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Detection and Analysis of Stopping Muons Using a Compact Digital Pulse Processor

The experiment performed consisted of the development and testing of the necessary tools to detect and analyze cosmic stopping muons, and the detection and analysis of said muons. The purpose of the experiment was twofold. The primary purpose was to detect and analyze cosmic stopping muons. The secondary purpose was to use the muon detection and analysis as a test-bed for the digital pulse processor technology and the associated software.

The digital pulse processor was a prototype unit designated the DDC-1, which was designed and built by Wojtek Skulski (Figure 1, Figure 2). The signal in inputted to the board directly from the signal source (in this case, a scintillator) and undergoes analog signal conditioning, in particular passing through a variable gain amplifier. It is then passed through a Nyquist filter and is converted into a 12-bit digital value at a rate of 48 MHz in the ADC. The signal is then examined by an FPGA, which triggers under programmable conditions (in this case, when a specific threshold value is crossed). The signal then enters a looping buffer of 1024 samples. When a trigger event occurs, the buffer stores a predetermined amount of samples surrounding the trigger event and then stops, activating a flag signal. The board is periodically polled through the USB interface, and when the polling detects the flag signal, the data in the buffer is sent to the computer, and the buffer starts looping again. A JTAG interface in located on the board for programming the FPGA. Other features of the board not used in the experiment include a reconstruction DAC and a direct digital interface for debugging purposes.

The software framework used on the PC end of the experiment was BlackBox, by Oberon Microsystems, Inc (http://www.oberon.ch). Without the combination of simplicity, versatility, and rapid prototyping capability that this framework provided, the experiment would have proven extremely difficult. Within this framework, Wojtek Skulski and Daniel Miner co-authored a persistent data object management system to manage the data acquired in the experiment. Elaborating on and customizing a basic DAQ framework authored by Wojtek Skulski, Daniel Miner developed various analysis and detection algorithms including double pulse detection, delay time detection, automatic event sorting, and automatic sorting of energy spectra (Figure 3). Daniel went on to write an offline data processing suite including versions of these features with more options, binning of histograms, smoothing with a moving average filter, normalized difference plots, and variable scale factor integration (Figure 4). The setup was then tested briefly using a liquid scintillator. When it was determined that the setup was functioning properly, it was decided to begin acquisition of data for the experiment.

Because of the compact and powerful nature of the system, the experimental setup, constructed by Daniel Miner and Wojtek Skulski was relatively simple, consisting of a scintillator and photomultiplier tube in a light proof enclosure, a high voltage supply, the DDC-1 board, a PC, and the associated cables (Figure 5, Figure 6). The scintillator used was a 5” high by 6” diameter cylinder of Bicron BC-400 plastic. The scintillator was prepared by painting the top of the scintillator with Bicron BC-620 reflective paint and covering it with a layer of aluminum foil. The side was wrapped in 2” Bicron white Teflon tape, and the bottom was wrapped in 2 layers of the same Teflon tape and one layer of aluminum foil. The entire scintillator was then placed in an aluminum lightproof assembly. The photomultiplier tube used was a 2” Hamamatsu R1847-13, coupled to the scintillator with Bicron BC-630 optical grease. The power supply used was a Tennelec TC 952, set to -1000 V. The experiment was run for (to within 5 minutes) 5 days and 15 hours, with data collection overseen by Daniel Miner.

The experiment functioned as follows. Muons stopping in the scintillator emit a pulse proportional to the energy lost in stopping and then undergo decay, releasing an electron and two neutrinos, with a mean decay time of 2.197 microseconds (Particle Data Group, 2000). The electron causes the scintillator to emit a second pulse proportional to its energy. Since the buffer is 1024 samples long and runs for 900 samples after triggering, and running at 48 MHz (20.8333 nanosecond period), the decay pulse must occur within 19.75 microseconds of the stopping pulse to be detected. Since the mean decay time is 2.2 microseconds, this is generally the case. When two pulses are detected within a single buffer period, the software does several things. Firstly, it records the time (in samples) between the peaks of the two pulses. Secondly, the area under the first pulse, which is proportional to the energy of the stopping muon, is recorded in a histogram. The same is then done with the area under the second pulse, which is proportional to the energy of the decay electron. Finally, the double pulse transient is stored in memory and on disk for further analysis. When only a single pulse is detected, the area under it is recorded in a histogram and the transient is discarded.

