Cosmic Ray Detector Hardware

How it detects cosmic rays, what it measures and how to use it…

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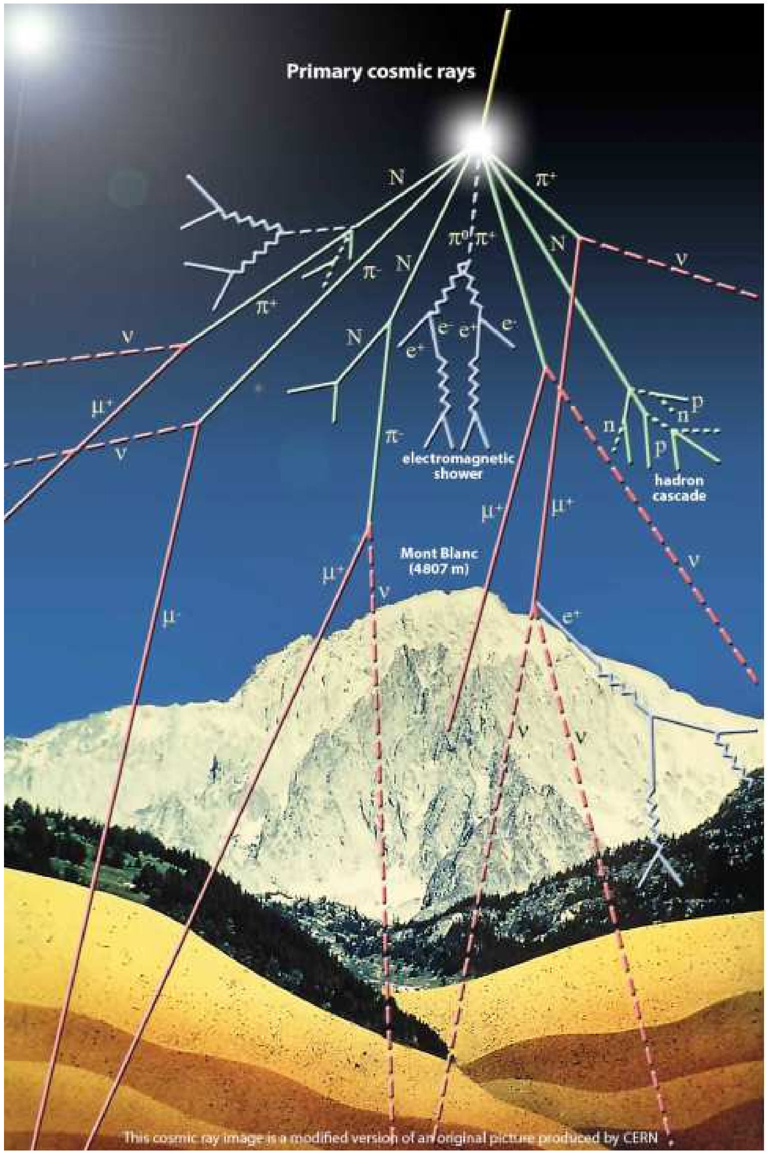
2012 QuarkNet Summer Workshop

What are Cosmic Rays?



- Mostly muons down here…
- Why are they called "rays"?
  - Purely historical
- How can we detect them?
  - Muons are like heavy electrons
  - They have an electric charge
  - "Ionizing radiation"…
  - Some of their energy is transferred to the electrons in the material the move through
  - That's what we detect…

Detecting Ionizing Radiation

Geiger Counters

Ion Chambers

Wire Chambers

GEM Detectors

An electric field does WORK on ionized gas atoms to produce a voltage pulse.

Solid State Detectors

Radiation creates electron/hole pairs in silicon or germanium that allow a current to flow.

Photographic Film

Photographic Emulsion

Ionization initiates a chemical reaction.

Cloud Chamber

Bubble Chamber

Ionization initiates a physical change in a gas or liquid.

