FSU HEP 75-6-5

MASTER

FLORIDA STATE UNIVERSITY

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IONIZATION IDENTIFICATION OF CHARGED PARTICLES IN BUBBLE CHAMBER EXPERIMENTS

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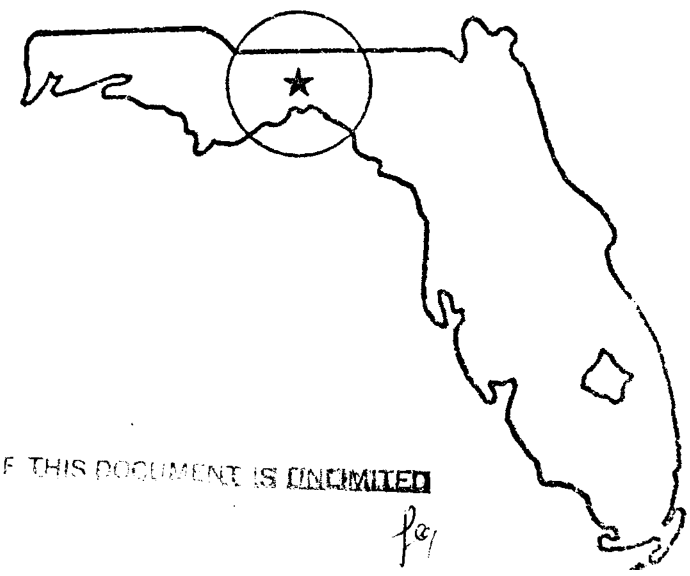
June, 1975



THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

IONIZATION IDENTIFICATION OF CHARGED PARTICLES IN BUBBLE CHAMBER EXPERIMENTS

by
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A Thesis

Submitted to the Department of
Physics in partial
fulfillment of the requirements for
the degree of Master of Science

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May, 1975

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ABSTRACT

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A computer program has been developed which identifies charged particles from bubble chamber photographs by comparing the pulse height information from an automatic measuring device (The Spiral Reader) to an expected ionization of various mass charged particles. Of all identifiable tracks made by charged particles of momentum below 1500 MeV/c, 70% were identified correctly, 28% could not be identified and 2% were incorrectly identified. Since a kinematical analysis takes precedence over ionization identification, only 16% of all events needed to be sent to human operators for identification. The identification programs in misidentification of 2% of all identifiable tracks corresponds to less than 1% of all events being incorrectly identified.

ACKNOWLEDGMENTS

The author is indebted to his major professor, Vasken Hagopian, for suggesting the problem and for his invaluable assistance in the development of the necessary computer code, to Sharon Hagopian, for her assistance in the gathering of preliminary background literature and to John R. Albright for his aid in the development of the presentation of bubble formation theory.

The author wishes to extend his appreciation to John Richey for his help in adapting established computer programs and to Oak Ridge National Laboratory and the University of Tennessee for carrying out measurements of the film on the Spiral Reader.

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I. INTRODUCTION

In high energy bubble chamber experiments, photographs of the chamber are taken in large quantities. Typical experiments have over 500,000 stereotriplet photographs.

The first step in analyzing these photographs is called scanning, the purpose of which is to locate the events of interest and eventually uniquely identify each of the particles involved. To do this the tracks made by charged particles must be measured and the three dimensional event must be reconstructed from the three photographs of the event. The energy and momentum of all charged particles in the event is then computed by using the curvature of the tracks (the chamber is in an external magnetic field). The process of attempting to identify the mass of each particle then begins.

The procedure is to assign hypothetical known mass values to each track and then use relativistic conservation of momentum and energy to determine which mass combinations hypotheses are possible. However, a kinematical analysis is usually not sufficient to uniquely identify the tracks. Further identification is then attempted by comparing the ionization (degree of track bubble density) that a

track of given mass would have, to the ionization that the track is observed to have. It is important to note that identification by ionization is less reliable than kinematic identification and is therefore used only after all the possible kinematical analyses are made.

The bubble chamber film is measured by a device called a Spiral Reader which measures coordinates on each track of an event. The Spiral Reader also records the bubble density of the track in the form of pulse heights. The coordinate measurements are used to reconstruct the event from the photographs and the pulse height information is used to identify the tracks via ionization. A computer program developed at FSU utilizes the pulse height information from the Spiral Reader and compares it to a predicted pulse height for a track of a given mass hypothesis. In this way the mass of a given particle is often deduced. This method is employed so as to reduce the number of ambiguities without resorting to a human being checking each event; a very time consuming process.

The reliability of the automatic identification program was determined by taking 416 identifiable tracks and comparing the identifications with ones carefully made by a human scanner. The program was found to identify 70% of these tracks correctly, less than 2% incorrectly and the remainder were labeled as unidentifiable. By utilizing this program only 16% of all events are sent to a human scanner for ionization identification as opposed to nearly all the events when all identification was done by human beings.