Once all the data was collected, it was decided to calibrate the energy (pulse area) spectra using a ray-tracing Monte Carlo simulation of the path length distribution through the cylinder scaled by an approximate MIP energy loss value for the scintillator plastic, 2.3 MeV / cm (Grupen, 1996). This would then be compared to the pulse area spectrum of the single pulses, as non-stopped muons can be approximated as MIP's. The Monte Carlo simulation software used was co-authored by Daniel Miner and Wojtek Skulski. The Monte Carlo software was tested by having it simulate wide, flat discs, for which the path length distribution could be analytically calculated for comparison. The test results can be seen in Figure 7. Although the peak height of the simulation versus the analytical equation do not match, it is believed that this is due to the fact that for the Monte Carlo simulation to "fill in" the analytic distribution completely, it would require an infinite number of samples. A simulation was then run for a cylinder with the dimensions of the scintillator and scaled by the MIP energy loss per unit length (Figure 8), obtaining a value of 31 MeV for the MIP peak. The single pulse energy distribution was then linearly scaled so that the position of the MIP peak matched this value (Figure 9). It should be noted that this calibration is not extremely accurate, as it does not take into account peak smearing caused by detector resolution and the exponentially decaying background radiation picked up by the detector. This same linear scaling was then applied to the pulse area spectra of the stopping and decay pulses of the stopping muon events (Figure 10).

Looking at the decay electron energy distribution, it should be noted that it has a relatively well-defined endpoint within 3 MeV of the known maximum electron energy from the beta decay of a muon of 53 MeV (Muon Decay, 1999). The spectrum of the stopping muon energy is, on the other hand, much wider and contains no notable features. It is a result of the characteristics of the Bethe-Bloch equation near the end of the stopping range.

The other significant experimental result obtained was the decay time distribution. The time distribution was calibrated by setting the width of each histogram bin to the period of the digitizer. The best experimental value obtained for the mean decay time with curve fitting was 2.12 microseconds, with an error of 0.04 microseconds (Figure 11). The curve fitting was done by Frank Wolfs.

Figure 1. DDC-1 with major components labeled.

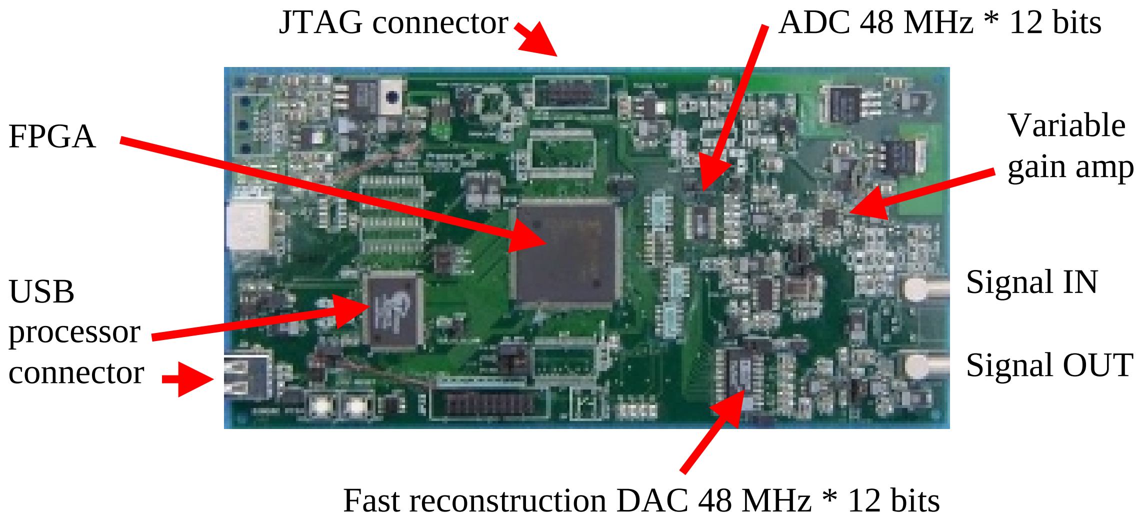

Figure 2. Block diagram of DDC-1.

