direction every time it reaches this tape, but at the highest or lowest level the operator has to set the *Stereomat* to a new contour.

AUTOMATIC ORIENTATION MODE

In this mode of operation, which can be used for the relative orientation, the operator inserts two plates, zeros the $Y$ parallax in the two Kappa stations and actuates the automatic orientation mode. The space rod carriage moves automatically through a programmed sequence of orientation stations continuously removing the $Y$ parallax while approaching each station and not moving to the next station before the position is reached and the $Y$ parallax is zero. The speed of this procedure is controlled by the correlation signal while movement of the $Z$ carriage is used to null the $X$ parallax. The usual time required to perform automatic relative orientation is from $3\frac{1}{2}$ to $4\frac{1}{2}$ minutes.

## Conclusions

The B-8 *Stereomat* represents a major technological advance towards completely automatic photogrammetric mapping. It is the first automatic instrument to be carried through development to a practical working equipment capable to meeting normal standards of accuracy and economy of operation.

The automatic relative orientation and contouring do much to relieve the usual drudgery of these operations. The real time production of high quality orthophotography provides an excellent planimetric base for map substitutes or compilation by normal color separation procedures. In addition the automatic profiling and digital recording of stereo model coordinates (available as an option) make the instrument adaptable to many other commercial and industrial applications.

The B-8 *Stereomat* represents the culmination of seven years of continuous research which have brought automatic mapping from an ideal in the photogrammetrist's mind to a practical reality.

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# *The Photogrammetry of the Tracks of Elementary Particles in Bubble Chambers* ‡*

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In high-energy particle physics the initial problem is to obtain information about the behaviour of particles which are invisible by any known means (the radius of a proton is $10^{-13}$ cm.) and which may be travelling at speeds greater than 180,000 miles per second, but at less than the speed of light. Some of the work is being done with the use of electronic counters, but the larger fraction is currently done by three techniques which employ the photographic process. These are the silver halide emulsion stack, the liquid hydrogen bubble chamber and the spark chamber. Counters provide immediate information but it is of a yes-or-no character, whereas the other methods are capable of actually mapping, with varying degrees of accuracy, an interaction between particles.

The emulsion stack is quite familiar and need be discussed only briefly.[1] Since individual silver halide crystals are rendered developable along the paths of charged particles, a sensitive detector may be built up with thick layers of specially sensitized emulsion having no base support. As the path of the particle may be through several emulsion layers and the track must be measured under a microscope, it is important to make each layer as thick as possible to lessen the problem of following the tracks from layer to layer. The usual compromise between the problems of scanning and those of processing these thick pellicles is to use emulsion slabs of 400 to 600 $\mu$ in thickness. As a 400 $\mu$ pellicle swells to over 1,600 microns during processing and dries down to about 200 $\mu$, due to the removal

* Work performed under auspices of the U. S. Atomic Energy Commission.
‡ Prepared for presentation at International Congress for Commission V.

of the undeveloped silver halide, the technique is subject to severe overall and local distortions which limit its usefulness. An emulsion stack is a relatively inexpensive, compact, continuously sensitive and readily portable detector. Among its disadvantages is the fact that it is a complex target of many different atoms. Moreover it provides no time resolution, induces a great deal of scattering and enclosure in a magnetic field is impractical.

Spark chambers are the newest devices to be used in particle physics.[2] They were developed over a period of years, but the addition of a pulse triggering technique in 1957, and the refinement, announced in Japan in 1959, of operating them in an atmosphere of neon, made these devices much more successful. A spark chamber depends on the fact that a charged particle passing through an arrangement of spaced metal plates in neon gas creates a path of sparks when a suitable voltage differential of about 10KV per cm. of gap is imposed. These sparks are photographically recorded in stereo pairs as is shown in Figure 1. The trail of ionization left by the passage of the charged particle apparently causes a preferential breakdown of the neon and thus sparks form along the tracks.

In addition to its relative simplicity and reasonable cost, the spark chamber has the appreciable advantage that when used in conjunction with an array of electronic counters, it can be selectively triggered. The chamber retains information about the path of the particle for about one-half microsecond. If information from the counters is favorable, voltage is applied and sparks created during this period. This results in a greater incidence of interesting events, which is an advantage over the statistical approach of the bubble chamber where every pulse of incoming particles is recorded without knowledge of the actual events. A sweeping electrical field is continuously applied to erase old paths of particles which gives a picture with very little background. The spark chamber suffers, however, from being a complex target, and its resolution is low as the sparks scatter somewhat from the exact path of the particle.