II. BUBBLE FORMATION AND BUBBLE CHAMBERS

A bubble chamber is a large vessel filled with a superheated liquid of hydrogen, deuterium or even a denser liquid that is used to obtain a photographic representation of the trajectory of charged particles. The pressure of the liquid is controlled by a set of hydraulic pistons. The liquid is initially kept at a pressure which is sufficiently high as to prevent boiling at the operating temperature. A charged particle passing through the liquid will ionize the atoms in the liquid along its path. If the pressure is suddenly decreased to a point where the liquid can boil, the liquid tends to form gas bubbles in the vicinity of the ionized atoms in the chamber. If the interior of the chamber is then quickly photographed, before the bubbles have time to grow too large (typical size 300 to 1000 microns) and rise to the chamber top, the result is a photographic representation of the trajectories of the charged particles that traveled through the chamber. The important feature here is that the bubbles tend to form first along the path of ionized atoms rather than just anywhere in the chamber. To understand the reason for this one begins by looking at a bubble suspended in a liquid.[1]

Let p' be the pressure that the gas bubble exerts on the liquid and let p be the pressure which the liquid exerts on the exterior of the bubble. p and p' are not equal because of the tangential surface tension around the bubble which will be denoted by σ (units of force per unit length). Let the bubble have radius r and let the bubble undergo a volume increase $dv = 4\pi r^2 dr$. The work done by p and p' is

$$dW = (p'-p)dV = (p'-p)4\pi r^2 dr$$

If the bubble is to increase in size without breaking then this work must be equal to the work done against the surface tension, i.e., $dW = \sigma dA$ where $dA = 8\pi r dr$ is the increase in the bubbles surface area.

Therefore

$$(p'-p)4\pi r^2 dr = \sigma 8\pi r dr$$

That is

$$p'-p = \frac{2\sigma}{r}$$

It is a straightforward thermodynamics problem to use the equilibrium conditions

$$g(p,T) = g'(p',T)$$

$$T = T'$$

and

$$p' = p+\frac{2\sigma}{r}$$

where T is the temperature of the liquid, T' is the temperature of the gas in the bubble, g(p,T) is the Gibbs free energy per mole of the liquid, and g'(p',T) is the Gibbs free energy per mole of the gas in the bubble,to show that the bubble radius r_e for which the bubble is in equilibrium is given by

$$r_e = \frac{2\sigma}{p_\infty e^{-\left[\frac{v}{v(p_\infty)}\frac{(p_\infty-p)}{p_\infty}\right]} - p}$$

where p_∞ is the pressure of the gas in a bubble of infinite radius, v is the volume per mole of the liquid and $v'(p_\infty)$ is the volume per mole of the gas in a bubble of infinite radius. When operating far away from the critical point $v/v' \ll 1$ then

$$e^{-\frac{v}{v'(p_\infty)}\frac{(p_\infty-p)}{p_\infty}} \doteq 1 - \frac{v}{v'(p_\infty)}\left(\frac{p_\infty-p}{p_\infty}\right)$$

and therefore

$$r_e \doteq \frac{2\sigma}{\left(p_\infty-p\right)\left(1-\frac{v}{v'}\right)}$$

Having found the radius required for a bubble to exist in equilibrium one must now examine the stability of such a bubble. Let N be the number of moles of liquid and N' be the number of moles of gas in the bubble and note that the surface energy of the expanded bubble is given by

$$W = \int_{V_{bubble}} (p'-p)dV = \int_0^r \left(\frac{2\sigma}{r}\right) 4\pi r^2 dr = 4\pi r^2\sigma$$

Then

$$\Delta G = Ng(p,T) + N'g'(p'T') + 4\pi r^2\sigma$$

$$- (N+N')g(p,T)$$

$$= \left[g'(p',T') - g(p,T)\right]N' + 4\pi r^2\sigma \qquad (1)$$

obtained by applying the basic thermodynamics equation

$$\Delta G = G_f - G_i$$

where ΔG is the change in the total Gibbs free energy of the system, $G_f = Ng(p,T) + N'(p',T') + 4\pi r^2\sigma$ is the free energy of the liquid, bubble, and bubble surface energy and $G_i = (N+N')g(p,T)$ is the free energy of the liquid before the bubble was formed. Using the thermodynamic definition of dg, namely

$$dg = -sdT + vdp$$

where s is the entropy per mole and the equilibrium equation

$$g(p,T) = g'(p + \frac{2\sigma}{r_e}, T)$$

one obtains

$$g(p,T) = \int_{p_\infty}^{p} vdp$$

and

$$g'(p + \frac{2\sigma}{r_e}, T) = \int_{p_\infty}^{p+\frac{2\sigma}{r_e}} v'dp$$

where constant temperature T was assumed. By assuming that the liquid is incompressible i.e., v = constant and that the gas is ideal, the equilibrium equation $g(p,T) = g'(p',T')$ and the fact that the gas is assumed ideal can be used to show that, to a good approximation, v' is a relatively insensitive function of p. One thus obtains

$$g(p,T) \simeq g'(p,T) + v'\frac{2\sigma}{r_e}$$

Now noting that $v' = \frac{4\pi}{3}r^3/N'$ one obtains from equation (1)

$$\Delta G = -v'\left(\frac{2\sigma}{r_e}\right)\left(\frac{4\pi r^3}{3v'}\right) + 4\pi r^2\sigma = 4\pi r^2\sigma\left(1 - \frac{2r}{3r_e}\right) \qquad (2)$$

