photography. Diffraction and depth-of-field effects enlarge the image by a factor of approximately two from the geometrical image, so that the bubbles on the film appear to be circles approximately 40 microns in diameter. It is necessary, therefore, to define the center of a row of bubbles to an accuracy of approximately 1/10 bubble diameter in order to match the mCs limit. It has been found possible to make measurements reproducible to ± 1 micron when film with resolution of 90 lines per mm is used.

MEASURING ENGINE

All measurements are made with respect to fiducial marks of known separation in the bubble chamber, hence the absolute scale of optical demagnification or of measuring-engine calibration are of little importance. The measuring-engine screw must, however, be uniform to within approximately $\pm$ 2 μ in 1 cm of travel if engine errors are to be small compared with mCs.

FILM STABILITY

We have made contact copies, on Panatomic X film, of a grid of lines with 1.0 cm separation. Measurements of these line spacings showed normal variations of $\pm$ 3 μ. Photogrammetric data attest that this amount of nonlinear distortion is to be expected in normally processed acetate-base commercial films, and that distortions as high as 15 μ may occasionally be observed.

Nonlinear thermal expansion of film could produce errors as large as the mCs limit if, for example, the temperature change of acetate-base film were 15°C and nonlinear distortions were as large as 3% of total thermal expansion.

MAGNETIC FIELD

The accuracy of magnetic-field measurements does not present a problem, because curvature measurements on tracks are inherently limited to an accuracy of a few percent, whereas magnetic-field measurements are normally made to an accuracy of a fraction of 1%.

OPTICS

Aberrations and distortions in the optical systems of the photographic equipment and the measuring equipment can be measured and corrected to the necessary accuracy by reference to a precise grid inside the bubble chamber.

TURBULENCE

Although it may be possible to achieve measurements that are limited only by the multiple-scattering effects, our experience indicates that gross motions of the liquid in the hydrogen bubble chamber often introduce momentum errors on 1-Bev/c meson tracks that can exceed the mCs limit. A track image may be displaced from true track position, because of liquid motion subsequent to the bubble formation, or because of aberrations introduced by mixing liquids of different index of refraction. The severity of these effects depends critically on flash delay, chamber recompression time, frequency of chamber expansion, temperature gradients in the chamber, and other physical and operational characteristics of the chamber. Two counter-rotating eddies, 12 cm in diameter, carrying liquid at the rate of 1 cm per second, can produce a track distortion of a 1-Bev/c particle as large as the mCs.

MEASURING AND COMPUTING PROCEDURE ADOPTED

Considerations of measurement speed, optical distortions, and camera aberrations led Dr. L. W. Alvarez to propose analysis by Servo-controlled coordinate measurements on the film, followed by calculation on a high-speed digital computer. The Cartesian coordinates of a set of points on a track (roughly uniformly spaced) are measured on a projection microscope and automatically recorded on punched cards. Such measurements are made on all tracks of an event in two stereoscopic views; in addition, several reference marks are measured in each view. Such a complete event undergoes ~~two principal~~ several stages of computation, ~~a~~ "geometrical" ~~and a~~ "kinematical" one.

[illegible]

Geometrical stage: From the x-y-coordinates points of the each track in the two stereo views, a representative set of points in space is calculated.* ~~This calculation is quite simple in "first-order optics," that is, in the approximation that the sine of the angle of a ray with respect to the optic axis is equal to the tangent. For H_2 bubble chambers, this approximation is adequate only in case all the ray angles are less than about 10° or 15°.~~ In order to describe the orbit of a track in space, the representative points are projected onto a horizontal and a vertical plane. A parabolic fit is made to the horizontal projection and a linear ~~one~~ fit to the vertical projection. (The magnetic field is vertical.) This is an adequate representation of a high-momentum track; however ~~(~~some corrections are necessary for low-momentum tracks~~)~~. The digital computer uses the magnetic field and the parameters of the best-fit curves to calculate and print out the momentum, direction, position, and length of each track, as well as some auxiliary information.

Kinematical stage: The equations of energy balance and momentum balance usually impose some constraints on the interrelations between the momentum components of the observed tracks. The computer calculates those constrained momentum components which most closely approximate the measured values ~~(according to the criterion of "least squares")~~. If the event can be interpreted in several different ways, the computer is made to calculate the best fit on the basis of each hypothesis. The relative goodness of fit may then allow one to choose among the various hypotheses.