The bubble chamber, invented in 1952 by Donald Glaser at the University of Michigan and for which he received the Nobel prize, is a lineal descendent of the cloud chamber developed by C. T. R. Wilson starting in 1896. One superiority of the liquid chamber as compared to the original gas chamber is that the higher

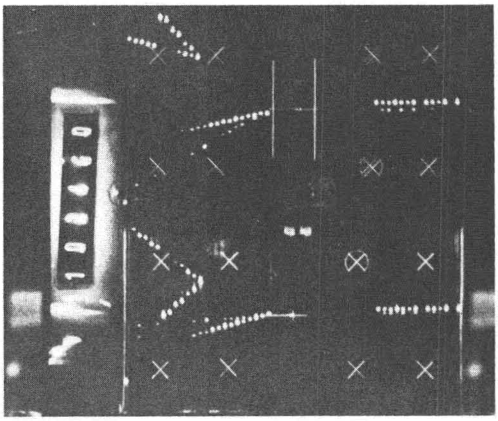

FIG. 1. A typical spark chamber photograph with a mirrored stereo view.

density of the liquid increases the probability of interactions in a given volume by two orders of magnitude. There is also less turbulence in the liquid and hence greater precision. In a bubble chamber a liquid, such as liquid hydrogen at $-248°C.$, is first held under pressure to prevent boiling. Upon abrupt, momentary release of the pressure, bubbles form where ionization took place along the paths of charged particles due to local thermal effects. Photographs are made at stereo angles of 10–20 degrees from a minimum of three camera positions at a demagnification of 5–15. The chamber is then recompressed to permit the cycle to be repeated. Such a device is able to produce a very large quantity of photographs when operated in conjunction with a high-energy accelerator capable of generating a beam of particles roughly every 1.6 seconds.

A typical single investigation calls for 100,000, or more, triads, and the yearly schedule for three bubble chambers operated with the 32 Bev Alternating Gradient Synchrotron at the Brookhaven National Laboratory, Upton, N. Y., runs into a few million photographs. Thus it has become possible to record the production, interaction and decay of elementary particles at a rate in excess of our sensible capacity to analyze them.[3]

Some 14 years ago cloud chambers were sent aloft in balloons or carried up high mountains in the expectation of recording only a few interesting events per day, but the modern bubble chamber will produce, typically, 20,000 triads a day. Chambers have also increased in size and complexity. For example, a bubble chamber 203 cm.$\times$75 cm.$\times$75 cm. containing 1,500 litres of liquid hydrogen has been built. With its magnet it weighs 450

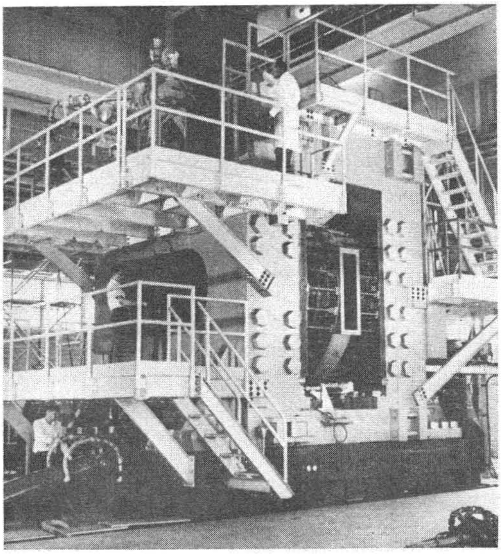

FIG. 2. The 203 cm. bubble chamber at the Brookhaven National Laboratory. The cameras and illumination port are on the middle balcony at the left with access to the chamber through a 165 mm. optical glass window. A hydraulic ram at the lower left is used to provide lateral motion and the whole 450 ton assembly can be rotated on a turntable beneath.

tons and requires five megawatts of power. It is shown undergoing final assembly in Figure 2. Such chambers will be operated and controlled, in part, by computers.

