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CONSTRUCTION AND PERFORMANCE OF A PLASTIC SCINTILLATING FIBER TARGET FOR A RARE KAON DECAY EXPERIMENT

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ABSTRACT

A K^+ stopping target consisting of 2269 plastic fibers, 2 mm diameter and 3.12 m long has been installed in an experiment searching for the rare decay K^+ to $\pi\nu\bar{\nu}$ at Brookhaven National Laboratory. The fibers are bundled onto 379 photomultiplier tube and base assemblies with single photoelectron resolution. After routing to the counting room, the signals are amplified and then distributed to TDC's and high-pass filter circuits that provide signals to ADC's and to fan-ins that provide a target energy-sum pulse used in the fast triggering logic. A minimum ionizing particle 3 m from the photomultiplier yields 1 photoelectron/mm path. The target provides transverse spatial resolution of 4 mm (FWHM) for the vertex of the K^+ decay and 2 ns timing resolution (FWHM) on the difference between the K^+ stop and the subsequent decay. Details of the target construction and operating performance are provided.

INTRODUCTION

Alternating Gradient Synchrotron (AGS) Experiment #787, a collaboration of Brookhaven National Laboratory, Princeton, and TRIUMF,[1] began data taking in February 1988 in a search for rare K^+ decays into π^+ accompanied by noninteracting neutrals. The branching ratio prediction of the three generation standard model (SM) is ~ 1 to 8 × 10^{-10} for the decay to $\pi\nu\bar{\nu}$. A very large window for viewing new physics exists between the SM prediction and the previous limit of 1.4 × 10^{-7}.[2]

The experimental challenge of searching for K^+ decay to $\pi\nu\bar{\nu}$ at the 10^{-10} level requires both high rate capability and excellent rejection of inter-

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acting backgrounds from ordinary K^+ decays. The challenge is confronted by a central drift chamber and adequate segmentation within a series of scintillation counters that measure the range and energy-loss pattern as well as the decay-time sequence to select π^+ and reject μ^+ decays of the K^+. The above systems are surrounded by lead-scintillator calorimeters to reject decays to photons. This is all contained within a 1 Tesla magnetic field.

At the AGS, the Low Energy Separated Beam LESB1 is set to a momentum of 775 MeV/c. Beam kaons are identified by a differential Cerenkov counter and a system of wire chambers and scintillation counter elements. The kaons are degraded in beryllium oxide and stop at the center of the spectrometer in a segmented scintillation fiber degrader called the target. The flux is about 2×10^5 stopping K^+/s with about 0.4 K^+/π^+ in the target. For adequate background rejection, design studies demonstrated that the vertex of the K^+ decay needed to be located to < 5 mm traverse to the beam and that the decay be unaccompanied by any other charged particle in the target in time coincidence with either the incident K^+ or with the outgoing π^+. Because the target is centered in a 10kG field and it was necessary to have little inert material that could reduce the gamma detection efficiency, plastic scintillating fibers with no inert light pipes were found to be desirable for the target material. Good time resolution was necessary both for background rejection and for triggering purposes. This led to the requirement that the fibers be routed to fast photomultiplier tubes.

This paper outlines the methods used for the construction of the target and describes the electronics used. We conclude with the results obtained with this target during the initial run of the experiment.

Target Construction

Fiber Production

The 2 mm diameter fibers were drawn by Optectron Corp. (Les Ulis, France) with a core of their S-101 styrene scintillator with refractive index 1.59, and a vinyl-acetate cladding, with index 1.46. In the core, butyl-PBD and POPOP shift the wavelength peak to ~ 440 nm. The 25μ cladding prevents damage to the clad-core interface where total internal reflection up to 6° captures 8% of the light for efficient transport to a photomultiplier tube (pmt). About 200 m length of fibers were drawn onto spools of about 1 meter diameter. The fibers were sent to Vacotec (Reconvilier, Switzerland) where a 1000Å Al coat was sputtered onto the fibers. The Al coat provided a protective coating for the fragile vinyl-acetate cladding, and also prevented possible mixing of light from one fiber to another. There was no measurable loss in performance of the fibers due to the sputtering process. The fibers were then sent to Brookhaven National Laboratory where they were cut to length and selected for the target.

Fiber testing and selection

The fibers were selected for the target on the basis of their response to a ^{106}Ru source. The fibers were cut to a length of 3.12 m and one end was polished by a rotating wheel holding various grades of polishing paper. The polished end of each fiber was positioned against a plexiglass light guide coupled to a photomultiplier tube, and the current drawn by the photomultiplier tube in response to the collimated ^{106}Ru source directed 3.0 m from the polished end was recorded. The current measured in response to the source was measured to be directly proportional to the photoelectron yield from a minimum ionizing particle. Sixteen fibers were measured in each setup by moving the source over the fibers with a motorized drive in a dark box.

Measurement of each fiber was found to be necessary because the response of the fibers within the same draw was found to vary by more than a factor of two. This variation was caused by differences in attenuation length generally due to imperfections in the core-cladding interface rather than from the intrinsic brightness of the scintillator itself. The typical fiber had an attenuation length of about 2 m. Repeatability of measurements was periodically monitored; variations due to measurement uncertainty was typically < 5%. Long term drifts were monitored by checking a series of calibration fibers.

Fibers were selected for grouping into bundles of six based upon their response to the ^{106}Ru source. The response variation from fiber to fiber in each bundle of six was kept to < 10% in order to minimize variations in light output from kaons coming to rest in different fibers mated to the same photomultiplier tube. The bundles of six fibers were epoxied together with Scotchtest Epon #8 over 2.1 m of their length in a two-piece Aluminum mold. This left 1.0 m of each fiber with no epoxy for routing to the pmts. Each of three molds had four precision slots milled for epoxying the fibers. The size of the resulting triangular bundles of fibers ("triangles") was identical to ~ .003" from each of the 12 slots. This precision allowed an interlocking stack of triangles to be used to form the target without gluing the individual triangles together. The molds were treated with a release agent to allow for relatively smooth removal of the triangular bundles. The target is 75% active, with the rest being mostly epoxy.

After the molding was completed, any residual flashing was removed manually, and the triangular end was squared off and hand polished. Occasionally, drops of epoxy had to be removed from the are fiber lengths. The response of the fibers to the ^{106}Ru source was again measured in order to eliminate the triangles that were damaged by the molding and releasing process (~ 10%).