The first derivative of ΔG with respect to r vanishes at $r = r_e$ and the second derivative with respect to r is negative at $r = r_e$. Hence G is a maximum at $r = r_e$ and since it is required that G be at a minimum for equilibrium a bubble of radius $r = r_e$ is unstable. Clearly from equation (2) if $r < r_e$ the bubble will shrink and if $r > r_e$ the bubble will grow.

It appears from equation (2) that the minimum energy an ionizing particle must deposit for bubbles to form and grow is slightly greater than $\Delta G|_{r = r_e}$. That is the energy deposited must be greater than $\frac{4\pi r_e^2\sigma}{3}$. In actual practice a slightly larger amount of energy is needed to account for the latent heat of vaporization of the liquid.

Having discussed the conditions necessary for bubble formation and growth it is now necessary to examine

how a charged particle moving through the liquid can deposit sufficient energy to cause bubbles to form along its path.

Ionization Probabilities

Ionization is the process by which an atomic electron is removed from an atom as a result of a coulomb interaction with a moving charged particle. Suppose a particle of mass m and initial momentum P is incident on a bound atomic electron (mass m_e) that is initially at rest. If P" is the incident particles momentum after the collision and P' is the momentum of the electron after the collision then a straightforward relativistic treatment of conservation of energy and momentum yields[2]

$$E' = 2m_ec^2\frac{P^2c^2\cos^2\theta}{\left[m_ec^2 + (P^2c^2 + m^2c^4)^{1/2}\right]^2 - P^2c^2\cos^2\theta} \qquad (3)$$

where E' is the kinetic energy of the electron and θ is the angle between the vectors $\vec{P}$ and $\vec{P}'$. To a good approximation atomic electrons can be considered as essentially free (since $Pc \gg m_ec^2 \gg$ ionization energy) and thus equation (3) can be used to determine the energy acquired by an atomic electron after interacting with an incident charged particle. It is now desirable to determine the probability that an incident charged particle of energy E will transfer an energy between E' and E' + dE' to an atomic electron while traversing a distance dx measured in mass per unit area (gm - cm^{-2}). That is $dx = \rho ds$ where ρ is the density (gms/cm^3) of liquid and s is the actual distance (cm) traversed.

Let $\Phi(E,E')dE'dx$ represent this probability and call the function $\Phi(E,E)$ the differential collision probability. Determination of the collision probability requires a relativistic quantum mechanical analysis if one wishes to deal with large incident energies. The results depend on the mass, spin and magnetic moment of the incident particles.

An Indian physicist, Bhabha[3] has calculated the collision probability for particles of mass m and spin zero to be

$$\Phi(E,E')dE' = \frac{2CM_e c^2}{\beta^2} \frac{dE'}{(E')^2} \left[1 - \beta^2 \frac{E'}{E'_m}\right] \qquad (4)$$

where $C \equiv .150 \frac{Z}{A}$ where Z and A are the charge and mass numbers of the atomic material, $\beta \equiv v/c$ where v is the velocity of the incident particle, i.e,

$$\beta = \frac{P}{(M^2c^2 + P^2)^{\frac{1}{2}}}$$

and E'_M is the maximum energy that can be transferred to the electron namely

$$E'_M = 2M_e c^2 \frac{P^2c^2}{M_e^2c^4 + M^2c^4 + 2M_e c^2 (P^2c^2 + M^2c^4)^{\frac{1}{2}}} \qquad (5)$$

For particles of mass M and spin ½ Bhabba, Massey and Corbin[4] have obtained

$$\Phi(E,E')dE' = \frac{2CM_e c^2}{\beta^2} \frac{dE'}{(E')^2}\left[1 - \beta^2 \frac{E'}{E'_M} + \frac{1}{2}\left[\frac{E'}{E + Mc^2}\right]^2\right] \qquad (6)$$

Fortunately in high energy physics the maximum transferable energy E'_M is usually much greater than the energy E' that is transferred to the electrons and both equations (4) and (6) reduce to

$$\Phi(E,E')dE' = \frac{2CM_e c^2}{\beta^2} \frac{dE'}{(E')^2}$$

Thus in the limit $E'_M \gg E'$ the collision probabilities become spin independent and depend only on E' and β.