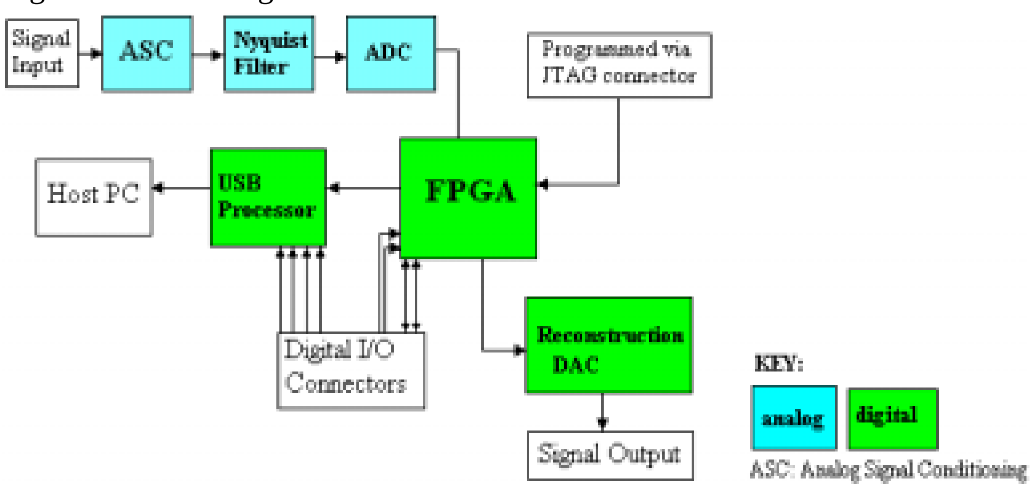

Figure 3. DAQ software screen shot.

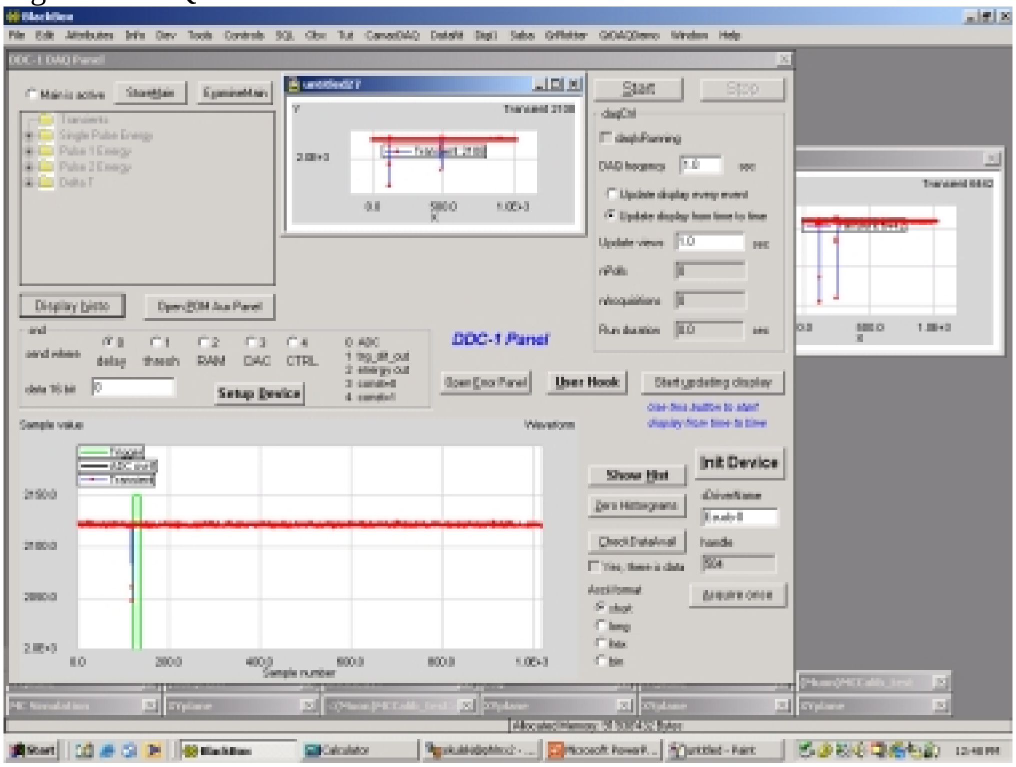

Figure 4. Offline processing software screen shot.