The nature of the photographic images can be seen in Figure 3 which is one of a triad from the 76 cm. bright field chamber. The tracks are recorded on the 70 mm. film as high contrast images of separate, or sometimes overlapping, bubbles having a diameter on film of 25–30 $\mu$. Also recorded are the external or "road" fiducial marks and the internal fiducials which are engraved on the chamber window. The picture number is in both Arabic and binary coded decimal form so that it may be read by both human operators and automatic equipment. The parallel tracks are the incoming beam which, if no interaction is produced, represent undesirable noise. The number of incoming tracks is controlled to a quantity representing a balance between the probability of an interaction and the undesirability of cluttering the image.

The physicist is interested in obtaining data from these photographs which will allow him to identify the nature of the interactions and the products thereof. Because the paths of the particles are at right angles to the magnetic field the tracks are curved. From knowledge of the curvature and of the magnetic field, the momentum and the sign of the charge of the particle can be determined. In addition to the curvature, the spatial distribution of the reaction products, in relation to each other and to the incoming particle, is required for analysis of the event.

The first step in "getting the physics out" is a scanning to locate significant events for measuring. The simplest form of scanning is done on optical projection machines which present any view of the triad at original size. A trained operator can scan some 400 pictures per day. The measuring process has consisted of recording on tape, for subsequent computer input, the location of the fiducial points and the coordinates in space of points along the significant tracks. Measuring machines of both projection and microscope viewing types have been built which assist the operator with various degrees of automation. At Brookhaven the machines automatically center on a track, but the motor driven stage must be guided by the operator who also determines the points to be recorded. Depending on the direction of the track in relation to the camera positions the stereo base line is shifted to the most advantageous pair. Some chambers are built with the minimum requirement of three camera positions, while the 50 cm. and 203 cm. chambers have four, representing a safety factor in operation, and giving a slightly more advantageous view of tracks at certain angles. With such semi-automatic equipment four events can be measured per hour.

A basic improvement in the measuring projector has been carried out at the Lawrence Radiation Laboratory of the University

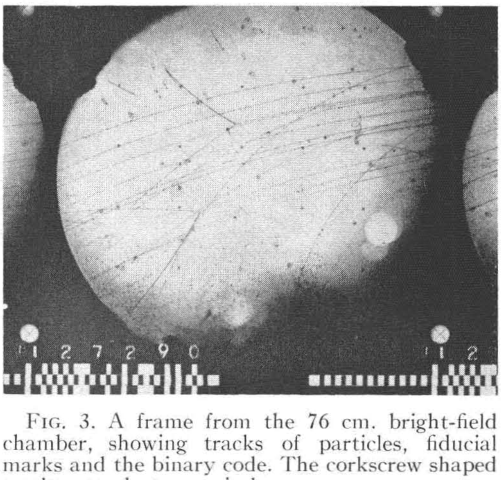


FIG. 3. A frame from the 76 cm. bright-field chamber, showing tracks of particles, fiducial marks and the binary code. The corkscrew shaped tracks are electron spirals.

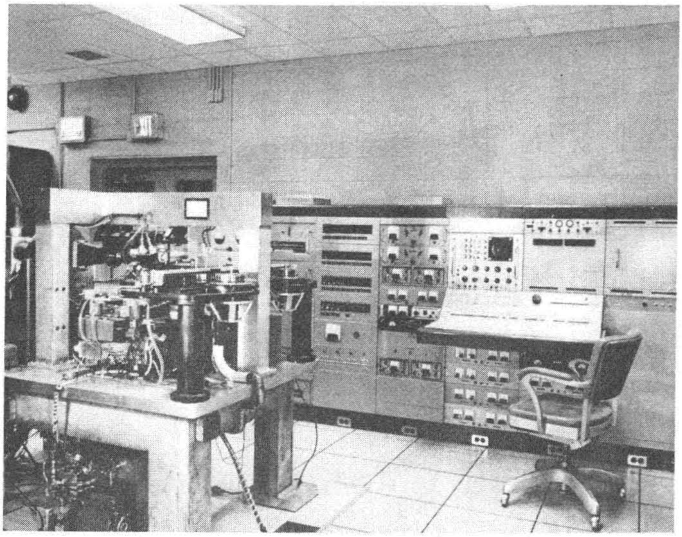

FIG. 4. The Mark I Hough-Powell flying spot digitizer with its associated control equipment.