One is now in a position to determine the average energy loss per gm - cm^{-2}. It is convenient to consider distant and close collisions separately. A distant collision will be one that results in the ejection of an electron of energy smaller than a quantity η and a close collision will be one that results in the ejection of an electron of energy greater than η. The value of η is chosen to be the energy below which the atomic electron must be considered as bound to its atom and above which the electron can be considered as essentially free. Let the average energy loss per gm-cm^{-2} for distant collisions be $k_{<\eta}(E)$ and for close collision be $k_{>\eta}(E)$. To compute $k_{<\eta}(E)$ one must consider electron binding energies and transition probabilities for atomic excitation. With the aid of the Born approximation Bethe[5] computed $k_{<\eta}(E)$ for particles of unit charge to be

$$k_{<\eta}(E) = \frac{2CM_e c^2}{\beta^2}\left[\ln \frac{2M_e c^2 \beta^2 \eta}{(1-\beta^2) I^2(Z)} - \beta^2\right] \qquad (7)$$

where I(Z) is called the average ionization potential of an atom with atomic number Z. Equation (7) is relatively insensitive to changes in I(Z). Wick, Halpern and Hall[6] have calculated I(Z) for various substances, but the relation suggested by Bloch[7] of $I(Z) = (13.5)Z$ yields quite reasonable results.

Note that equation (7) is valid for all unit charge incident particles with velocity large compared with the velocity of the atomic electrons.

Computation of $k_{>\eta}(E)$ is somewhat simpler since the electrons can be considered as free.

The result is simply

$$k_{>\eta}(E) = \int_{\eta}^{E'_M} E'\phi(E,E')dE'$$

Using for example equation (4) one obtains

$$k_{>\eta}(E) = \frac{2CM_e c^2}{\beta^2}\left[\ln\frac{E'_M}{\eta} - \beta^2\right] \qquad (8)$$

where it was assumed that $\eta << E'_M$.

The total energy loss per gm-cm^{-2} or the ionization loss denoted by k(E) is the sum of $k_{<\eta}(E)$ and $k_{>\eta}(E)$. That is

$$k(E) \equiv -\frac{dE}{dx} = \frac{2CM_e c^2}{\beta^2}\left[\ln\frac{2M_e c^2 \beta^2 E'_M}{(1-\beta^2) I^2(Z)} - 2\beta^2\right]$$

Note that this expression is independent of η as expected. Using equation (5) in place of E'_M one obtains

$$k(E) = \frac{2CM_e c^2}{\beta^2}\left[\ln\frac{4M_e^2 c^4 \beta^4}{(1-\beta^2) I^2(Z)} - 2\beta^2\right] \qquad (9)$$

These results were obtained without consideration of the screening of the electric field of charged particles passing through the chamber by atoms in the medium. This so called density effect can be neglected when the medium is gaseous, but not when it is liquid. Fermi[8] has calculated that the quantity Δ to be subtracted from k(E) in equation (9) for the case of singly charged particles is given by

$$\Delta = \frac{2CM_e c^2}{\beta^2} \ln\varepsilon \text{ for } \beta < \varepsilon^{-\frac{1}{2}}$$

$$\Delta = \frac{2CM_e c^2}{\beta^2}\left[\ln\frac{\varepsilon - 1}{1 - \beta^2} + \frac{1 - \varepsilon\beta^2}{\varepsilon - 1}\right] \text{ for } \beta > \varepsilon^{-\frac{1}{2}}$$

where ε is the dielectric constant of the medium.

If we now note that the typical bubble radius in a bubble chamber is observed to be about 275 microns and if we use the expression

$$P = .3HR$$

where P is the momentum in MeV/c of a charged particle moving perpendicular to an external magnetic field H measured in kilogauss and R is the radius of the circle the particle moves in measured in cm then we find that an ionized electron that is to rotate in a circle of typical bubble size requires a momentum of

$$P = (.3)(15)(.0275) = .124 \text{ MeV/c}$$

where the usual value of the magnetic field applied to a bubble chamber of 15 kilogauss was used. The energy of this electron is about 1.5×10^4eV. Thus any electrons whose energy is significantly higher than this, say 10^5eV will form a circle of bubbles in the chamber rather than a single bubble. Such an electron is known as a delta (δ) ray. Since for bubble track formation one is interested in electrons which do not have sufficient energy to be δ rays one can obtain the average energy per gm-cm^{-2} deposited to form bubbles using only equation (7) with $\eta = 10^5$eV and equation (10) for a density correction. That is with $\eta = 10^5$eV the energy deposited to form bubbles is given by equations (7) and (10) and the energy deposited to form δ rays is given by equation (8).

Figure 1 shows $k_{<\eta}(E) - \Delta$ for liquid deuterium normalized to unity for large P/Mc. Plotted along side is the curve $1/\beta^2$ where β(P/Mc) was obtained for the equation

$$\frac{P}{Mc} = \frac{P}{\sqrt{1 - \beta^2}}$$

and $\varepsilon = 1.228$ for liquid deuterium.