Crystal Scintillator

Organic Scintillator

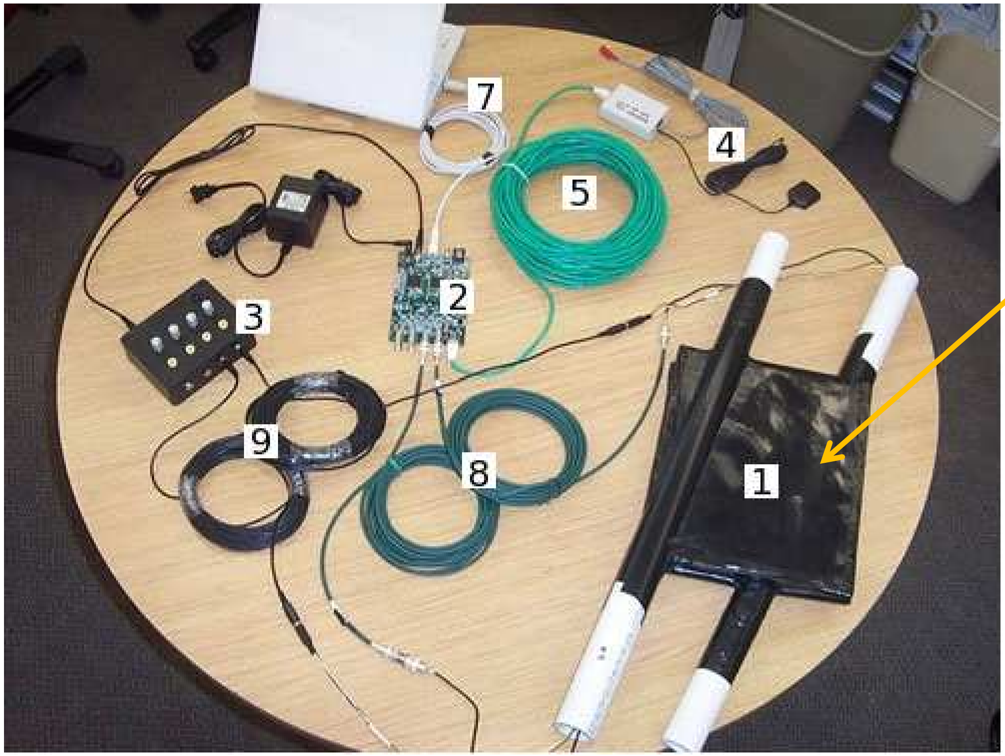
Recombination of electrons and ions produces light!

Plastic Scintillator

Plastic Scintillator

- See, for example, Saint-Gobain, Inc.
- Clear plastic traps light by total internal reflection.
- Doped with a secret chemical that emits light when ionized, but does not re-absorb it.
- Easy to cut, polish, bend, glue…
- How much light is produced?
  - A muon travelling through 1 cm of plastic scintillator might produce about a thousand photons
  - Most of them would be blue
  - They bounce around inside the scintillator until they either escape or are absorbed
- Usually wrapped in tin foil or white paper and then in black plastic or opaque paper to keep other light out.

The Cosmic Ray Detector



Plastic scintillator wrapped in white paper and black plastic.

- Next… how do you detect the light?
  - A few hundred photons at a time…

Photomultiplier Tubes

- Photoelectric Effect:
  - A photon kicks an electron out of the surface of a metal (usually an alkali like K or Cs)
- A photoelectron is accelerated in an electric field
  - If its in a vacuum it can gain a lot of energy
- If it hits a metal surface, it might eject another electron
  - If the metal is coated with a secret chemical it might eject two or three…
- These can be accelerated and can eject more, etc…
- The multiplication factor (we call this the "gain") can be large: $3^{12} = 0.5 \times 10^6$
- The pulses are FAST… typically lasting about 50 ns or less.