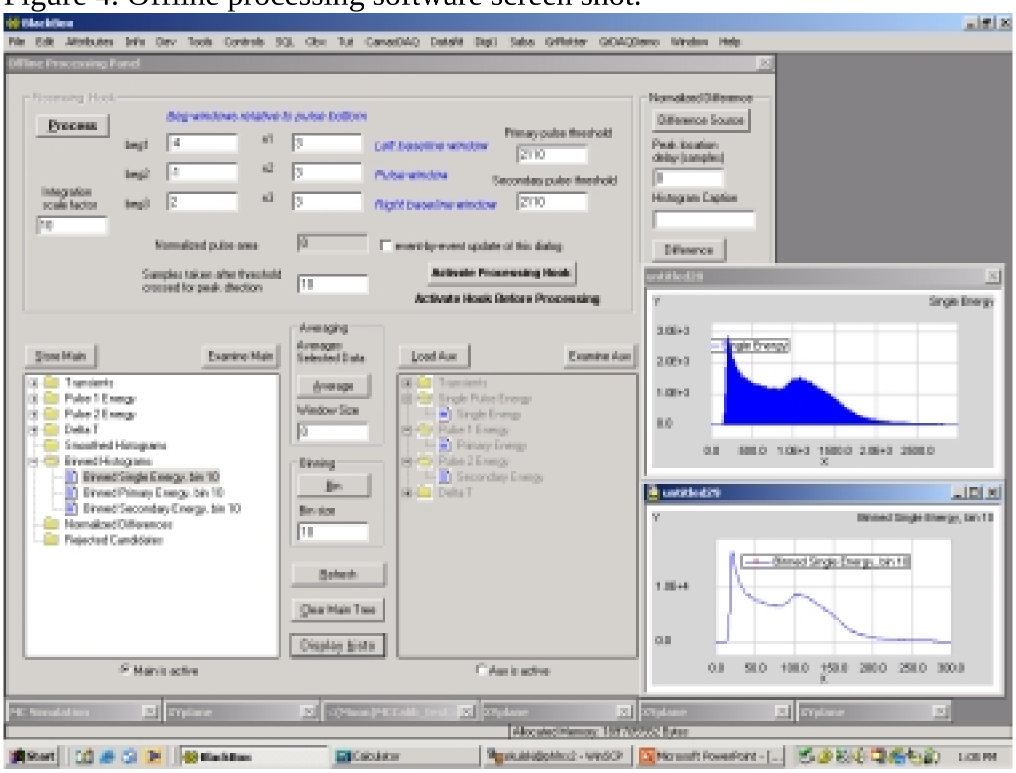

Figure 5. Photograph of experimental setup (black blanket removed from detector assembly).

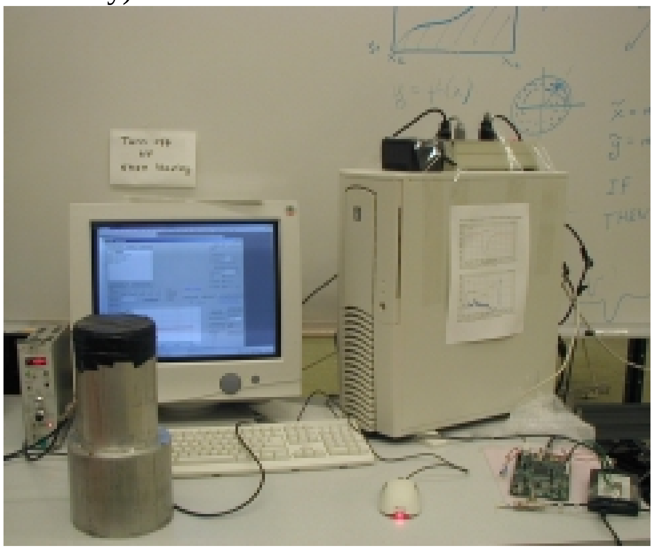

Figure 6. Block diagram of experimental setup.