of California, at Berkeley, under the direction of L. W. Alvarez. This new measuring instrument is called the SMP for Scanning and Measuring Projector. As in an ordinary scanning projector the bubble chamber image is projected on a horizontal table. The operator moves a circular aperture about 6 mm. in diameter along the tracks to be measured. The portion of the image transmitted through the aperture is caused to move in a circular path by a rotating mirror assembly underneath the table surface. In its motion the image in general, and the track being measured in particular, passes over five holes called "bench marks" distributed in a 1 cm. $\times$1 cm. square array over an opaque sheet below the scan table surface. By measuring the angle of the rotating head when the track passes over a bench mark, its position in the original projected image is accurately determined. The coordinates so measured are transmitted directly to a digital computer. This collaboration of man and computer can measure about 10 events per hour.

The general need for processing more data than is possible with existing techniques led to a proposal in 1960 by P. V. C. Hough and B. W. Powell, then at l'Organisation Europeene pour la Recherche Nucléaire (CERN), for a flying spot digitizer which would transfer the track coordinates directly to the memory of a computer.[4] Since then Hough-Powell machines have been built at CERN, at the Lawrence Radiation Laboratory, at the Brookhaven National Laboratory and elsewhere. The mark I version for 35 mm. film with its associated control equipment is shown in Figure 4. A mark II model for 70 mm. film, which is now under construction, is shown in Figure 5. The method of generating the spot shown diagrammatically in Figure 6, is one familiar to early workers in television.

A rotating disk contains eight approximately radial slits each 20 $\mu$ wide. Light from a high pressure mercury arc, passing through the radial slits and a fixed slit, eight miles downstream, forms a fine spot of light which traverses a line 480 times per second. Appropriate curvature of the slits ensures a square shaped 20 $\mu$ aperture moving at a constant speed. The spot is reduced 2.1$\times$ and split optically to both a bubble chamber film frame and a precision grating consisting of 16 $\mu$ wide strips alternately clear and opaque. By counting grating lines and interpolating between them, the coordinate of the flying spot in its direction of motion on film is known to a few microns.

The film, held by vacuum to a precision stage, is moved in the coordinate perpendicular to that of the flying spot at a rate of 1.5 cm./sec., giving a line separation of 30 $\mu$. As the diameter of the spot on the film (with aberrations) is 15–20 $\mu$ in diameter, and bubble images are typically 25–30 $\mu$, the 30 $\mu$ line spacing ensures that every bubble is located by the flying spot. The stage motion is digitized by reference to a moire fringe pattern.

The flying spot is attenuated by the bubble image some 25–75%, depending on the direct-

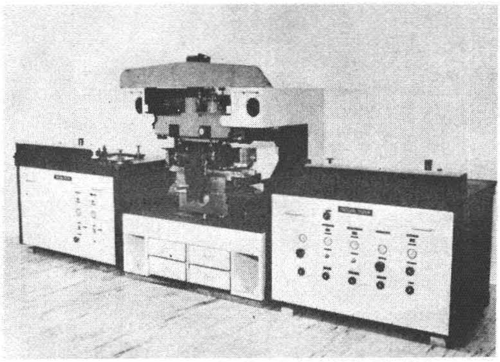

FIG. 5. The Mark II Hough-Powell which is now under construction for 70 mm. film.

ness of hit and the photographic and operating parameters of the bubble chamber. The width of the bell-shaped attenuation curve is roughly the sum of the spot and bubble diameters, i.e. 40–50 $\mu$. It is possible to find the center of the area of the attenuation curve to a standard deviation of 3–4 $\mu$ from the much larger full width at the base. The flying spot coordinate is thus of a precision comparable to that obtained from a measuring projector, but some 16 flying spot points are obtained for each measuring projector point, so the accuracy is potentially four times greater. In practice the system operates with a standard error of 1–2 $\mu$.