Neither the human eye nor optical measuring devices can distinguish between the values given by the two curves for a given P/Mc. For low P/Mc the tracks are so dark that saturation occurs and even though the two curves

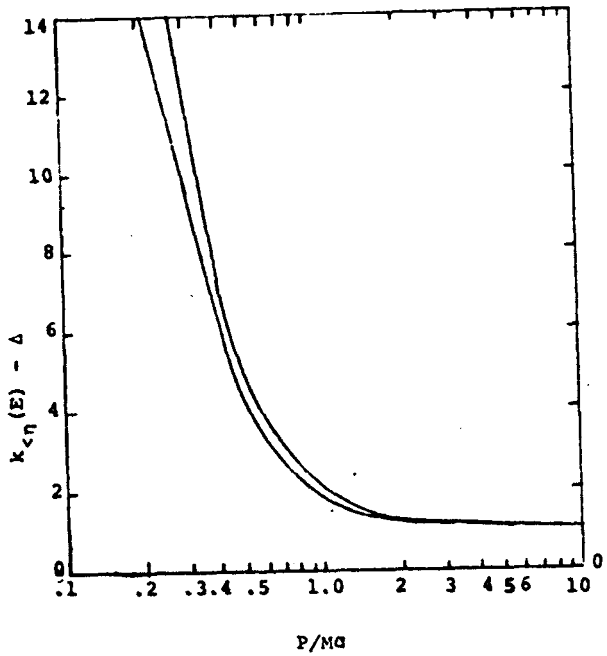

Fig. 1 - The lower curve shows $k_{<\eta}(E)-\Delta$ vs P/Mc for $\eta = 10^5$ev, I(Z) = 14.9eV and ε = 1.228 normalized to unity for large P/Mc. The upper curve shows $1/\beta^2$ vs P/Mc.

may differ greatly, one can only consider the track as very dark. The cases of interest occur mainly for ionization between 1.0 and 2.0. In this region the approximation of $1/\beta^2$ for ionization differs from the theoretical expression by only about 10%. Since the smallest reliable distinction in this region is between tracks whose ionizations differ by 30% or more, the approximation that ionization is given by $1/\beta^2$ is a good one. One can therefore determine the ionization of a track by knowing the mass and momentum of the particle that created the track. Finally, it must be noted that the photographs of tracks yield track ionizations that are projections of the actual track onto the plane on which the camera is mounted. Thus, a track that "dips" out of this plane appears to be darker than it would if it were parallel to this plane. Thus on the film one computes the ionization to be $1/(\beta^2 \cos\theta)$ where θ is the angle the track makes with the plane of the cameras (dip angle).

III. DATA REDUCTION

The analysis of bubble chamber film consists of three basic steps. First, the film must be scanned so the events of interest can be located, secondly, the events must be measured by accurately measuring several points in each of three views for each track of the event (each event is simultaneously photographed from three different angles so that the 3-dimensional event can be reconstructed from the film) and thirdly, the measurements must be translated into a mathematical representation of the event so that the event can be analyzed.

In order to employ computerized ionization identification, the film must be measured on a device known as a Spiral Reader.[9] The operator of the Spiral Reader looks at a projected image of an event on a table and a magnified image on a TV screen. His task is to center the vertex of the event on a cross hair which appears on the TV screen. Once this is done, the Spiral Reader, with the aid of a small computer, sets a narrow radially oriented slit in a spiral motion from the vertex. Whenever the slit passes a spot on the film that cuts out more than 20% of the light passing through the slit, the location of that point from the vertex is recorded in polar coordinate. The

slit is about 10 bubble diameters long and therefore tracks not almost parallel to the slit, such as crossing tracks, are never measured but tracks that radiate out from the vertex are almost always measured. The Spiral Reader operates with reasonable accuracy but is limited in that because the slit is radial, tracks that turn through angles greater than 20 to 40 degrees of arc are not digitized. This condition imposes a slight limitation on the length of the measured track.

Most Spiral Readers measure only about 5cm of track length on the film which reduces the accuracy of the momentum determination. The error, however, is fairly small. Since the Spiral Reader employs lenses to focus the slit, there are optical distortions that must be corrected for in order to obtain accurate measurements on the film plane.

Once the event is digitized a sophisticated computer program called "POOH",[10] given only the position of the event vertex, the number of tracks to be found, and in the case of short tracks, a so called "crutch point" which the operator measures at the end of the track, extracts from about 1000 points per view those points which are actually on the tracks of the event.

The process of filtering out stray tracks and other unwanted points is a complicated one; POOH uses a special subroutine that "matches" the tracks in the 3 different views to do this.