An Al mirror was vacuum evaporated onto the polished and lacquered epoxied ends of the triangles in order to reflect the scintillation light traveling away from the pmt back towards it. The response of each triangle was rechecked to insure that the Al mirror was of good quality. The response for light generated close to the mirror was typically 1.6 times the response without the mirror. The triangular Al mirror coating was designed to be about 1% transmitting to external light. This allowed light from a light emitting diode (LED) calibration system to enter the fibers 3.12 meters from the pmt to check the response of all the channels. A picture of the end of the target, looking downstream, taken before the LED's were installed is shown in Fig. 1.

A black teflon protective sleeve was pushed over the six fibers in the unglued region for mechanical protection and to reduce the probability of optical cross talk. Finally, a brass mounting sleeve was slid over the six fibers and a 1" long × .29" diameter UVT (ultra-violet transmitting) plexiglass light pipe mixer block was glued onto the six polished fibers for coupling to the pmt. This block served two purposes. First, it mixed the light from the fibers so that variations in the photocathode response of the pmt were uncorrelated with individual fibers. Second, it captured the fiber ends for coupling to the pmt.

<u>Electronics</u>

Crowded conditions on the downstream end of the spectrometer where the target pmts are located means each of the 379 units had to be small. One cm diameter Hamamatsu R1635-02 pmts and miniature base circuits slide into 8 inch long pieces of 3/4 inch iron pipe with threads on both ends. A spring ahead of a felt light seal forces the dry photocathode window against the six fiber optical mixer-coupler. The dry optical joint is preferred to facilitate field replacement of pmt-base units and to achieve stable long term optical couplings.

The pmt's have high gain first dynodes for good one photoelectron sensitivity. The manufacturer provided gains greater than 3.5×10^6 at 1400 Volts. The gain at two different voltages and the relative quantum efficiency was determined for each pmt. The relative quantum efficiency for each pmt was matched to the brightness of each triangle. After the target was installed in the spectrometer, average signals from muons in $K_{\mu 2}$ triggers were used to set final gain values.

The voltage to each tube is supplied by the LRS-1440 system. Figure 2 gives a schematic view of the electronic systems, consisting of a LRS 612A 10x amplifier, a splitter-filter box, the ADC and TDC systems, and the energy sum units. The filter box was designed to cancel the low frequency component caused by the long cables to the ADC units. The target was used in the fast modular trigger by requiring an energy sum pulse of over 5 MeV coincident with the beam logic indicating the presence of a beam kaon. The number of target elements hit at any time was used with a Level 1 trigger system that responded in 5 μs. This was used as an estimator of the range of the decay particle in the target to produce an on-line rejection of $K_{\mu 2}$ decays.

Results

The target was installed in the center of the E-787 spectrometer in January, 1988. The initial data for this experiment was taken from February to May, 1988. For each triangle, the TDC start times and widths were recorded on the multiple hit LRS 1879 FASTBUS TDC system from 500 ns before the event until 500 ns after the event with 2 ns least count. The minimum width was set to 80 ns from the LRS 4413 CAMAC discriminator units in order to provide a signal of number of triangles hit for the Level 1 trigger. The threshold was set to 30 mV, well below the ~ 90 mV pulse from a single photoelectron. The LRS CAMAC 4300B FERA ADC's gate width was set to 130 ns for this run. Figure 3.a shows an event display of the target FERA information, looking downstream, for a typical $K_{\pi 2}$ event. The TDC information for the first hit in the time window -50 ns to +50 ns for this same event is shown in Fig. 3.b. Another event in which a photon converts within the target is shown in Fig. 3.c.

A pattern recognition program[3] sorted the "hit" triangles into clusters of stopped kaons, charged decay products connected with the stopped kaon, separate photon conversions, and random backgrounds by using the target four-space: x, y, energy, and time. Triangles that were spatially adjacent were formed into clusters of candidate kaons or decay products based, to first order, upon the energy information. This is because most K decay products traveling within the spectrometer tracking acceptance are close to minimum ionizing and travel within 30° of the perpendicular to the fibers. Therefore, the decay products deposit < 2 MeV per triangle. The stopping kaons have both a large dE/dx and travel parallel to the fibers and typically deposit > 5 MeV per triangle. Triangles that are disconnected from the longest kaon or pion tracks are kept in a "disconnected energy" class which can be used to identify photon conversions from π^0 decay in the target.

The ultimate rejection of backgrounds for this experiment requires a good understanding of the continuity of the tracks made by the kaon and possible decay product(s) to the rest of the apparatus and the range and deposited energy of the pion track. In addition, the energy deposited by the kaon should be proportional to the distance of penetration of the kaon into the target and should hence correlate with the longitudinal information of the drift chamber track. In addition the presence of other tracks seen in the target can be used to eliminate background processes. The time information is important here, because only tracks that are coincident in time with either the K or π need be considered as backgrounds. Tracks that occur at other times are indicative of accidentals from other beam particles and need not necessarily cause the event to be rejected. Another motivation for good time resolution is that the time difference between the K and π indicates that the kaon has come to rest in the target before its decay; this in turn eliminates in-flight decays for which the range, momentum, and energy correlations may not be used to eliminate $K_{\pi 2}$ and $K_{\mu 2}$ backgrounds.

In the sections below, we discuss the results obtained to date from the fiber target. We discuss its time resolution and tracking ability. We also discuss how it is being used in the experiment to peak the resolution functions for background reduction.

Energy information

As mentioned above, the energy in each triangle is used in the pattern recognition program, in first order, to separate incident K's from decay products. A Monte-Carlo program indicated the necessity of scaling the observed energy up by 25% to correct for the amount of inert epoxy and cladding in the target. The gains of the triangles were matched by centering the average energy-loss for $K_{\mu 2}$ decays. Figure 4 shows the resulting average number of channels in the FERA system for these calibration events. With the calibration of about 7 channels/photoelectron and an average path in a triangle of ~ 4 mm, this shows that the photoelectron yield is ~ 1 per mm path.

Time information

The TDC units provide information on the leading and trailing edges of all pulses in the target over a 1 μs time span. The response of the triangles to the time of the kaon and the time of the pion can be very accurate, in principle, because each kaon typically excites up to 5 triangles, and the pion excites up to 25 triangles, depending upon the origin of the vertex in the target. In practice, this is limited by the small number of photoelectrons seen in each triangle and the intrinsic time response of the scintillation material itself.