When a bubble center is found the grating count is trapped electronically, temporarily stored until the I.B.M. 7094 computer is free to accept it, and then transmitted. At the completion of each scan line the perpendicular stage ordinate is transmitted. Thus the flow of information into the computer consists of a series of ordinates of bubbles encountered on one scan line, the coordinate of the scan line itself, the same information for the next scan line, and so on, until some 2,000 scan lines have been traced and from 15,000 to 40,000 coordinates have been stored. The possibility of a track which runs parallel to the scan line is dealt with by the ability to turn the scan at 90 degrees upon computer instruction.

Figure 7 is an original bubble chamber photograph from the 50 cm. chamber which, as is indicated in the accompanying diagram, contains the production and decay of both a cascade and an anti-cascade particle. Figure 8 is a photograph of the display on a cathode ray tube of the digital information contained in the computer memory after the frame in Figure 7 was scanned by the Hough-Powell machine.

The scan of a bubble chamber frame is completed in four seconds and the stage is returned in two seconds. As the next frame to be measured may be at some distance along the roll of film, it is desirable to move the film quite rapidly to conserve computer time. This is done by using vacuum capstans to drive the film and vacuum tanks for tensioning, much in the manner that tape is moved in a computer. This has allowed a film transport of six meters/sec. All the frames of interest are scanned on one film roll and then the other two rolls are successively fed through the Hough-Powell to transmit the entire triad. Thus the measuring time for one event is 18 seconds as compared to the 15 minutes required on a standard measuring projector.

Since efficient use of the computer is essential, the operation of the flying spot digitizer

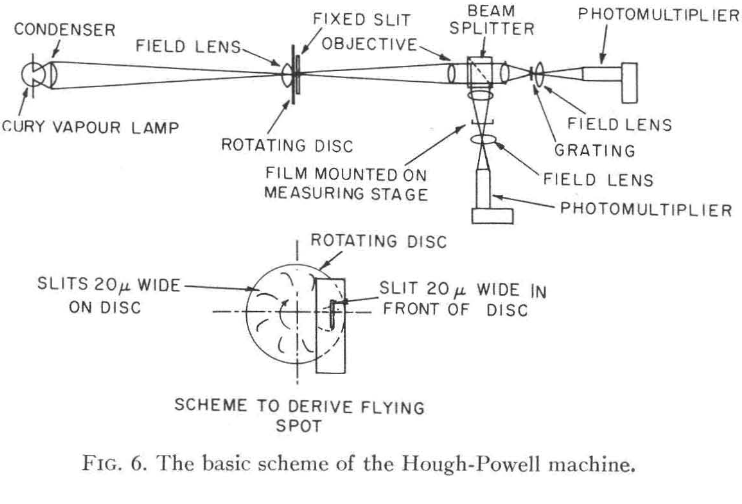


FIG. 6. The basic scheme of the Hough-Powell machine.

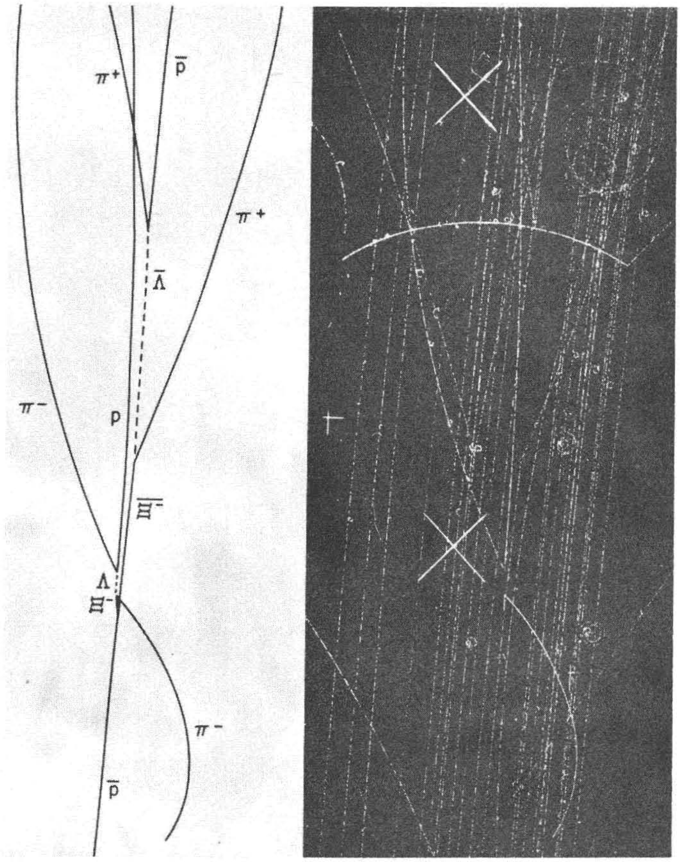


FIG. 7. Part of a frame from the 50 cm. chamber. The associated diagram shows the production and decay of both a cascade and an anti-cascade particle.