The Spiral Reader possesses one additional feature which enables one to computerize ionization identification. When the Spiral Reader encounters a dark spot it not only records the radius and azimuth of the point, but also a "pulse height." The pulse height is a fairly accurate measure of the fraction of light cut out by the point and can therefore be used to determine the tracks ionization. The pulse height is a voltage reading that ranges from about 40 for a very light track to around 90 for a very dark one. (Tracks for which less than 7 points were measured are assigned a pulse height of zero). For each track POOH averages the pulse heights for the first 8cm of tracks and records this average so that it can later be used for ionization identification. Once POOH has reduced the Spiral Reader output so as to have 7 to 12 points for each track in each view, removed the spurious tracks, and computed an average pulse height for each track in each view, it records this information on magnetic tape. This tape serves as the input for a geometrical reconstruction program coded at the Lawrence Berkeley Laboratory called the Three View Geometry Program (TVGP).[11] TVGP uses the information from the 3 views to construct a 3-dimensional representation of the event. Before this can be done however, it is necessary for TVGP to determine the constant curvature of each track in each view. The actual tracks

possess a slightly varying curvature because of energy losses of the particle toward the end of the track. The determination of such energy-losses is mass dependent and it is therefore necessary for TVGP to fit curvatures for each track for different mass hypotheses. The final result is that the 3-dimensional representation of the event will be different for different combinations of mass possibilities for the various tracks.

After TVGP has determined the possible representations of an event a kinematical analysis program called SQUAW[12] is used. SQUAW uses the curvature of the tracks for each set of TVGP possible mass combinations to determine the energy and momentum of each track. It then employs relativistic energy and momentum conservation to eliminate TVGP mass combinations that do not obey these conservation laws. TVGP mass hypotheses where all outgoing tracks are visible are classified as 4-C (four constraint) fits since for each track the mass and the three momentum components are known. That is, there are four more energy and momentum constraints than there are unknown parameters to be fitted. Mass hypotheses that include one neutral (unseen) particle with a given assigned mass are classified as 1-C fits since there is one more constraint (the mass of the neutral particle) than there are unknown parameters to be fitted. There are similarly 2-C, 3-C etc., constraint fits.

The objective of SQUAW is to eliminate those mass combination hypotheses which are kinematically impossible. Ideally one wishes to eliminate all but one mass combination and thus uniquely classify the event. However, while kinematics usually eliminates many of the TVGP hypotheses, it rarely eliminates all but one.

In an attempt to reduce the number of hypotheses further, one resorts to ionization identification. That is, using the value $1/(\beta^2 \cos\theta)$ where θ is the dip angle for the ionization, one can compute what the ionization would be for a track of a given momentum and mass and then look at the track to see which of the possible ionizations the track has. For example, a track with a momentum of about 850 MeV/c would have a $1/\beta^2$ ionization of about 1.01 if it were a pion, but would have a $1/\beta^2$ ionization of about 2.1 if it were a proton. Knowing this, one could look at the actual track and see if the track looked twice as dark as minimum or about equally dark as minimum and could thus determine whether the track was a proton or a pion and thus eliminate another mass combination hypothesis.

Frequently the values of ionization from $1/\beta^2$ for different mass hypotheses do not differ by a large enough margin to enable a positive identification. However, when such identifications can be made, mass hypotheses can be eliminated.

In the following chapter, a method of utilizing the POOH pulse height information to obtain computer ionization identification of tracks is disusssed.

IV. *IDENTIFICATION OF POSITIVE TRACKS*

As noted in Chapter III the average pulse height information for each track in each view that is computed by POOH can frequently be used to identify tracks by means of ionization. The darkness of a track is directly related to the ionization of the tracks.

Before the track identifications can be made, a subroutine called KINCHK fails certain mass hypothesis combinations according to the following criteria: (1) If enough poorly measured variables for a track are dropped by SQUAW so as to result in a particular mass hypothesis fit having no constraints (0-C), then that hypothesis is rejected and a failure code of 901 is assigned to the hypothesis; (2) If the χ^2 probability of a mass hypothesis fit combination is below o.1% then the hypothesis is rejected and assigned a failure code of 902; (3) If, for a mass hypothesis combination in which there is a missing neutral particle (mm), the calculated value by SQUAW of the mm is less than the smallest mass single neutral particle possible and there are no constrained fits with the same charged particle mass combinations then the hypothesis is rejected and assigned failure code

903; (4) If the identifying number of a mass hypothesis combination is invalid (caused by an idiosyncrasy in SQUAW bookkeeping procedures) then the hypothesis is rejected with failure code 904; (5) If an event has two stopping protons then all mass hypothesis combinations having a single proton or a deuteron are invalid and these hypotheses are rejected with failure code 905; and (6) Track identification by ionization is attempted only if there are at least two possible mass hypothesis combinations for the same charged particles and if the calculated ionization for a pion and a proton differ by more than .4. Ionization values above 4.0 are assigned a value of 4.0 to account for the saturation of track darkness.

After KINCHK has eliminated all invalid mass hypothesis combinations the process of track identification begins.