The fiber scintillation material has a time emission distribution made up of several components, the fastest of which is about 3.1 ns (mean), and the slowest observed is > 750 ns (mean).[4] Figure 5 shows the number of hits vs time in the target starting 1.2 μs after the prompt times. A time constant of ~ 750 ns is observed. More than 30% of the light arrives at the pmt with a time constant longer than the 3.1 ns fast component. Since our system responded to the first photoelectron in each triangle, there is a non-negligible probability that some triangles with less than several photoelectrons from traversing pions will have a TDC fire time much later than the true event time. Indeed, in the "typical event" shown in Fig. 3b, one can see some triangles with recorded times more than 5 ns later than the bulk of the triangles.

The leading edge time from each triangle can be weighted by the energy to arrive at the best estimator for the kaon or pion time. Figure 6 shows the time difference between the kaon and the muon for a $K_{\mu 2}$ calibration run. The data comes from the target, with no information from the rest of the apparatus. The rate of rise of the distribution shown in the inset is consistent with an rms time accuracy of 1.0 ns, or about 0.7 ns resolution for each particle.

Position resolution

The K and π or μ tracks found in the target are translated and rotated into registration with the drift chamber. A small quadratic correction for energy loss in the target centers the triangles from the K decays on the extrapolated drift chamber orbits through the target. In a circular coordinate system, the pi-triangles define linear projected tracks. A linear least square fit here has a transverse rms of 1.8 mm in radius that is appropriate for objects with 6 mm dimensions. Six mm divided by square root of 12, 1.6 mm, is expected.

Target Range Extraction. The π or μ track is extrapolated towards the triangles of the K track. The uncertainty of the range measurement is estimated to be the full width of the locations of the kaon triangles close enough to the fitted line to have hosted the decay. This uncertainty then varies with the number of triangles on the kaon trajectory and the opening angle between the kaon track and the trajectory of the decay particle.

The x-y projected range in the triangles is corrected to a true range component by correcting for the dip angle from the drift chamber. The longitudinal target range uncertainty is about 4 mm (FWHM).

Consequences to experiment

The results as described above for the target energy, time and position information have been used to establish the continuity of the data in the beam area with the rest of the detector. Cuts based upon the time difference of the kaon and pion in the target are used to reject kaon decays in flight and a small background of beam pion scattering events. The continuity of the target track with the drift chamber track is used to eliminate background events as well as to reject errors in pattern recognition in either the target or in the drift chamber.

By extrapolating the energy, momentum, and range back to the origin in the target, the best possible use of constraints is used to establish the possibility that any given event is consistent with known backgrounds. For example, Fig. 7 shows the raw momentum of $K_{\pi 2}$ events as calculated in the drift chamber. The rms of the distribution is 4%. By correcting each pion momentum to the origin for the target momentum loss, the rms approaches 2%. Thus a significantly tighter constraint on the momentum can be used to eliminate these events.

CONCLUSIONS

A plastic scintillating target made of 2 mm diameter fibers has been constructed and installed as the stopping target for AGS experiment #787. The target has operated successfully and reliably, yielding about 1 photoelectron per mm path for a minimum ionizing particle 3 m from the photomultiplier tubes. The target provides transverse spatial resolution of 4 mm (FWHM) for the vertex of the K^+ decay. In spite of long time components from slow scintillator components seen at the single photoelectron level, we have achieved a 2 ns timing resolution (FWHM) on the difference between the K^+ stop and the subsequent decay. Backgrounds caused by accidentals, pion interactions in the target, decays in flight, as well as common $K_{\pi 2}$ decays are reduced by incorporating the target's spatial and time information into the analysis programs.

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REFERENCES

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2. Y. Asano, et al., Phys. Lett. 107B, 159 (1981).

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4. J. Flournoy, private communication.

