RELATIVISTIC RISE MEASUREMENTS WITH VERY FINE SAMPLING INTERVALS

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Introduction

The motivation of this work was to determine whether the technique of charged particle identification via the relativistic rise in the ionization loss can be significantly improved by virtue of very small sampling intervals. We used a fast-sampling ADC and a longitudinal drift geometry to provide a large number of samples from a single drift chamber gap, achieving sampling intervals roughly 10 times smaller than any previous study. A single layer drift chamber was used, and tracks of 1 meter length were simulated by combining together samples from many identified particles in this detector. Using these data we have studied the resolving power for particle identification as a function of sample size, averaging technique, and the number of discrimination levels (ADC bits) used for pulse height measurements.

There is a considerable amount of literature¹ on the question of the choice of gas sample length to optimize the mass resolution for various experimental applications. Nonetheless, until recently² the application of sample sizes less than 1 cm NTP has not been examined critically, and the consensus has been that very small sample sizes would bring little improvement. As a practical matter, transverse drift detectors such as EPI, ISIS, CRISIS, etc. would have been intolerably costly if they had been designed with sub-cm gas sampling.

The outstanding difficulty with this technique has been the long Landau tail of the energy loss distribution due to the small and thus statistically variable number of very energetic collisions. The standard approach to this problem is to take many independent samples and then retain only the 50% or so with the lowest dE/dx ionization loss, thus reducing the effect of the δ -ray component in the samples retained. Since the average energy loss in 1 cm of Argon is ≈ 3 KeV one cannot eliminate δ -rays of that energy clearly in such samples. By taking much smaller samples we expected to be able to use truncation techniques to eliminate δ -rays much more efficiently. We also expected to demonstrate that one could use crude ADC resolution such as 1, 2 or 3 bits.

A 1 cm sample of Argon contains many low energy primary collisions and the measured energy thus has less information about the shape of the underlying energy loss distribution than could be obtained from smaller samples. In this work we will show that improved knowledge of the shape derived from smaller samples can contribute substantially to the ability to identify particles.

Description of the Apparatus

The ionization detector is shown in Fig. 1. The ionizing particle passes through the drift chamber in the direction of drift field. Thus by sampling the

current amplitude from the chamber in short time intervals, it is possible to obtain the ionization in very short track length samples. The chamber gas was 80% Ar, 20% CO₂ and was operated with a drift field of ≈ 1.5 KV/cm which corresponded to $\approx .25$ mm of gas length for each 10 ns time interval. One has to be cautious of a literal translation of time to track length because diffusion tends to mix adjoining samples (below .5 mm). Furthermore the very nature of the current waveform which has a fast risetime (< 4 ns) but a long $1/(t + t_0)$ tail ($t_0 \approx 1$ ns),³ which tends to correlate the avalanche size content of many time samples and thus reduce the resolution of independent samples.

The electronics for the dE/dx measurements are shown in Fig. 2. Low noise amplifiers (equivalent noise charge 3,000 electrons)⁴ were attached to each of four anode wires. The chamber was operated at a gas gain of $\approx 3 \times 10^4$. A small portion of the signal from each amplifier went to individual ADC's and TDC's. The remaining signals were mixed and passed through a relay controlled attenuator. The signal then was shaped by two pole-zero filters and an integration time constant (4 ns) was applied. This shaped signal went to two 5-bit 100 MHz flash encoders. The flash encoders have a time aperture uncertainty of less than 100 ps. Thus the time slices were very uniform.

These measurements were done in the BNL AGS B4 beam. Runs at ± 3.5 GeV/c were tagged to select $p^\pm$, $\pi^\pm$ and $e^\pm$ using Cerenkov counters C1 and C2, shower counter S and time-of-flight counters T1 and T5, Fig. 3. In addition, the trigger selection was gated to equalize the number of each particle type. Time-of-flight and shower counter pulse heights were recorded so that subsequent analysis cuts could insure the purity of the p , π and e samples.