cannot be left to a human operator but is put under the control of the computer with information flowing into the computer and instructions fed back to the Hough-Powell machine. Thus, on command of the 7094 to move to a particular picture, the Hough-Powell computes the picture number difference and programs the acceleration and deceleration of the film.

In principle it is possible to program the computer to recognize the picture starting from the individual bubble coordinates, and a promising program has in fact been written by R. Marr and G. Rabinowitz of the Applied Mathematics Department at Brookhaven.[5] Such "pattern recognition" by computers is just at the frontier in their rapid encroachment on once purely human domains of activity. A year or two of development will be required for consolidation of the advance, for testing in physics applications and for integration with the computers, just now becoming available, which provide sufficient computing speed per dollar for economically justifiable replacement of human scanners.

In the interim, human guidance of the computer is established at a conventional scan table, as shown in Figure 9, by the rough digitizing of three points along each track, together with the external or "road" fiducials. These coordinates, together with the picture number and a number indicating the geometry of the event, are stored on punched cards. This information is used by a 1401 computer to produce scan tapes for each view. When the scan tape is read by the computer it instructs the flying spot digitizer to move the film to the required picture number and make a measuring scan of the frame. The rough digitized points are used by the computer to construct an arc of a circle with an error band on each side of the arc. These "roads" are about 300 $\mu$ wide on the film, and the computer will now accept only those coordinates

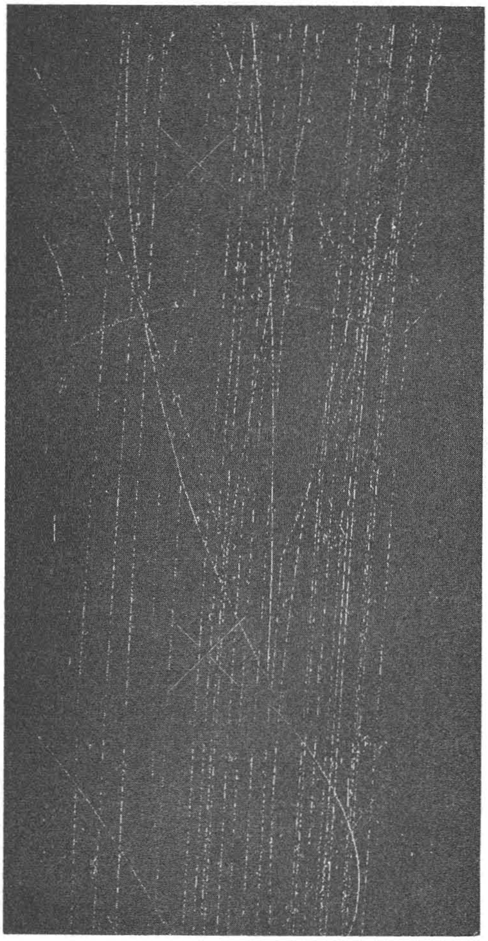

FIG. 8. A cathode ray tube presentation of the output from the computer memory of the frame in Fig. 7.

within the roads ignoring the rest. In practice it has proved very difficult to filter out the extraneous information contained within the roads, such as crossing tracks, bits of electron spirals, parallel tracks, etc. At the time of writing, one picture in five may require human intervention, so work on the filter program continues.

Figure 10 is a cathode ray tube display, with a grossly exaggerated vertical scale, which shows that the filter program has successfully handled two parallel tracks within the road. The X's, with the exception of the end points which mark the extremes of the track, are master points generated by the computer by averaging bubble coordinates. In Figure 11, however, the computer has been thrown off by tracks which cross through gaps in the track being measured, and has generated erroneous master points which must be eliminated in the next stage of the filtering program. Bubble distribution along the tracks is determined by a hit-miss sequence of digitizing. This is an important constraint used in the later analysis program. Groups of coordinates are averaged for greater accuracy and to compress the information into the subsequent analysis programs called "Fog-Cloudy-Fair," which involve typically about 50,000 words of machine-language programming and several minutes of 7094 computing time per event.