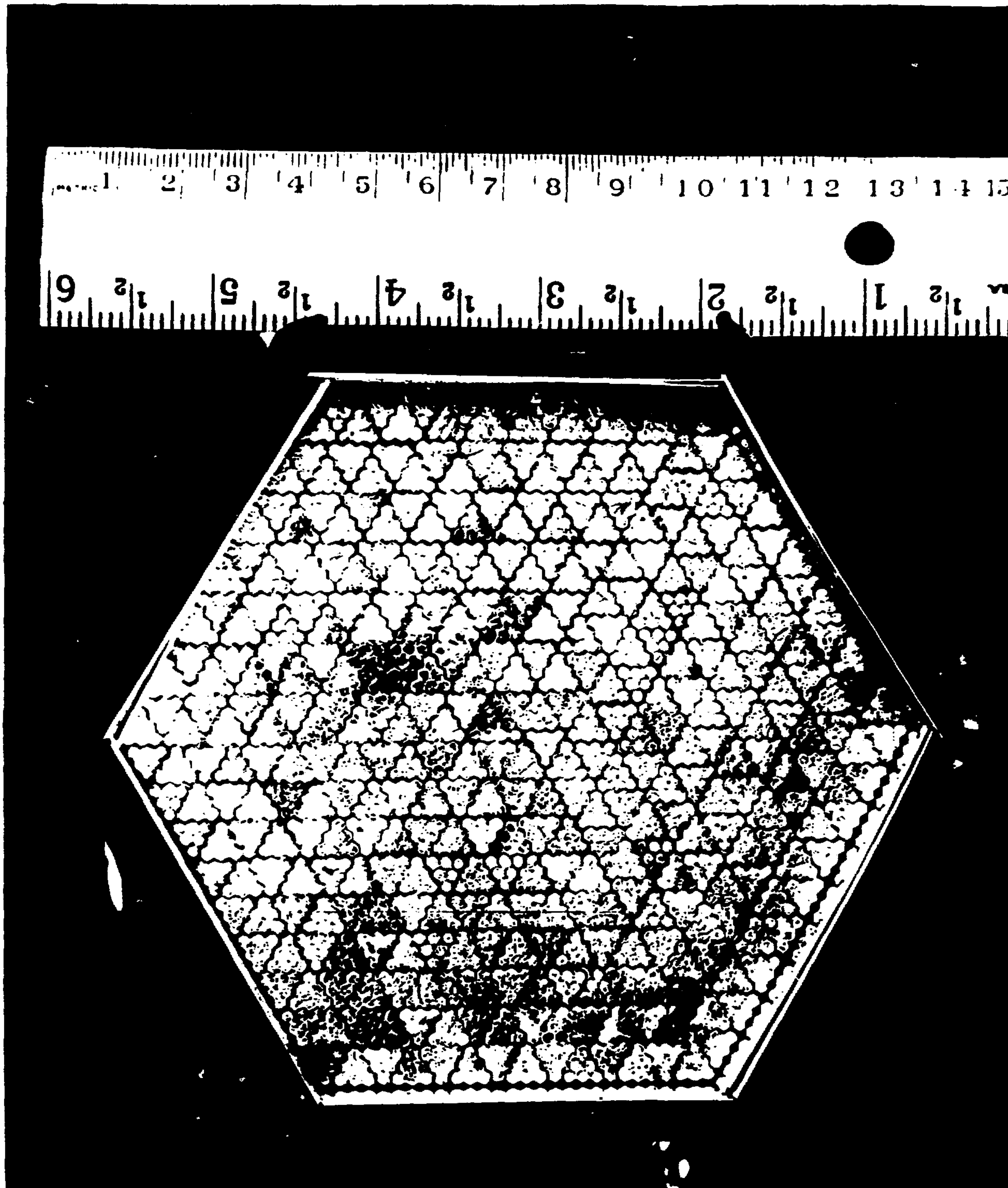

Fig. 1. A photograph of the end of the target, looking downstream, is shown.

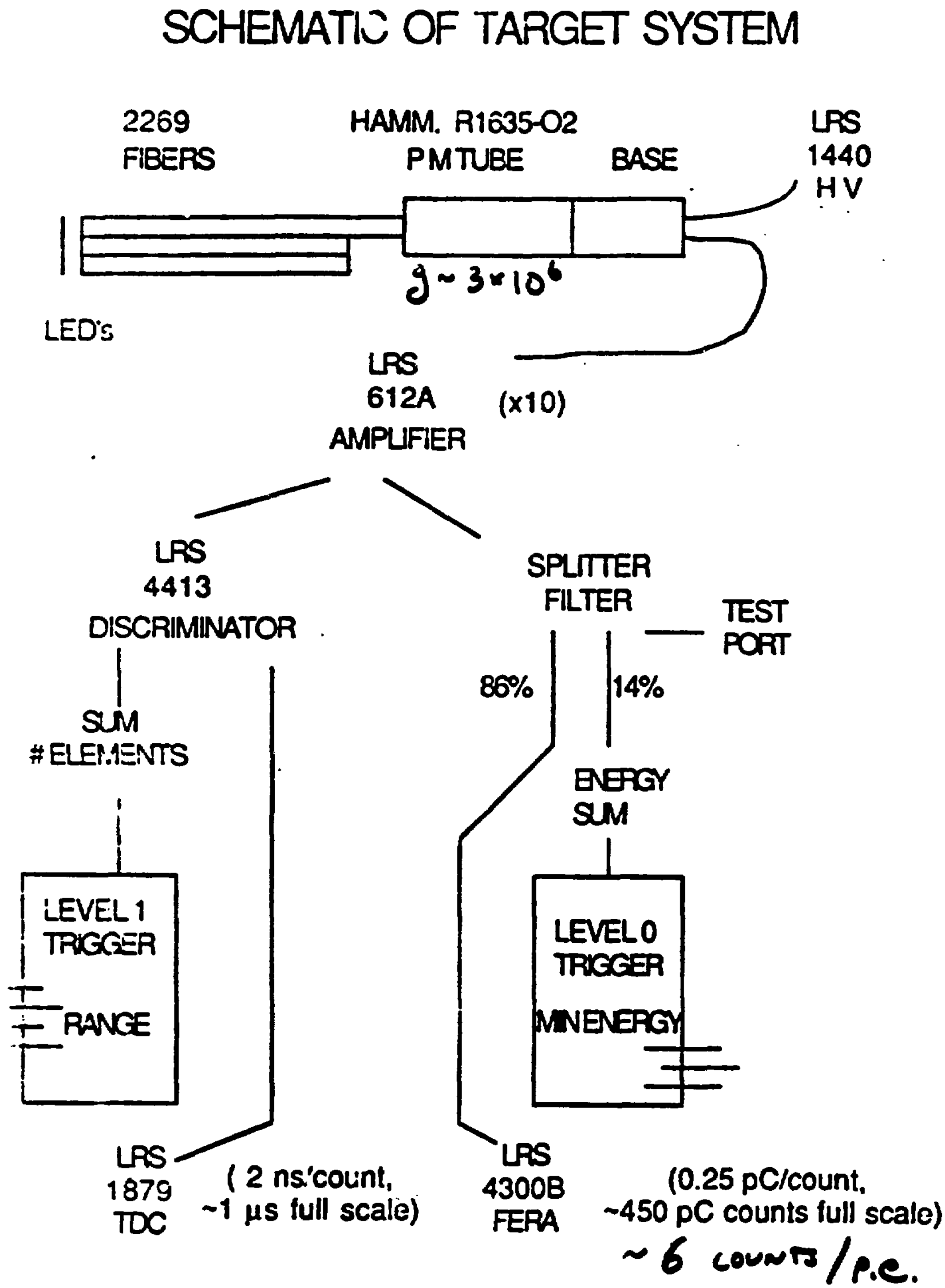

Fig. 2. A schematic view of the electronic systems, consisting of a LRS 612A 10x amplifier, a splitter-filter box, the ADC and TDC systems, and the energy sum units.