Photomultiplier Tubes

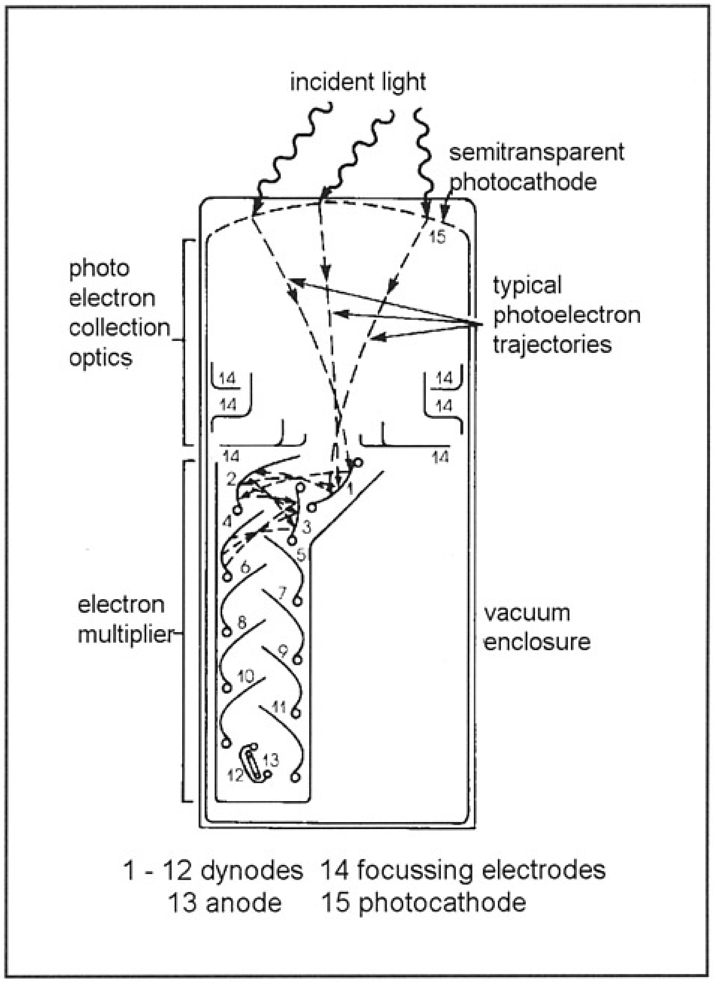
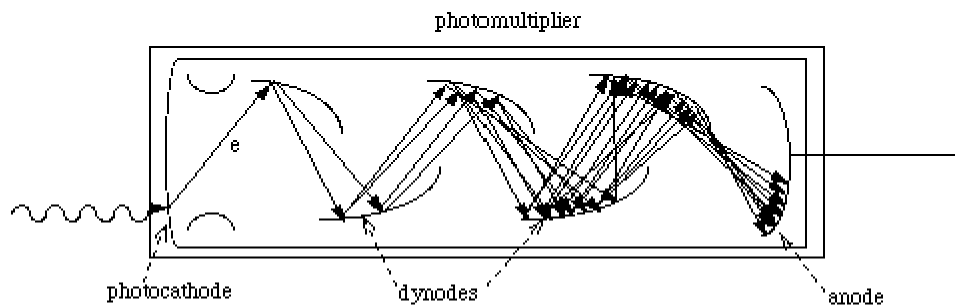


Fig. 4.1 Schematic of a photomultiplier tube.



The electric field between the anode and the last dynode accelerates many, many electrons: it does WORK on them.

This induces a voltage pulse at the anode.