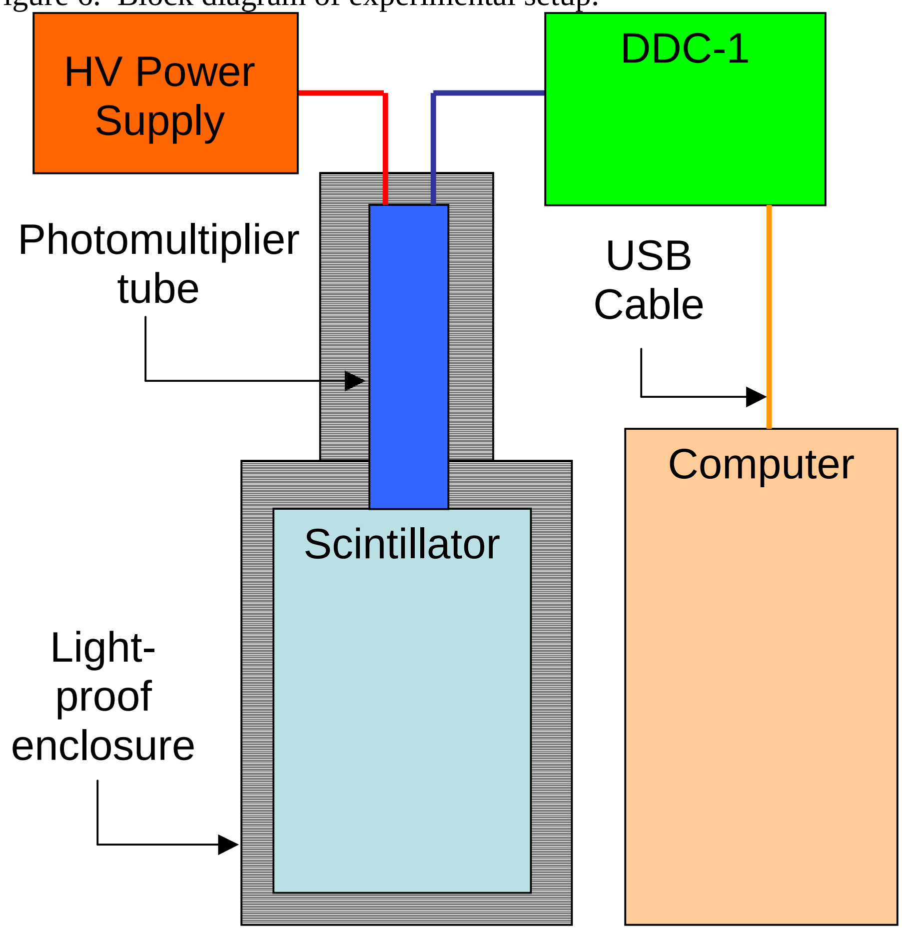

Figure 7. Monte Carlo simulation test results.