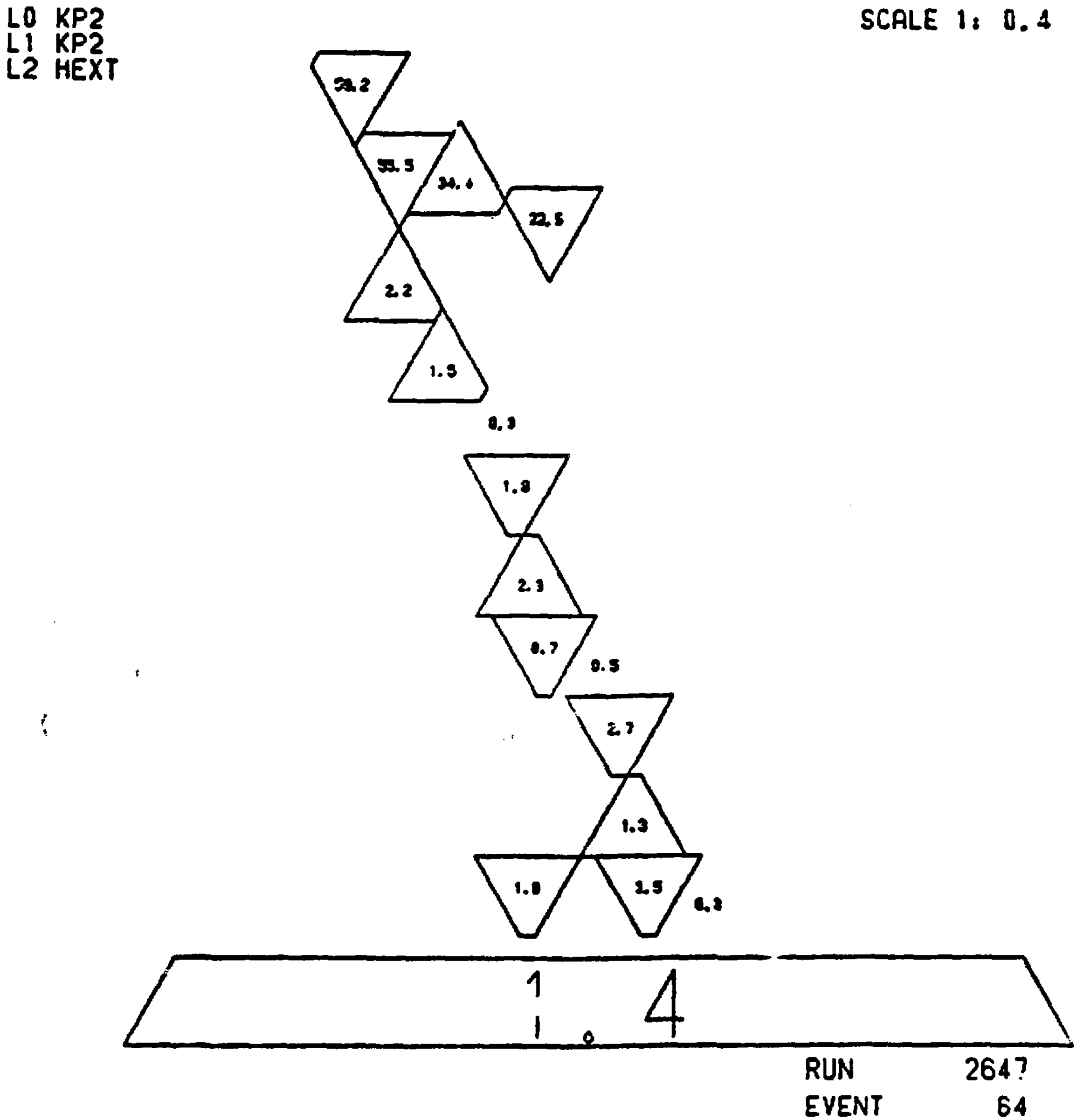

Fig. 3a. A view of the target showing the pulse height information for a $K_{\pi 2}$ decay. The units are in MeV.

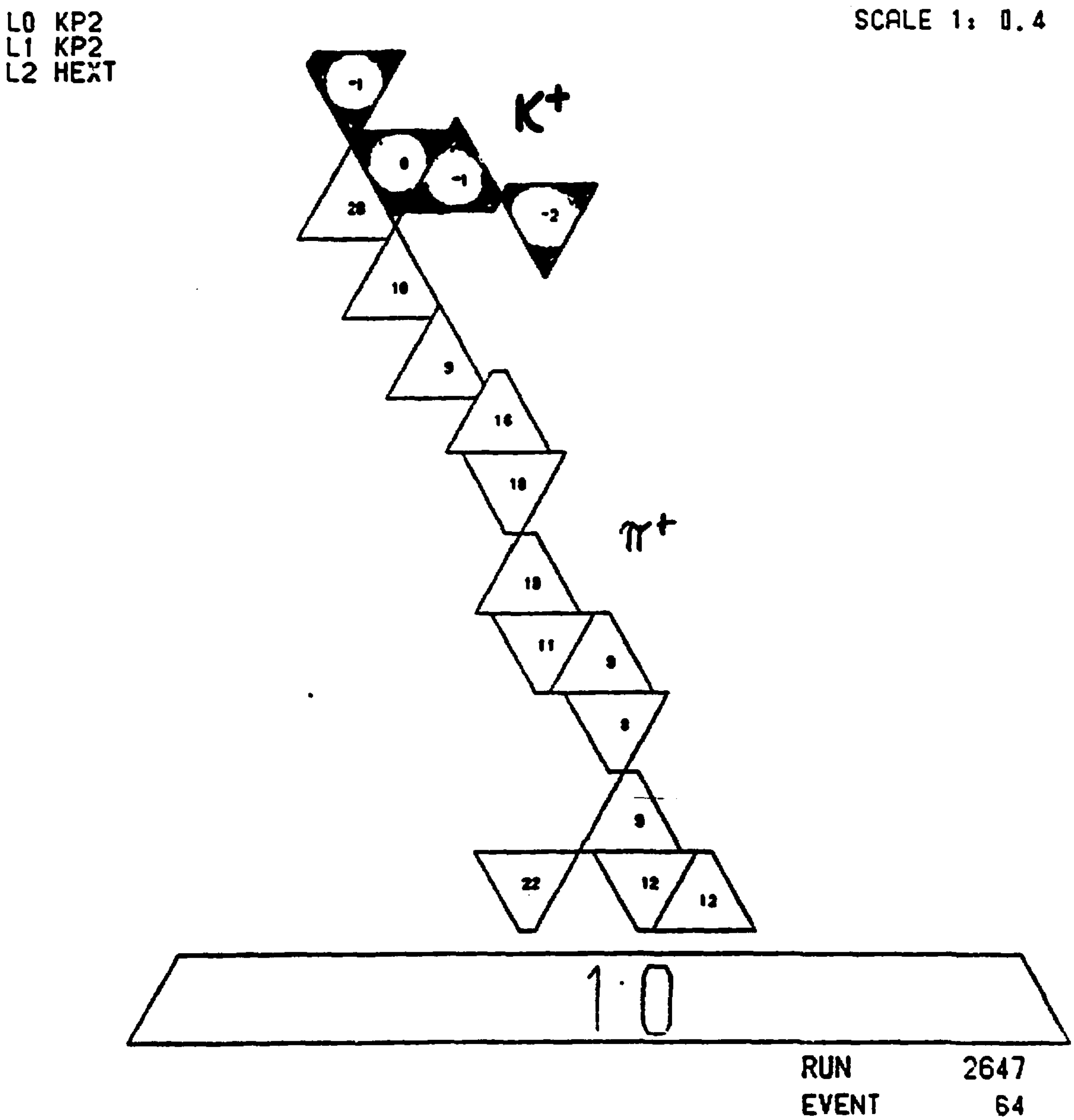

Fig. 3b. The TDC information, within ±50 ns of beam particle time for the same event. The units are ns.

