PROBLEMS IN THE MEASUREMENT OF IONIZATION IN TRACKS IN A CLOUD CHAMBER

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The study of the interaction of nuclear particles at high energies gives information on the most elusive, yet the most important problems in the physics of elementary particles. In this study the nature of the particles created in an interaction must be determined. To identify such particles a property characteristic of a given kind of particle must be distinguished; the mass and the charge (including the sign of the charge) are sufficient to distinguish all known particles, although other properties may be used in some cases.

Suppose, for example, it is desired to study the interaction of a proton emerging from the new accelerator in CERN, in Geneva, with another proton in a liquid hydrogen target. In the collision, enough energy is available to create several particles: mesons, hyperons, anti-nucleons and nucleons, and if a full knowledge is to be gained as to the details of the interaction it is essential to identify the reaction products. It is also important to know the energies, momenta, and angular distribution of the products of the interaction.

It is not the purpose of this paper to describe all the methods available for the detection and analysis of the particles emerging from such a nuclear interaction. Rather, I will describe a particular method that has been used, which involves certain statistical problems that have not been solved.

A cloud chamber may be used for detection and identification of the reaction products. If the cloud chamber is in a magnetic field, the deflection of the particle may be measured, giving the sign of the charge and the momentum of the particle. To complete the identification of the particle, the velocity may be measured, which combined with the momentum, a function of the mass and velocity, yields the mass.

Since the operation of the cloud chamber is critical in the statistical problem, a brief outline of the principles on which the operation of this instrument is based is in order. A cloud chamber is a device which makes visible the tracks of charged particles passing through it. It contains a gas such as air or argon or helium, or a mixture of these, plus a vapor such as alcohol. When a charged particle passes through the chamber, leaving a trail of ionized gas behind it, the chamber is suddenly, adiabatically expanded. The resulting drop in temperature of the gas produces supersaturation of the vapor, which condenses preferentially on the ions left by the fast particle. In a properly operated chamber, there are very few liquid droplets produced during the expansion except for those on the ions. The track then consists of liquid droplets which can be illuminated and either seen visually or photographed through a glass window in the cloud chamber.

In a cloud chamber the velocity is measured in terms of the ionization produced by the particle as it passes through the gas and vapor in the chamber. It is the condensation of the vapor on the ions produced by the passage of the charged particle that makes the track of the particle visible, and if this condensation can be quantitatively measured, the ionization, and thence the velocity, can be found.

The energy loss by ionization of a charged particle is given by

$$-\frac{dE}{dx} = \frac{2\pi ne^4}{mv^2}\left[\log\frac{2mv^2\eta}{I^2(1-\beta^2)} - \beta^2 - \delta\right] \tag{1}$$

where n = number of electrons/cm^3, m = mass of electron, v = velocity of charged particle, $\beta = v/c$, I = average ionization potential of gas, η = maximum energy transfer, δ = correction for polarization in gas. The ionization is related to dE/dx by $I = (1/W)\, dE/dx$, W being an empirically determined number, the energy loss per ion pair. Note the $1/v^2$ dependence at low velocities, and the logarithmic rise due to relativistic effects at the higher energies, which eventually levels off because of polarization effects.

The most accurate determination of the ionization loss is made by counting the individual droplets of vapor that condense on the ions along the track of a charged particle. A statistical analysis of this measurement was made by R. R. Read [1], and since the present paper raises further statistical questions, it is worthwhile to review briefly the nature of the ionization act, and the technical features of the measurement procedure.

An ion pair is created when the electromagnetic field of the passing charged particle interacts strongly enough with an atom to raise it to an energy state which allows one of the electrons to appear in the continuum, as a free electron. Ordinarily, in a cloud chamber the free electron rapidly attaches to an atom of the gas or vapor, and the net result is two charged atoms; one positive, lacking its knocked-out electron, and the other negative. These two ions diffuse apart in the gas until the sudden drop in temperature on expansion of the cloud chamber causes them to be fixed in space by the formation of liquid droplets on the ionic charge. Under conditions normally existing in a cloud chamber, a droplet always forms around the positive ion, but the chance of formation of a negative droplet varies from zero to 100%, depending on the degree of expansion.

In some cases the free electron produced in the original interaction with the electromagnetic field of the passing particle may have sufficient energy to ionize atoms in its own right. Thus a given "primary" ionization may give rise to a number of "secondary" ions as the energetic electron passes through the gas. A cluster of droplets, called a blob, is then produced. If there are so many droplets within a blob that they cannot be resolved, the blob is rejected and not counted. The quantity η (1) is the minimum energy required to produce a blob that cannot be counted.

Let us now review the statistical processes involved. Read's model involved the following assumptions, which seem reasonable physically. I quote from Read's thesis:

"1. The number of primary ionizing collisions has a Poisson distribution.

"2. The number of secondary ionizing collisions is a random variable with the same distribution for each primary collision. This distribution does not depend on the primary particle.

"3. The event that an ion acquires a droplet is independent of that of all others. The probability of this event is a constant depending only on the sign of the ion and the experimental conditions within the chamber.

"4. The ions diffuse away from their points of birth by Brownian motion."