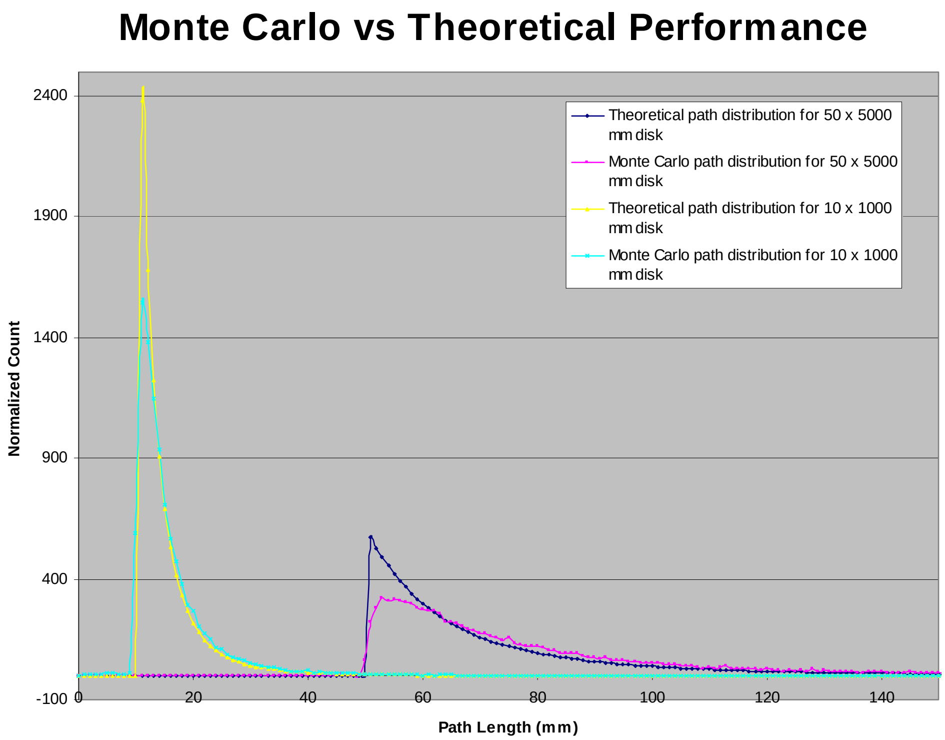

Figure 8. Monte Carlo MIP energy distribution for scintillator.

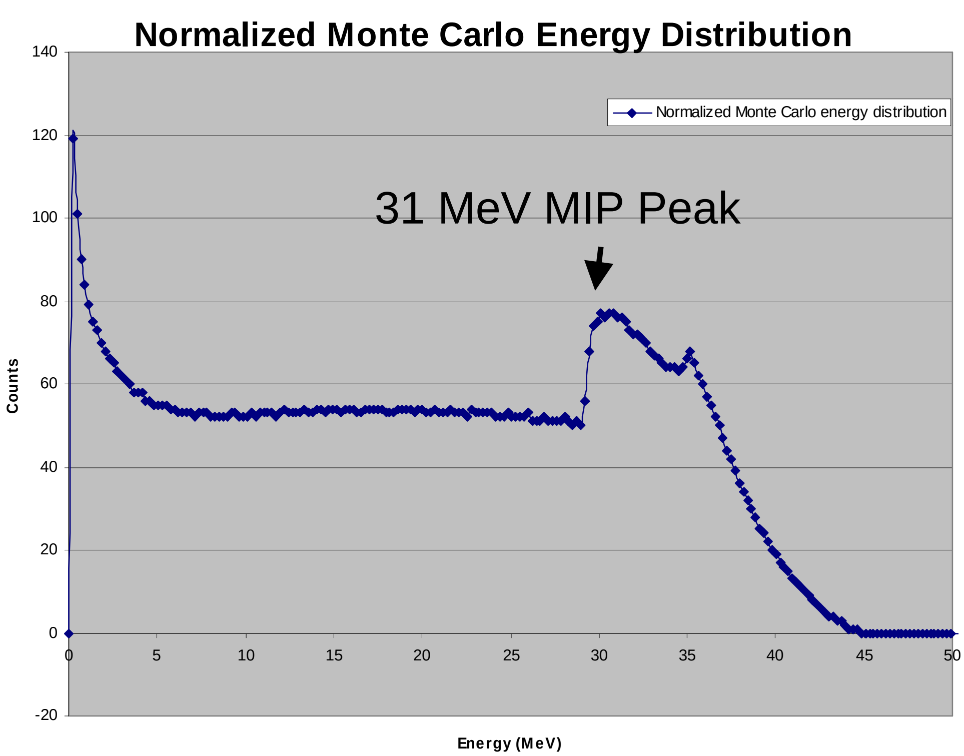

Figure 9. Calibrated single pulse energy distribution.