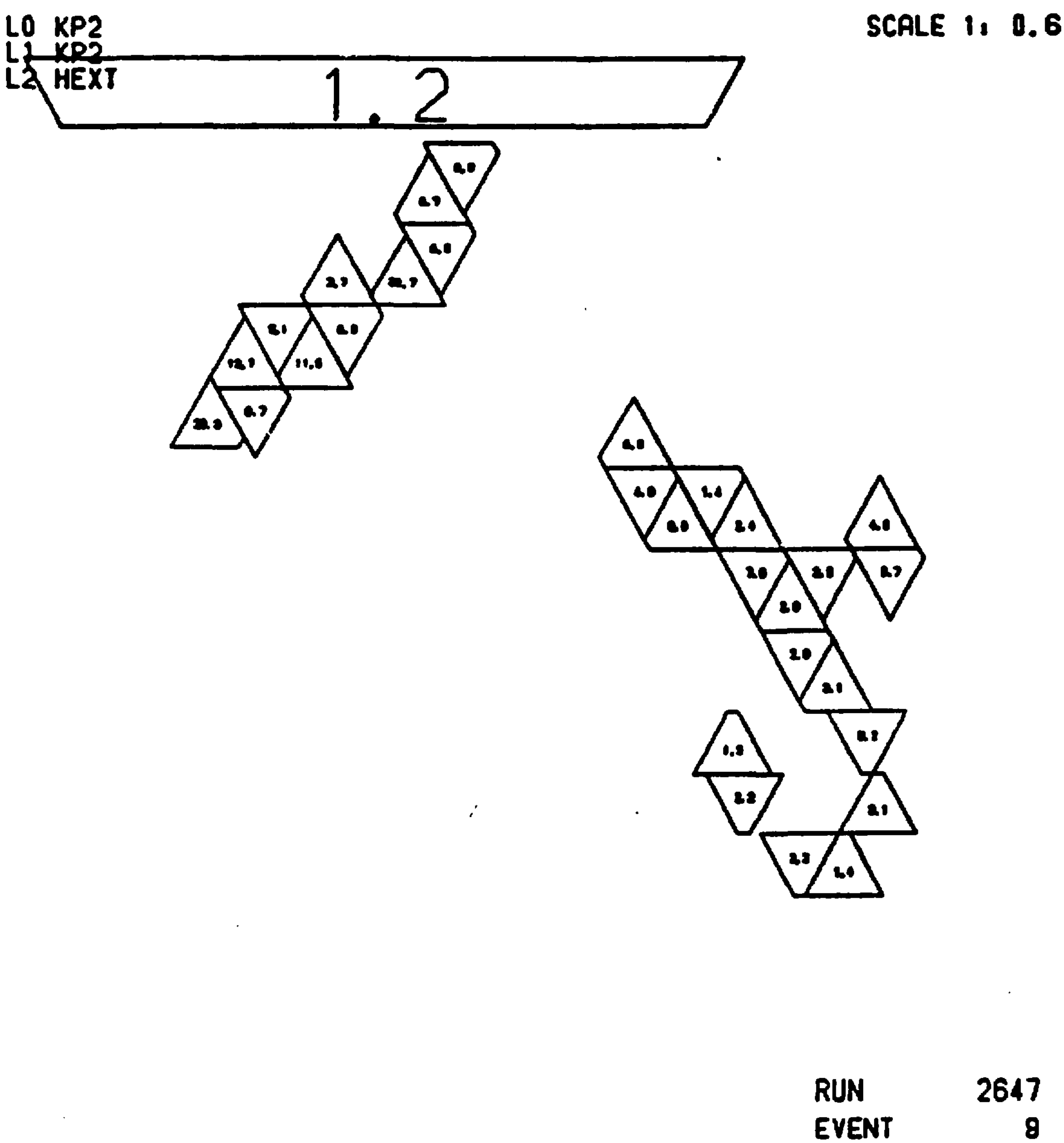

Fig. 3c. Another event showing a photon conversion in the target.

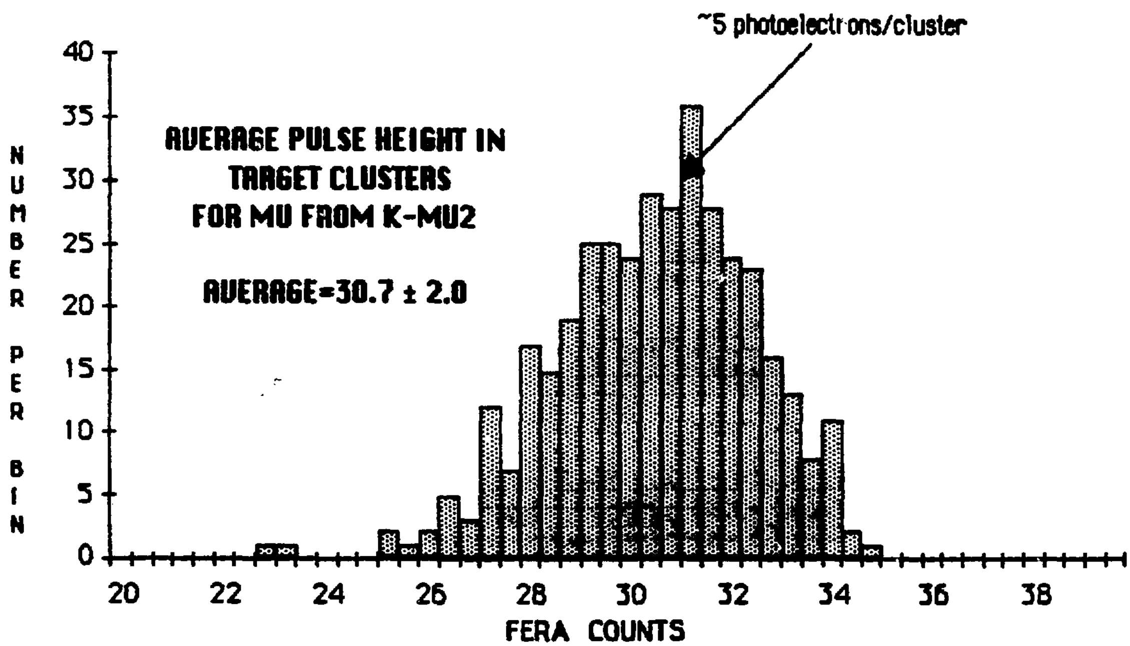

Fig. 4. The average number of channels in the FERA system for $K_{\mu 2}$ calibration events. This represents about 1 photoelectron/mm path length.