In 1967, J. S. Danburg and G. R. Lynch of the University of California at Berkeley[13] empirically determined the following equation:

$$PH_{ij} = PMX_j \left[1 - \left(\frac{PMX_j - PMIN_j}{PMX_j} \right)^{BD_{ik}} \right] \qquad (11)$$

where PH_{ij} is the pulse height of the i^{th} track in an event in the j^{th} view, PMX_j is the average maximum pulse

height of any track in the j^{th} view, $PMIN_j$ is the minimum pulse height for any track in a given event in the j^{th} view and BD_{ik} is the value $1/(\beta^2 \cos\theta)$ for the i^{th} track in an event for mass hypothesis combination k. Here at FSU it was determined from a large sample of events that satisfactory values of PMX_j are

$$PMX_1 = 83 \text{ for view 1}$$
$$PMX_2 = 80 \text{ for view 2}$$
$$PMX_3 = 86 \text{ for view 3}$$

The technique for determining $PMIN_j$ that was developed at FSU consists of solving equation (11) for $PMIN_j$ namely:

$$PMIN_j = PMX_j \left[1 - \exp\left\{ \frac{\ln\left(\frac{PMX_j - PH_{ij}}{PMX_j} \right)}{BD_{ik}} \right\} \right]$$

and determining, by using all tracks in an event that are less than 1.2 times darker than the minimum ionizing beam track, an average value for $PMIN_j$ for each view which is designated as $PMAV_j$. The next step was to replace $PMIN_j$ by $PMAV_j$ and the known ionization values BD_{ik} by a predicted ionization BDP_{ij} for the i^{th} track of an event in the j^{th} view in equation (11) and solve for BDP_{ij} i.e.,:

$$BDP_{ij} = \frac{\ln\left(\frac{PMX_j - PH_{ij}}{PMX_j}\right)}{\ln\left(\frac{PMX_j - PMAV_j}{PMX_j}\right)} \quad (12)$$

Equation (12) determines a predicted ionization BDP_{ij} from the POOH pulse height PH_{ij}. The quantities BDP_{ij} are compared with BD_{ik} in an attempt to determine which mass hypothesis to choose for the i^{th} track according to the following criteria: (1) Tracks whose azimuthal angle measurements differ by less than 3° are considered as overlapping tracks and thus give erroneous pulse heights. Such tracks are considered as unidentifiable. If the difference between the quantity $\frac{1}{P\cos\theta}$ where P is the track momentum and θ is its dip angle for two overlapping tracks is greater than .0007 then the tracks separate rapidly and are therefore considered as identifiable; (2) Defining

$$X \equiv \left|\frac{1}{BDP_{ij}} - \frac{1}{BD_{ik_1}}\right|;\ Y \equiv \left|\frac{1}{BDP_{ij}} - \frac{1}{BD_{ik_2}}\right|$$

where k_1 and k_2 are two mass hypotheses for the i^{th} track. If $X > Y$ the track is identified by view j as having a mass of hypothesis k_2. If $X < Y$ the track is identified by view j as having a mass of hypothesis k_1; and (3) Letting k_1 correspond to a mass hypothesis of a track being a pion and letting k_2 correspond to a mass hypothesis of a track being a proton if a track is classified as a proton by all three views then the final identification of the track is a proton. A track is not identified as a proton unless all views agree. If two views classify a track as a proton but the third does not, then the final identification is "unidentifiable." If a majority of the views classifies a track as a pion then the final track identification is a pion. All other possible combinations of view identifications result in a final identification of "unidentifiable" for the track.

These identifications are presently being made by a subroutine named IDENT of a program called POSTSQUAW. After the tracks of an event have been identified all mass hypothesis combinations inconsistent with the identification are rejected with failure code 910. Ionization determinations that, for any reason; cannot be done automatically but are expected to be identifiable visually by a human being are sent to a scanner who makes the final identifications.

V. RESULTS AND CONCLUSIONS

The automatic ionization identification programs reliability was tested using a sample of 416 identifiable tracks. Each of the tracks was carefully identified by a human scanner and the results were compared to the identifications made by the automatic program. The program was found to identify 70% of the tracks correctly and 2% of the tracks incorrectly. Of the remaining 28% of the tracks 39% were labeled as unidentifiable because pulse heights in the three views were not consistent enough to merit specific identification and 61% were labeled unidentifiable because the track to be identified overlapped with other tracks. Tracks involved in overlaps have erroneous pulse heights associated with them and thus the pulse height information is not valid for use in track identification. It should be noted that incorrect identification of 2% of all identifiable tracks corresponds to an inaccurate identification of about 1% of all events.

From a sample of 458 events only 88 (16%) were labeled as having identifiable tracks that the automatic program could not identify. Hence, only 16% of the events

have to be viewed by a human scanner where as before almost all of the events had to be.

Figure 2 shows the calculated ionization (obtained from the average pulse height of the three views) versus the theoretical ionization $\frac{1}{\beta^2 \cos\theta}$. Most of the calculated points fall within 20% of the theoretical values. For the purpose of ionization identification these deviations are reasonable since tracks whose ionization differ by 20% are essentially indistinguishable.