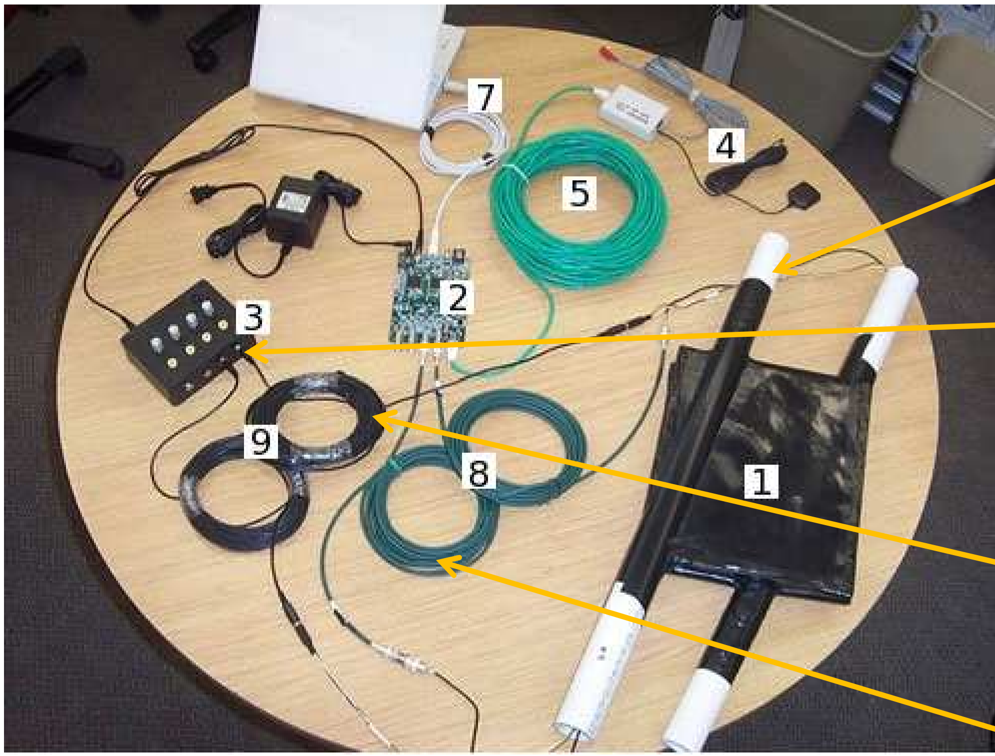
A stronger electric field produces more secondary electrons, and produces a bigger pulse.

Technical point: How do you generate the right voltages on each of the dynodes? Starting from only 5 volts?

Photomultiplier Tubes

- The electrons in the photocathode don't need much energy to escape the metal
  - That's why a photon can knock them out
- Sometimes they get energy from other sources
  - Thermal energy, radioactive decay (eg, potassium-40) , cosmic rays
- These produce pulses at *random* times
- We call these pulses "noise" or "dark current"
- More voltage usually means more noise…

The Cosmic Ray Detector



Photomultiplier tubes (PMT's) are inside the white plastic things.

This box lets you adjust the voltage on the PMT's.

Two cables come out:

- One set of wires provides power to the PMT and sets the voltage
- The other cable carries the signal to the electronics.

- Next, how do you detect the voltage pulses?