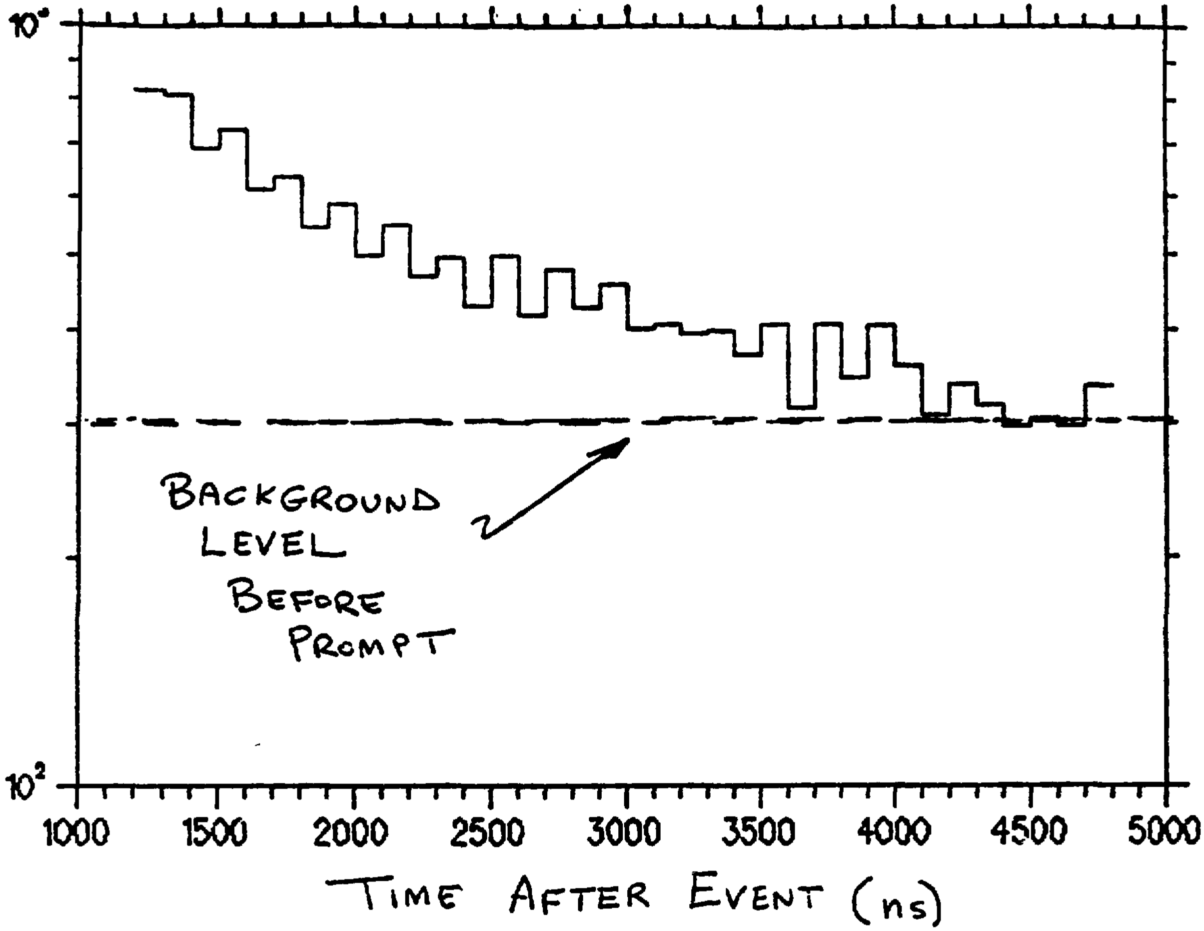

Fig. 5. The time of pulses from some triangles with times > 1.2 μs after the prompt event. Independent measurements[4] confirm this is a property of the scintillator material itself and not due to electronic effects or light "trapping" in the core or cladding.