Between AGS spill cycles a few test events from both a current pulser at the amplifier inputs and a Fe⁵⁵ γ source were recorded. In particular, the Fe⁵⁵ events were used to control the overall long term gains to $\approx 1\%$. The current pulser verified that amplifier gains were stable to $< 1\%$.

Time Adjusted Pulse Height Distributions

Several hundred Fe⁵⁵ events were recorded with each data run. Adding the pulse height vs. time of all events gives a composite pulse shape (Fig. 4). To minimize the cross correlation of the time samples, the two pole-zero adjustments were made to minimize the tail of this distribution without producing undershoot. Fe⁵⁵ and pulser events were recorded before every beam spill and used to normalize the system gain. Because Fe⁵⁵ produces a 5.9 KeV localized cluster of ionization the system gain was reduced 10 times during this portion of the beam cycle.

Tracks that pass near the anode wire produce avalanches almost immediately relative to the particle

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passage while tracks passing near the field wires begin producing avalanches 50-60 ns later. In order to see the average pulse height shape, all events of each type were summed with the time referenced to the leading edge (Fig. 5). The leading edge amplitude is ≈ 3 times higher than that from the long flat tail because ionization is collected from both sides of the anode plane for the first 3 mm. Also near the anode the drift velocity is higher. The long flat plateau corresponds to ≈ 1 cm of uniform drift field. The dE/dx information used in this work was taken from a limited part of each event, ≈ 5 mm of gas, in order to minimize uncertainties due to varying drift velocity near the anode and uncertain length of track near the field cathode. Samples were selected from time bins 17 to 36.

One meter long tracks of 5 different time sample sizes were assembled by taking contiguous samples from each event. The 40 ns sampling for example uses bins 17, 18, 19, 20 for its first sample, bins 21, 22, 23, 24 for the second one, etc. until a full meter of track is assembled. The sample sizes were 10, 20, 40, 160 and 640 ns corresponding to approximately .25, .5, 1, 4 and 16 mm per track sample. The 16 mm track segments required the combining of samples from 3 events.

Time Slice Pulse Height Distributions

The data presented are from 3.5 GeV/c negative beam runs although the positive beam runs yielded indistinguishable results. Figure 6a, b and c through 8a, b and c show pulse height distributions $P(E)$ of e , π and p for time slices of 20, 160 and 640 ns corresponding to approximately .5, 4 and 16 mm of gas. Following standard practice we use the truncated mean as the measure of ionization loss. For one meter of gas the samples are ordered from minimum to maximum pulse height. 100% sample retention means 100% of the samples are retained and summed to measure the ionization in one meter of gas. 90% retention means the smallest 90% of the samples are retained and summed, etc. Dash marks are included on these figures to show where 50% and 90% of the samples occur. 100% retention is simply the integral of the $P(E)$ distribution and does not depend on sample size.

We define R_A to be the ratio of summed energy losses for tracks retained at $A\%$ of the total number of samples. Thus R_{100} corresponds to the rise in the measured average energy loss. (This number is not usually quoted in the literature.) For electrons and protons at 3.5 GeV/c, we find $R_{100} = 1.36$. A more frequently quoted number is the ratio of the most probable energy losses and we observe this ratio to be 1.52 in good agreement with previous measurements.² The fact that the two ratios are not the same indicates the shape of $P(E)$ is also changing as the rise occurs. The fractional energy $g(A)$ contained in samples retained to $A\%$ of the total samples is plotted vs. percent retention A in Figs. 9a, b, c, and d.

$$g(A) = \frac{\int_0^{A\%} E \cdot P(E) dE}{\int_0^{100\%} E \cdot P(E) dE}$$

Relativistic Rise vs. Sample Size and Truncation

$R_A(e,p)$ can be written $R_A(e,p) = g(A)_e/g(A)_p$ $\approx R_{100}(e,p)$ where $R_{100}(e,p) = 1.36$ is the untruncated relativistic rise. At 3.5 GeV/c protons are at the minimum of the relativistic rise curve and the electrons are fully saturated on the Fermi plateau. We find that in general $g(A)_e > g(A)_p$ so the procedure of truncating the data enhances the observed relativistic rise $R_A(e,p)$. For the 640 ns samples and a retention of 40% of the samples we find $g(A)_e/g(A)_p \approx 1.12$ which