Since the expansion takes place after the primary particle has passed through the chamber and since the Brownian motion separates the ions rapidly compared to the relatively slow mechanical procedure necessary to expand the cloud chamber, the track of the particle, originally defined by ion pairs concentrated in a cylinder of diameter 10^{-7} to 10^{-5} cm, depending on the velocity, becomes a column of droplets, of diameter of the order of 1.5 mm, at the moment of photography.

A cloud-chamber photograph is made by flashing a bright light on the droplets and using the scattered light to form images of the droplets on the film. Normally the size of the droplet image depends on the optical properties of the camera and the film, not on the droplet size. A typical image size is 0.015 cm diameter. The image of the track on the film is, of course, two-dimensional, with the droplet images projecting from three dimensions in the chamber to two on the film. Again typically the width of the track on the film may be 0.015 cm, and thus the track cited is 10 droplet images wide.

Another feature of cloud chamber photography is the use of stereoscopic pairs of photographs. With two lenses separated by a few inches it is possible to have two views of the track, and with appropriate viewing devices the droplets can be counted stereoscopically, permitting improvement of the accuracy of count and rejection of droplets in the general background of the chamber.

Typically a cloud chamber track at the minimum of the ionization curve might average 20 droplets per centimeter in the chamber, or with the demagnification considered above (10:1), 20 drops per millimeter on the film. In a track 50 cm long in the chamber there would be about 1000 droplets, some formed on positive ions, some on negative ions.

Some of the statistical problems in the estimate of ionization have been discussed by Moyal [2], and measurements of ionization have been used by Fretter, Friesen, and Lagarrigue [3], Kepler et al. [4], and by Hansen and Fretter [5], to identify particles at relativistic velocities. We have made use of the studies of Read [1] in estimating the error in the ionization measurement. Read counted several tracks, determined the distribution of droplets along the track and compared it with the theoretical prediction of his model.

In his statistical study, Read [1] called attention to the importance of the counting error. He observed that "the number of droplets *counted* does not necessarily correspond to the number present." The physical reasons for this were not clear at the time of his study but certain ideas have emerged from these recent experiments which may have an important bearing on his observation. A recent work in this laboratory by T. Aggson [6] calls into question some results obtained by Rousset et al. [7] on the grounds that the effect of overlapping drop images was not correctly estimated.

Before taking this up, however, I should like to explain the difference in technique of drop counting between the present method and that discussed by Read. Formerly, in counting a track of some 1000 droplets, a transparent scale divided into equal intervals was placed over the track in the counting microscope, and the number of droplet images in each cell was counted and recorded by the observer. Read was interested in the cell-by-cell counting statistics. Recently, however, we have dispensed with cell counting and have counted full-length tracks, either in toto or between fiducial marks in the cloud chamber.

Our statistical problems have thus changed, and we are attempting now to determine errors under the new procedure which, as far as we can determine empirically, is just as accurate as cell-by-cell counting, and much less time consuming.

Let us now consider the errors made in the counting of droplet images in a track when some of the droplets are so close together that the images on the film merge and two or more droplets are counted as one. The following factors must be taken into account in estimating such errors:

1. *The number of droplets per unit length.* Clearly the overlapping will be greater if the number of droplets is greater.

2. *The width of the track vs the diameter of the droplet images.* Very wide tracks or very small droplet images reduce the overlapping effect.

3. *The separation angle of stereoscopic photography.* Widely separated lenses will produce separate images in one view or the other, unless the droplets are very close together in space.

4. *Statistical effects.* The distribution of ionizing events along the track and the diffusion of the ions before they are immobilized by formation of a droplet must be recognized. Whether the nature of the ionizing process, particularly the secondary processes, produces clustering of droplets should be considered.

5. *Overlapping of drop images in blobs.* As explained previously, occasionally an electron liberated in a primary ionization event has sufficient energy to ionize other atoms, and can produce a concentration of ions and resulting droplets called a blob. In such blobs the overlapping effects are critically important, and can affect the judgment of the observer as to whether a blob should be rejected from the counted portion of the track.

Aggson [6] has calculated a correction for the effect of overlapping droplet images, using a simplified model. He has assumed a random distribution of N spherical drops of radius r in a cylindrical volume $\pi R^2 L$, where R is the effective radius of the cloud-chamber track and L is the distance measured along the track. He then defined two drops as overlapping if their centers are closer than $2r$, and by elementary probability theory found that the correction is given by $(16/3)(r^3/R^2)(N/L)$. It is seen that the correction depends linearly on the number of drops per unit length and critically on r and R.

Aggson has also calculated an expression for the correction if the stereoscopic counting of the tracks is taken into account. Actually the droplets are counted in a stereoscopic microscope, using both lens views, and the track is clearly seen as three dimensional. Although the distance between drops when resolution becomes possible under these conditions is not well defined, Aggson concludes that again the correction depends linearly on N/L, but not so critically on r and R, having the form $\pi(r^2/R)(N/L)$.

It is clear, as Aggson points out, that this is a crude treatment. The distribution of droplets in the track is not uniform, but more likely Gaussian due to the diffusion of ions from the point of formation. He also makes no provision for clustering of drops due to secondary collision effects. It would therefore be most desirable if a more complete and physically accurate model could be constructed which would predict not only the drop overlap correction but also guide us in the estimates of accuracy we must make in connection with our measurements of ionization.

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