An independent and rather different approach to pattern recognition by machine is being investigated by I. Pless, of the Massachusetts Institute of Technology, with the collaboration in programming of Horace Taft of Yale University and A. H. Rosenfeld of the Lawrence Radiation Laboratory. Rather than communicate to the computer the coordinates of individual bubbles, Pless's instrument is designed to recognize the line segments of which the tracks can be considered to be composed. An individual line segment in the picture is detected, and its position and direction determined, by projecting a short line segment generated on a cathode ray tube onto a negative, and sweeping in both position and angle until a match is obtained.

The bubble chamber information presented for analysis by a computer is not a perfect

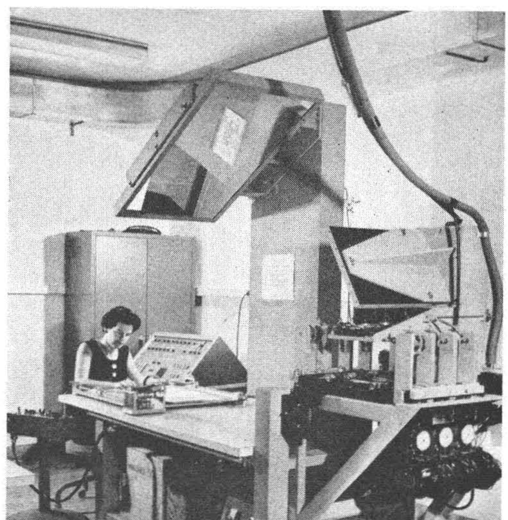

FIG. 9. A scanning projector equipped for rough digitizing.

representation of the event because the chamber itself does not provide a perfect recording medium. The particle tracks which one wishes to measure are influenced by near misses with protons in the chamber, therefore displaying spurious scattering. The chamber may exhibit turbulence due to non-uniform temperature throughout the volume, and the magnetic field may not be uniform. The system suffers from the conventional optical and photographic distortions.

The computer is programmed to reconstruct the event in space, and to look for the possible solutions for the topology indicated by the event type number which has been assigned by the scanner. Among the requirements that must be met are that momentum, charge, and energy must be conserved in the interaction. The momentum is proportional to the curvature of the track in the magnetic field. Momentum and velocity define the mass of the particle, but as particles approach the speed of light they reach a minimum ionizing value and bubble distribution can no longer define velocity. If momentum cannot be balanced a neutral particle must be postulated. The charge of the ionizing particles is given by their direction of curvature in the magnetic field.

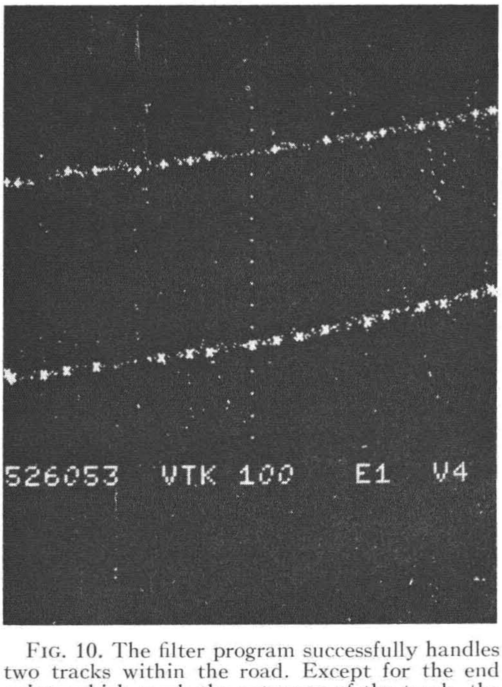


FIG. 10. The filter program successfully handles two tracks within the road. Except for the end points which mark the extremes of the track, the X's are master points which are generated by averaging.