The computations described above are currently carried out on an IBM type 650 magnetic-drum data-processing machine with a memory capacity of 2000 ten-digit words and a speed of about 100 multiplications per second. The analysis of events in the 72-inch hydrogen bubble chamber, now nearing completion at Berkeley, will be sufficiently more complex to require the use of an IBM 704 electronic data-processing machine (8192 memory locations, 4000 multiplications per second).

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*(See, for instance, Bassi et al., Nuovo cimento 5, 1729 (1957) for a discussion of bubble chamber stereoscopy).

PRESENT LIMITS ON ANALYSIS SPEED

Measuring the coordinates along tracks of an event by means of ordinary microscopes can require more than an hour; the measurements are particularly subject to operator error when they are made on a routine basis for many hours. J. V. Franck's group has developed a projector for making rapid, error-free measurements of the coordinates along track images. The machine is basically a projection measuring engine with servomotor control of the engine stage position, to provide automatic centering of the image while the stage is being translated at speeds up to 2.5 mm per sec, and coordinates are being recorded in IBM punched cards. The precision of the machine depends upon the use of carefully designed servo loops, and of accurate lead screws. X and Y lead screws, each with a correction bar, can move the stage 12 cm in the X direction and 7 cm in the Y direction. Coordinate measurements are made by determining the angular positions of the 1-mm-pitch lead screws, by means of rotary encoders. The accuracy of tracking can be continuously monitored by observation of a cathode-ray tube mounted at the lower edge of the viewing screen. The film being measured is projected at 30 diameters magnification on a transmission-type viewing screen. Illuminated cross hairs on the screen give visual indication of the region of the track being measured. The film is rigidly held to the moving stage by a vacuum platen, so that measurements are made with respect to a fixed optical axis.

cm?

Wang digitizer?

With this "Franckenstein" measuring projector, a good operator can record all the data from a normal event in 5 minutes, and will average ten events on a routine 2-hour shift.

Computation of an event from IBM punched-card coordinate data requires 2 to 5 minutes.

Study of the output result from the IBM computation averages 10 to 30 minutes per event, depending on the experiment. This individual scrutiny and remeasurement or recalculation of questionable events is now the most time-consuming part of the data reduction.

PROBLEMS OF HANDLING LARGE NUMBERS OF EVENTS

The large number of possible reactions, the variability of appearance of interactions, and the importance of being alert to possible new phenomena make it very important for a trained physicist to look at the bubble chamber pictures. Cataloging of events and maintaining broad cross-indexing with minimum expenditure of time is very important. Sketches or photographs of events--whether understood or not--have proven very important for interpreting and evaluating the numerical results of the IBM computations. Quick photographic projection prints are made directly on the scanning machine with "copy-rapid" type of paper in all cases that are considered to be unusually interesting, or of uncertain interpretation at the time when they are first observed. The sequence of events in a characteristic experiment is as follows:

1. The film is searched for interesting events. Events are recorded, by frame number and type.
   - "Rush" events are given special handling.
   - "Peculiar" events are given to a physicist for further study.
     - A photoprint is made and filed in the "Zoo" book.
   - "Normal" events are sketched by the physicist.

2. Events are measured on "Franckenstein" by reference to the sketch.

3. Momentum, angles, etc. are calculated for each track by use of a digital computer.
   - If the computation gives an unreasonable answer, an error card is printed.
     - The physicist studies the error card and corrects the sketch.
     - The event is remeasured and rerun through the computer.
   - If the computation gives a reasonable answer, Step (4) follows.

4. A kinematics computation is carried out via digital computer.
   - If the computation gives an unreasonable answer, an error-output sheet is printed.
     - The physicist studies the output sheet, and reruns Steps (1), (2), (3), and (4) as needed.
   - If the computation gives a reasonable answer, a record is made in the master log.

5. Events are tabulated or sorted according to such items as angular distribution, up-down asymmetry, branching ratios in production, and cross sections.

SUMMARY

The need for rapid precision analysis of bubble chamber photographs has led to the method of analysis adopted at the University of California Radiation Laboratory. The choice of this method was dictated by the necessity of developing a system quickly. The accuracy of measurement is sufficient to match the present operating conditions of the chamber; the speed of measurement and computing has been sufficient to keep up with the rate of accumulation of "strange particle" events. The bottleneck at present is the examination of individual events after computation.

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