The momentum P of a track in terms of its mass M and velocity βc is

$$\left(\frac{P}{Mc}\right)^2 = \frac{\beta^2}{1-\beta^2}$$

It is desirable to determine an effective momentum, P_{eff}, which represents the curvature of a track as seen on the actual bubble chamber film, that is P_{eff} is calculated by taking into account the dip of each track i.e.:

$$\left(\frac{P_{eff}}{Mc}\right)^2 \equiv \frac{\beta^2 \cos\theta}{1-\beta^2 \cos\theta}$$

Figure 3 shows P_{eff} versus the calculated pulse height for tracks that the program attempted to identify. It is easily seen that protons and pions are fairly well separated. That is to say that the calculated ionization of a proton with a given P_{eff} is significantly higher than the calculated ionization for a pion with the same P_{eff}. Hence, a track with a given momentum can usually be distinguished as a pion or a proton via ionization identification. The smooth curves are the theoretical values of the ionization as a function of P_{eff}.

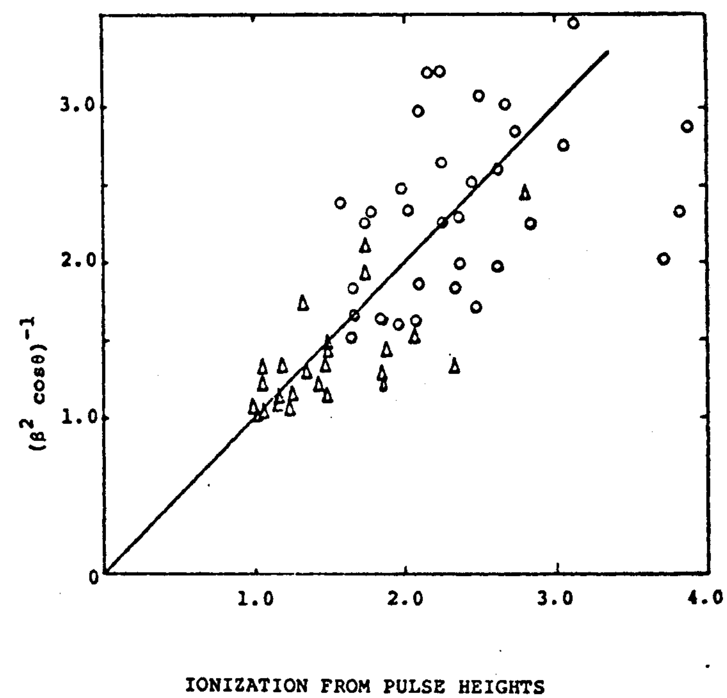

Fig. 2 - Calculated ionization obtained from the average pulse height of the three views for a track vs. the theoretical value of $1/(\beta^2 \cos\theta)$ where θ is the dip angle of the track. 0 - protons, Δ - pions.

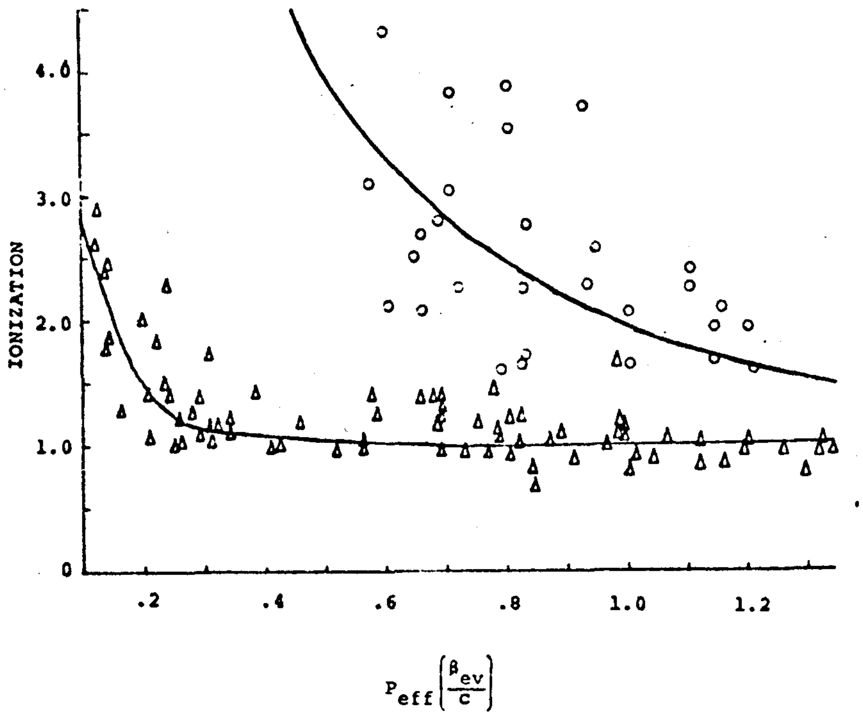

Fig. 3 - $P_{eff} = \sqrt{\frac{M^2c^2\beta^2 \cos\theta}{1 - \beta^2 \cos\theta}}$ versus the ionization calculated from the pulse height information of the Spiral Reader. The curves are the theoretical ionization vs P_{eff}. The upper curve is for protons, the lower curve for pions 0 - identified as protons, Δ - identified as pions.

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