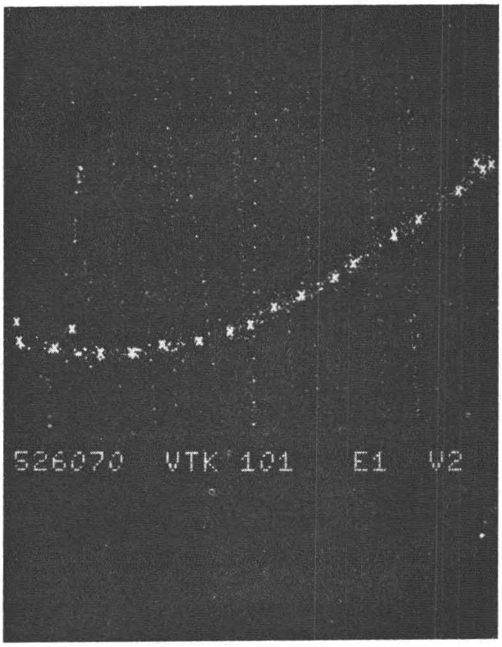


FIG. 11. The program is thrown off by tracks crossing through gaps in the main track and generates erroneous points which will be eliminated in the next stage of computer filtering.

As an example, in one experiment protons of a known energy were passed through the liquid hydrogen bubble chamber. Trained scanners looked for events having four outgoing prongs. Events of this topology will involve the production of two or more mesons. The three principal final states will be (I) proton, proton, $\pi^+$, $\pi^-$ (II) proton, proton, $\pi^+$, $\pi^-$, $\pi^0$, and (III) proton, neutron, $\pi^+$, $\pi^+$, $\pi^-$. These four prong events are found with a frequency of about one every ten frames and several thousand were collected from the experiment.

The sequence of analysis is as follows:

(I) The momentum of all the visible prongs is summed.

(II) If momentum balances, the energies of the outgoing prongs are summed. (This value will equal the incoming energy when the correct masses are assigned to the particles.)

(III) If momentum does not balance, find the missing momentum by subtraction.

(IV) This, combined with the total outgoing energy of the visible tracks, give the mass of the missing neutral particle and thus identifies it.

The answers from the computer are in terms

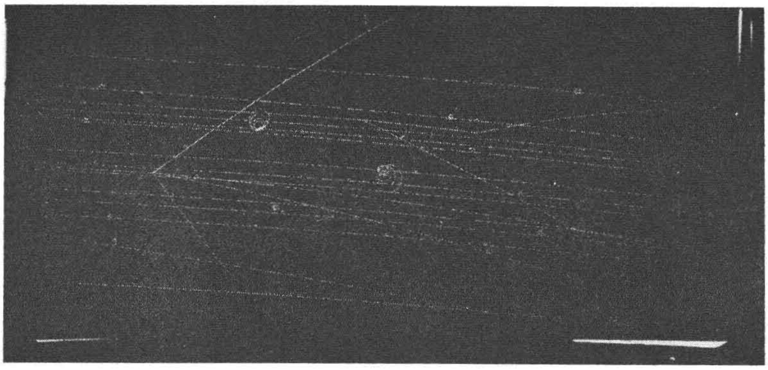

FIG. 12. A four prong event as discussed in the text.

of how much it had to distort the tracks in space to make a kinematic fit for these possibilities, thereby leaving the final decision to the physicist.

After the particles are identified, a study is made of the distribution of the momenta and angles of the nucleons (protons and neutrons) and pions. Also the data are examined for possible correlations between pairs of particles. For example, the $\pi^+$ particle may be found to leave the interaction center in association with one of the protons. From such studies one can form a model, or theory, of the interaction, and learn something about the fundamental problem of the role played by the $\pi$ meson in holding the protons and neutrons of the nucleus together.

The attack on the problem of bubble chamber data by means of the flying spot digitizer has been an international effort by several groups, at CERN under B. W. Powell, at the Lawrence Radiation Laboratory with H. S. White who has designed the overall program system, and at the Brookhaven National Laboratory under P. V. C. Hough. R. B. Palmer of Brookhaven and other members of these laboratories, including the Rutherford Laboratory, Harwell, England, have made contributions. The author gratefully acknowledges the assistance of P. V. C. Hough and E. L. Hart of Brookhaven in the preparation of this paper, as well as the help and criticism of L. E. Varden of Columbia University.

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