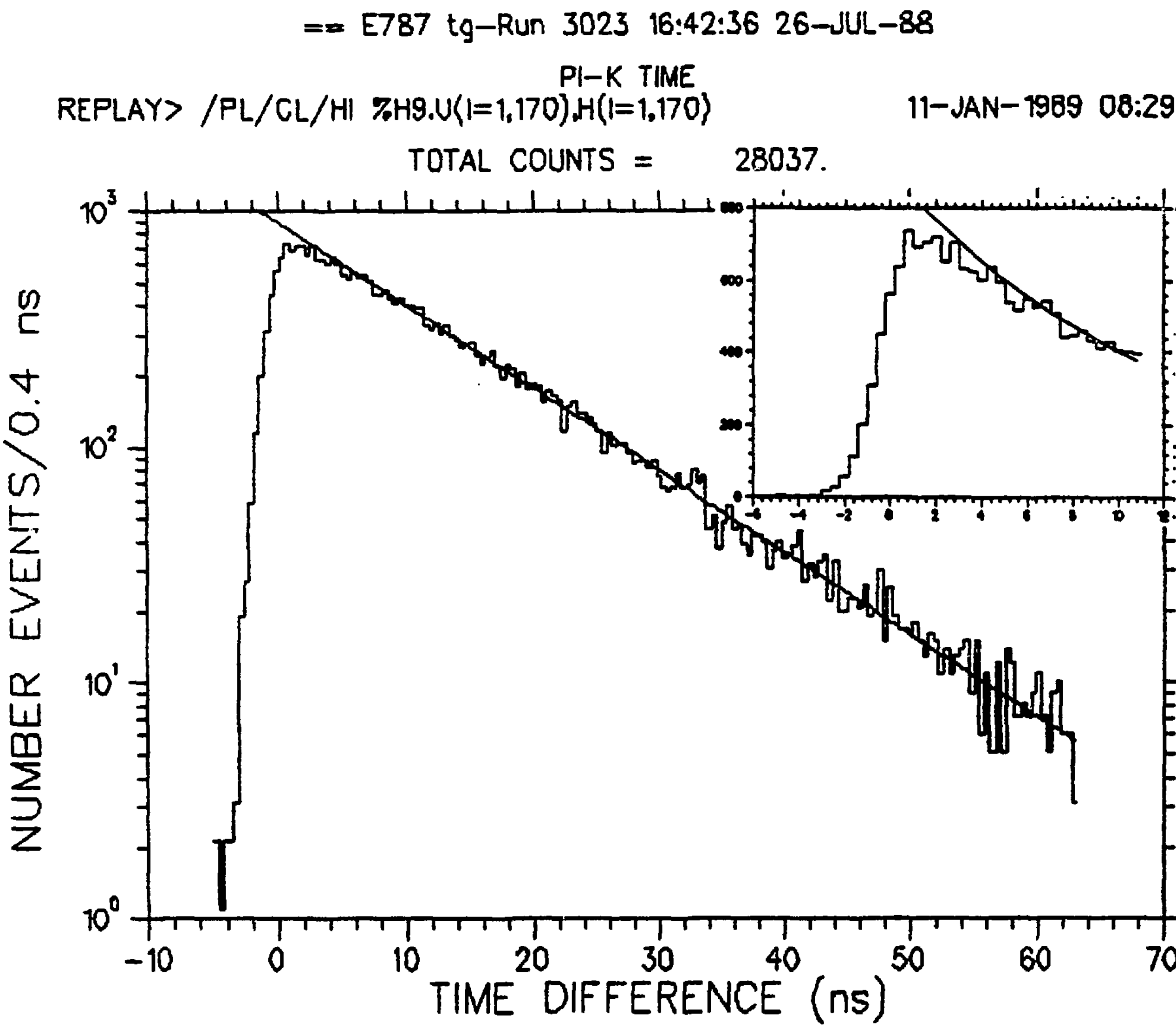

Fig. 6. This shows the time difference between the kaon and the muon for $K_{\mu 2}$ calibration events. The insert expands the region near time = 0.

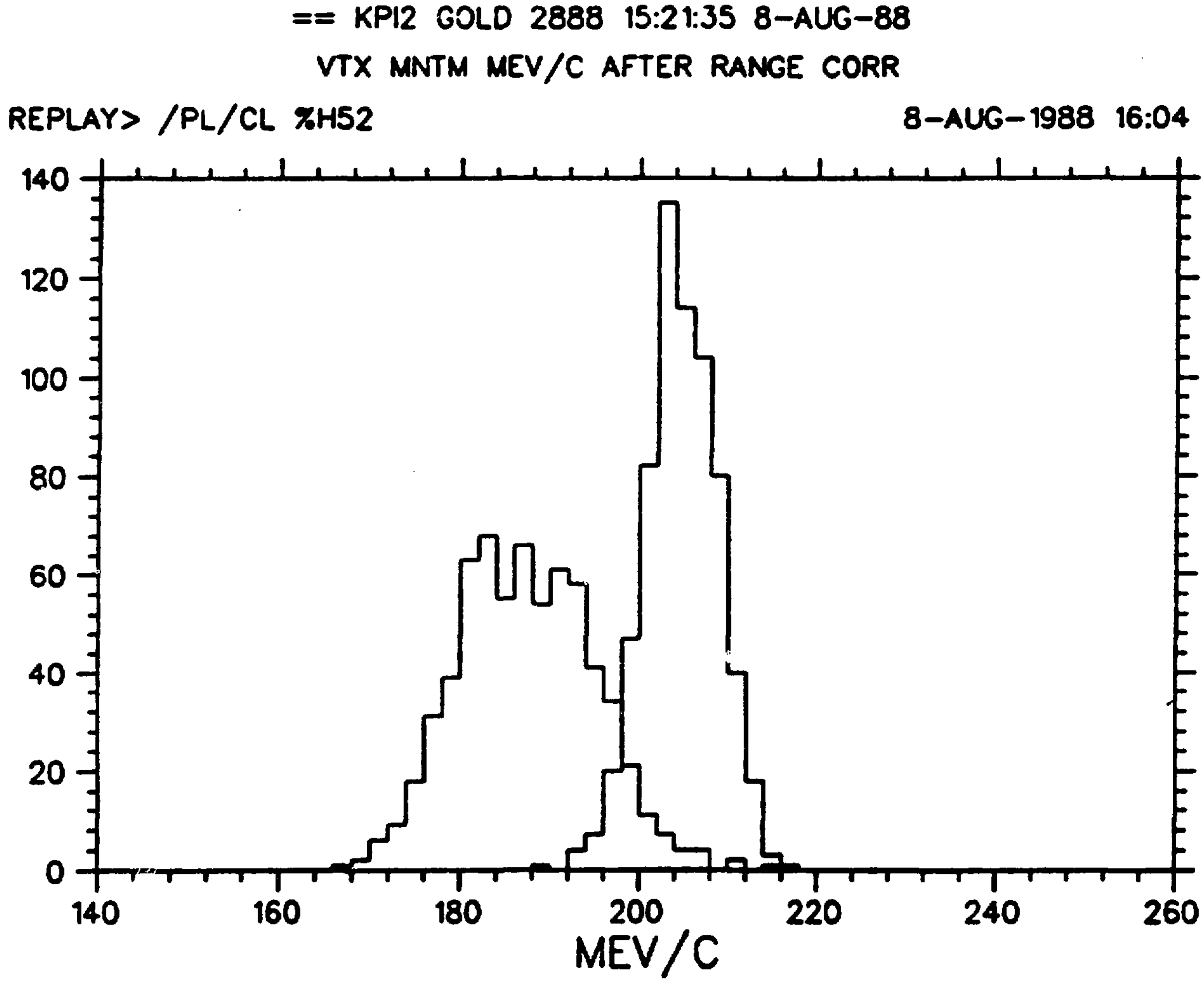

Fig. 7. The raw momentum of $K_{\pi 2}$ events as calculated in the drift chamber and after correction to the vertex.