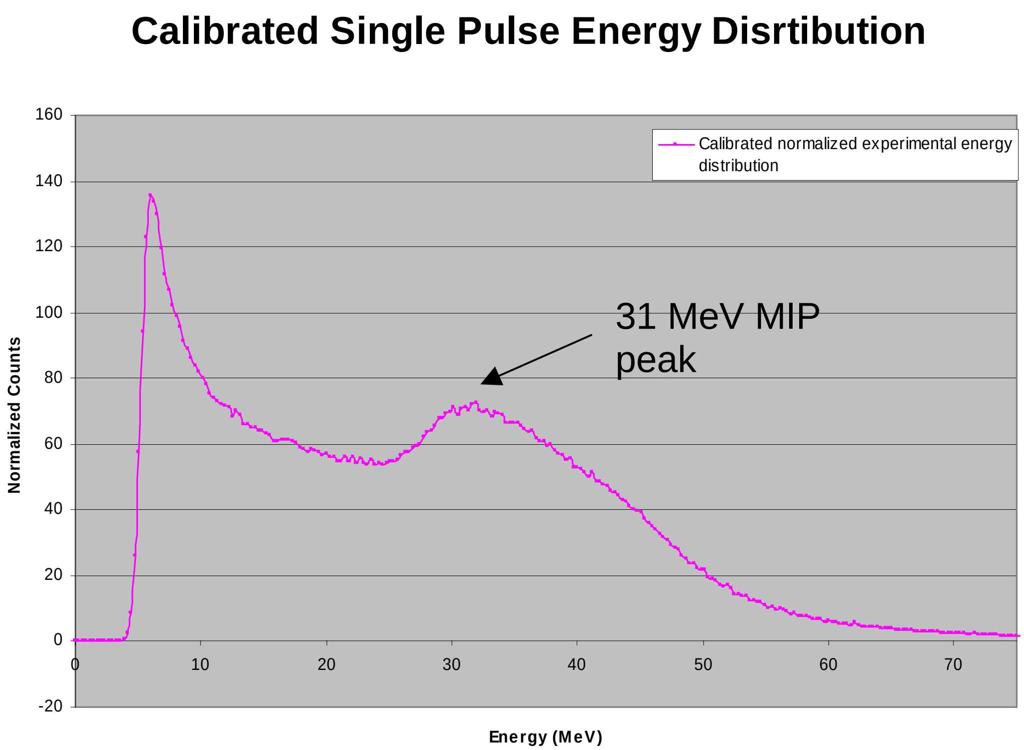

Figure 10. Stopping muon stopping and decay energy distributions

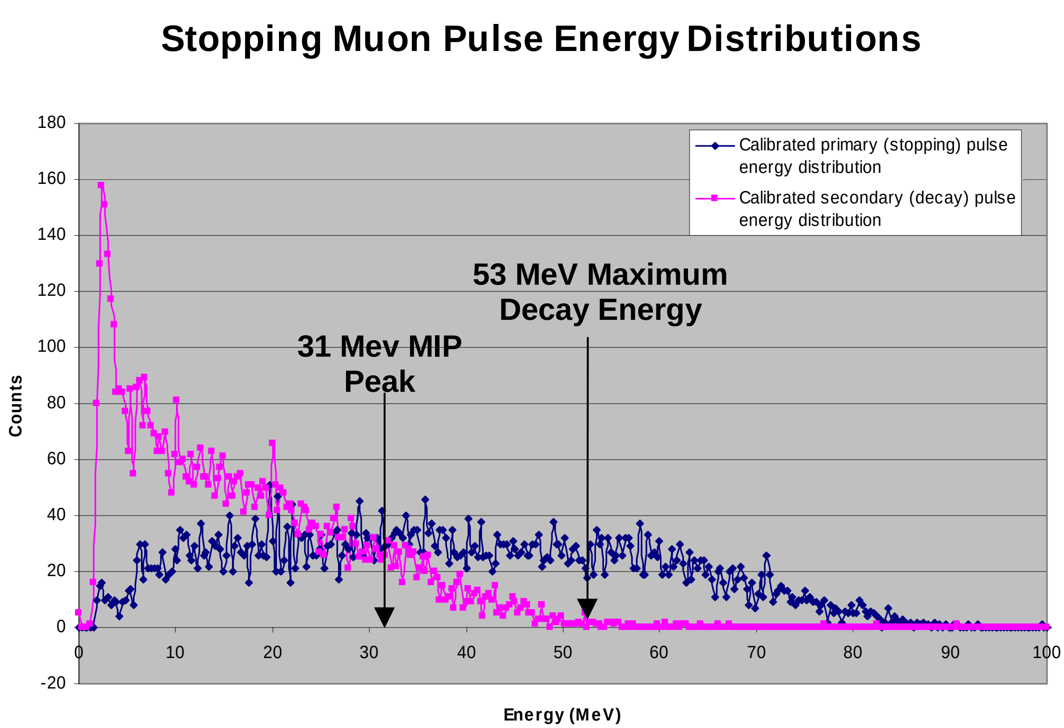

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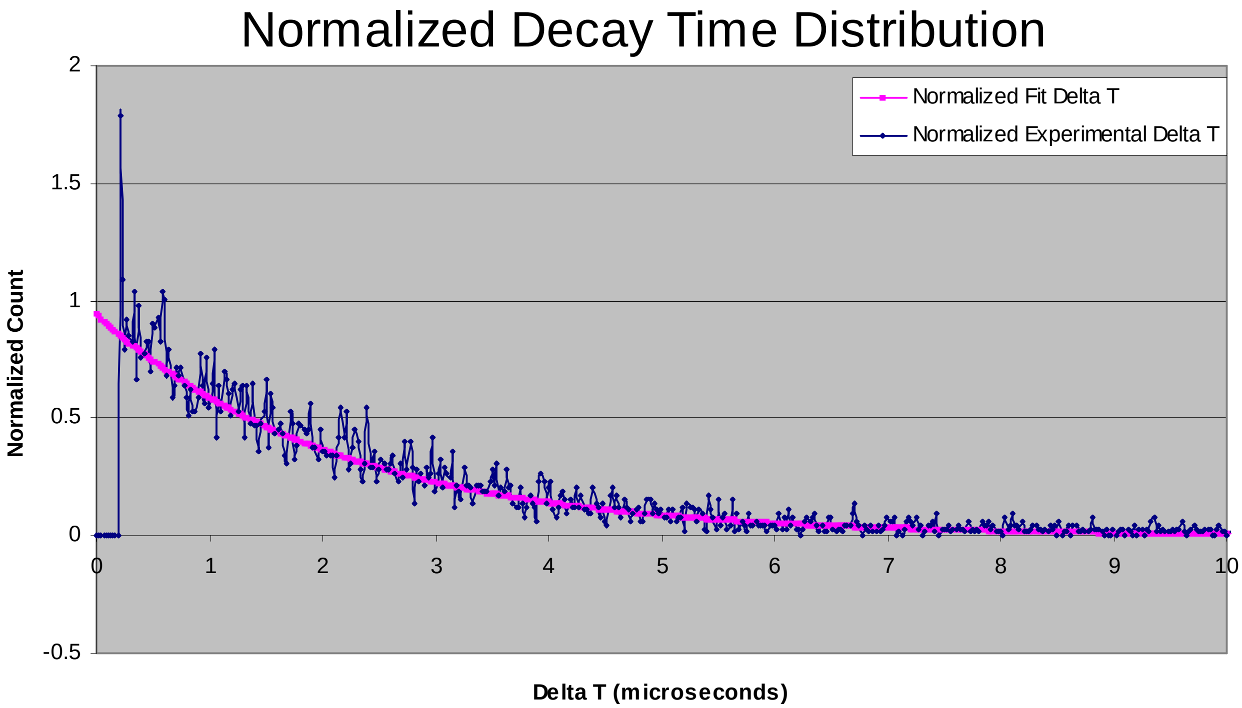
Figure 11. Experimental and fit decay time distribution



References

[1] Oberon Microsystems, Inc. http://www.oberon.ch

[2] Particle Data Group, Particle Data Book, Particle Data Group, Berkeley, 2000.

[3] Claus Grupen, Particle Detectors, Press Syndicate of the University of Cambridge, New York, 1996.

[4] Muon Decay, http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/ykphd/chap4-9.html, Super-Kamiokande Official Home Page, 1999.