yields a $R_{40}(e,p)$ of 1.52 in good agreement with other data. For this case about 25% of the energy is retained. The actual energy cutoff point per sample is ≈ 3 Kev for this ≈ 16 mm of gas. We find $g(A)_e/g(A)_p$ for this sample length is essentially the same from 10% sample retention to 90% sample retention, so the observed relativistic rise is not sensitive to the level of truncation once the largest few percent of the samples are removed.

For the 20 ns samples, as expected, we do a much cleaner job of eliminating the energetic collisions. The energy cutoff for 40% sample retention is ≈ 100 ev and the retained energy is only about 12% of the total. Most significantly $g(40)_e/g(40)_p$ is now 1.37 which gives $R_{40}(e,p) = 1.84$. In fact $g(A)_e/g(A)_p$ increases from about 1.12 at 90% sample retention to 2.18 at 10% sample retention resulting in corresponding increases in the relativistic rise. This dramatic rise in $g(A)_e/g(A)_p$ is the result of the fact that there is relatively more energy in the smaller samples for the electrons than for the protons. One has to be careful in translating this into a statement about the $P(E)$ distributions because the same percent sample retention corresponds to different energy cutoffs for electrons and protons. However, by comparing Fig. 6a and 6c, we can observe that $P(E)$ for protons (at the minimum of the dE/dx curve) has a substantial number of zero energy samples while the corresponding $P(E)$ for electrons has many fewer zero samples. Thus there is a sample retention level ($\approx 15\%$) for which the retained proton energy will be essentially zero, while the retained electron energy will be finite. The calculated relativistic rise for this level of truncation would be very large, but this does not appear to be a practical approach because the amount of retained energy is very small and the relative statistical fluctuations are large. As the fraction of retained samples is increased, the average energy in the retained samples increases, thus the effect of the distribution of zero and small energy samples on g_A is diluted and R_A will approach R_{100} . As shown below, we find that sample retentions of from 30-60% seem to be the best compromise for particle selectivity.

This effect has not been observed previously because as can be seen from Fig. 8a and 8c, when the data is taken using "large" (≈ 16 mm) samples, there are no zeros for either protons or electrons and the average fractional retained energies per sample are not very different. The information about the distribution of the small energy losses has been lost by averaging over a sample which contains many individual energy loss events. In fact, in the limit of very large samples one would expect $P(E)$ to become relatively narrow, thus g_A would become a straight line and $R_A \rightarrow R_{100}$ for any A .

Figure 10 is a plot of the observed $R(e,p)$ and $R(\pi,p)$ as a function of sample size and truncation which summarizes these results. The increase in the observed relativistic rise for small samples is the result of our being able to use our more detailed information on the energy loss (particularly on very small losses) to emphasize differences in the underlying $P(E)$ distributions for the electrons and protons.

Since the observed relativistic rise depends on the shape of the $P(E)$ distributions at lower energies it can be affected by shifts or uncertainties in the electronic baseline offsets for the amplifiers and the ADC. The three particle types were recorded simultaneously minimizing any such effects, and the baseline was stable during the data taking. We estimate that the baseline offset uncertainty is less than 1/4 of the lowest ADC level. With 40% of the samples retained, this could produce a systematic error which varies

smoothly from 20% for the 20 ns samples to 2.5% for the 640 ns samples.

Particle Identification Selectivity

The observation of enhanced relativistic rise with small sample size and severe truncation is not sufficient to assure improved particle identification selectivity. The separation of the particles must be related to the width of the sample distributions. Figure 11 shows how this varies with sample size for the electron data. This is the percent standard deviation σ of a 60% retained sample of 30 one-meter tracks.

To compare our results in particle selectivity with other results we define a figure of merit S .

$$S_{A-B} = \frac{|E_A - E_B| - 2\sigma_B}{\sigma_A}$$

where E_A and E_B are the truncated mean particle A and B energies and σ_A and σ_B their standard deviations. S is the number of standard deviations particle A lies from particle B when a selection threshold is set to give 97.5% efficiency for detecting particle B. Figure 12 gives these S values vs. sample size for our data taken at 3.5 GeV/c with 40% and 60% truncations. One must take care in interpreting many standard deviations too literally. From our data we cannot show that these distributions are gaussian beyond 2σ . Indeed the rare high energy knock on electrons will effect the distributions. Possibly the spatial resolution of this kind of drift chamber will allow elimination of these cases.

Included in Fig. 12 is a point for ISIS 1 taken from the review paper of Ref. 2. This S value was calculated from the pulse height distributions for π and e at 500 MeV/c which is equivalent to p and e at 3.5 GeV/c.

We attribute the higher selectivity value of our 16 mm sample data to the fact that our data were taken with a single layer of gas using one ADC. Thus the usual variances that arise in a multi-layer device due to gain variations, offset corrections, cross talk, etc. were eliminated. A multi-layer detector utilizing fast ADC's and longitudinal drift would of course also be susceptible to these effects. Although the observed relativistic rise is sensitive to the baseline offset the sensitivity S is not.

ADC Resolution

A retained sample cut of 40% for the 10 ns samples corresponds to an energy cutoff ~ 100 ev. This suggests that although the dynamic range of energy losses ranges from 0 to many Kev, the most useful information will be in the range of ~ 100 ev. Thus a simple four or eight level ADC (2 or 3 bits) with an upper threshold of ~ 100 ev. and resolutions of 25 to 13 ev. may be sufficient to provide excellent particle selectivity. We note that for our 40% retained samples all samples above the fourth level were removed and thus a 4 level ADC with the appropriate threshold would reproduce this result.

Comparison With a Model

We have compared our data with theoretical predictions of a recently published model by Allison and Cobb.² This model uses the experimentally measured photoabsorption cross sections for various noble gases and a convolution method to calculate ionization

energy distributions applicable to detectors with thin layers of gases. We observe quite good agreement with our data for sample thicknesses $\gtrsim 5$ mm. For samples thinner than 5 mm the agreement is not quite as good. The predicted distributions tend to be narrower and peak at lower energy losses. This is probably caused by the fact that the model ignores diffusion of the drifting electrons which introduces correlations in adjacent samples because of our method of ionization sampling. This effect is, of course, more important for sample thicknesses of the order of a diffusion length (~ 0.5 mm).

Further analysis of the model predictions with a truncated mean method similar to the one used for the analysis of our data reveals characteristics similar to the ones discussed in the previous sections although the effect of the relativistic rise as a function of sample size and truncation is not as pronounced as it appears in the data.

Summary

We have studied the ionization loss in small gas samples using a longitudinal drift ionization detector and fast analog to digital conversion techniques. We find this technique can substantially improve the mass resolution capability of gas particle detectors. We have also shown that only a rather coarse ADC resolution is required to capture all the information needed with the truncated mean sampling method of determining the relative energy loss.

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Figure 1 4 x 4 inch drift chamber with 12 μ anodes, 80 μ field wires

Figure 2 Electronics for dE/dx measurements

Figure 3 Experimental setup for dE/dx measurements including TOF, shower counter and two Cerenkov counters for e, π and p identification.

Figure 4 Sum of thousands of Fe^{55} events to show the average pulse shape.

Figure 5 Sum of thousands of electron events to show the average pulse shape.

Figure 6 a,b,c Pulse height distributions of 20 ns samples.

Figure 7 a,b,c Pulse height distributions
of 160 ns samples

Figure 8 a,b,c Pulse height distributions of 640 ns samples

Figure 9 Normalized energy vs. % samples retained for a) 640 ns samples, b) 160 ns samples, c) 20 ns samples, d) 10 ns samples.

Figure 10 Relativistic rise vs. sample size and degree of truncation.

Figure 11 Standard deviation versus sample size for 1 meter tracks.

Figure 12 Particle identification selectivity
S versus sample size