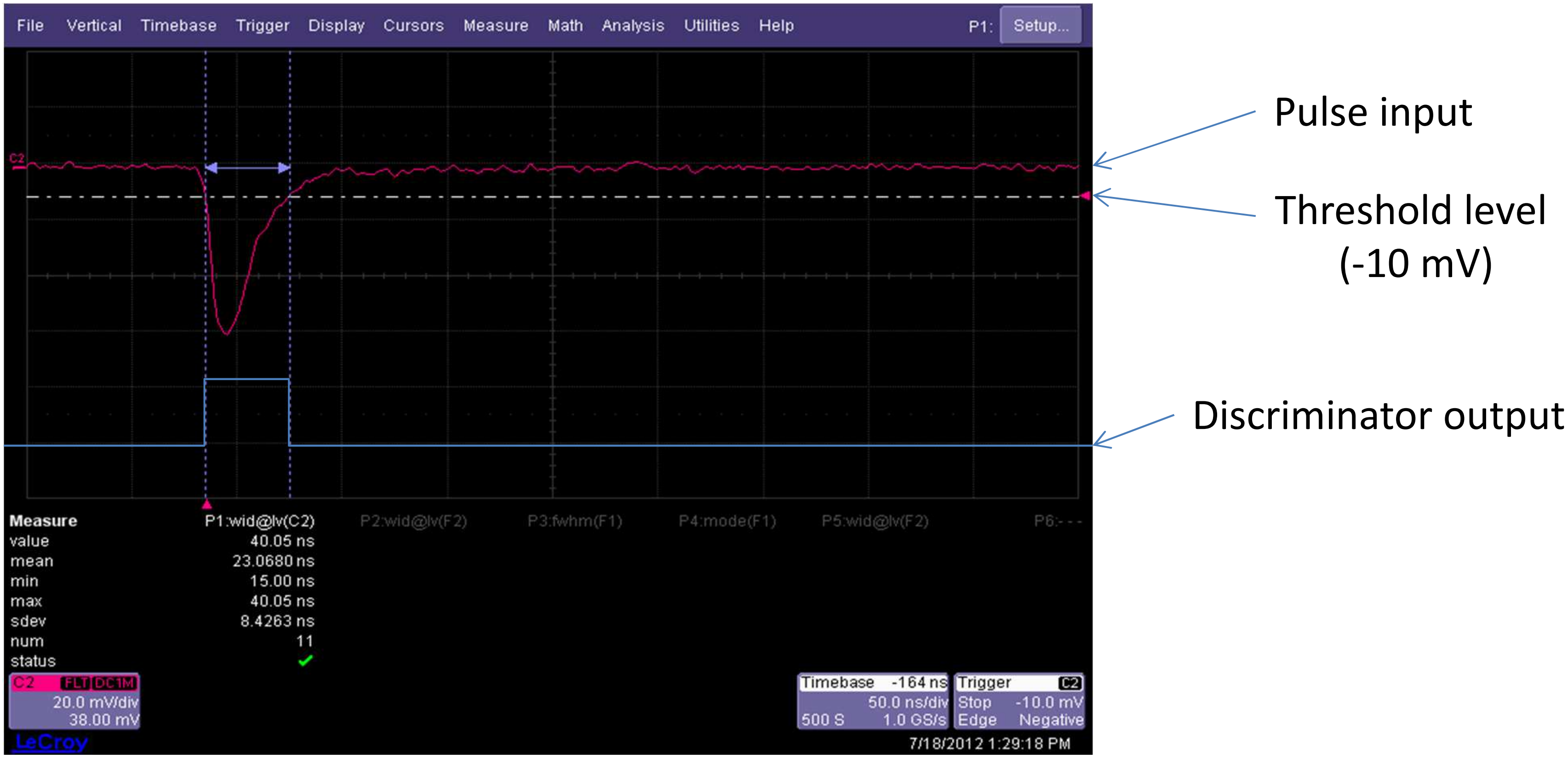
Cables

- Coaxial cables carry the signals from the PMT to the DAQ board with very little distortion
  - Exactly the same physics as a pulse propagating down a rope…
- Speed of signal propagation: ~20 cm/ns
  - Two thirds the speed of light
- The black cables are about 50 feet long
  - Propagation delay is about 75 ns
- Sometimes, some fraction of the energy in the pulse is reflected from connectors in the cable…
  - Would this ever show up as a second pulse?
  - If it did, when would it arrive?

Discriminator

- A “discriminator” is an electronic circuit that compares an analog input signal to a reference voltage
  - You can usually adjust the reference voltage
- The output is a digital logic level
  - zero volts when $V_{in} < V_{ref}$
  - 3.3 volts when $V_{in} > V_{ref}$
- They usually switch very quickly.
- You can see this using an oscilloscope…

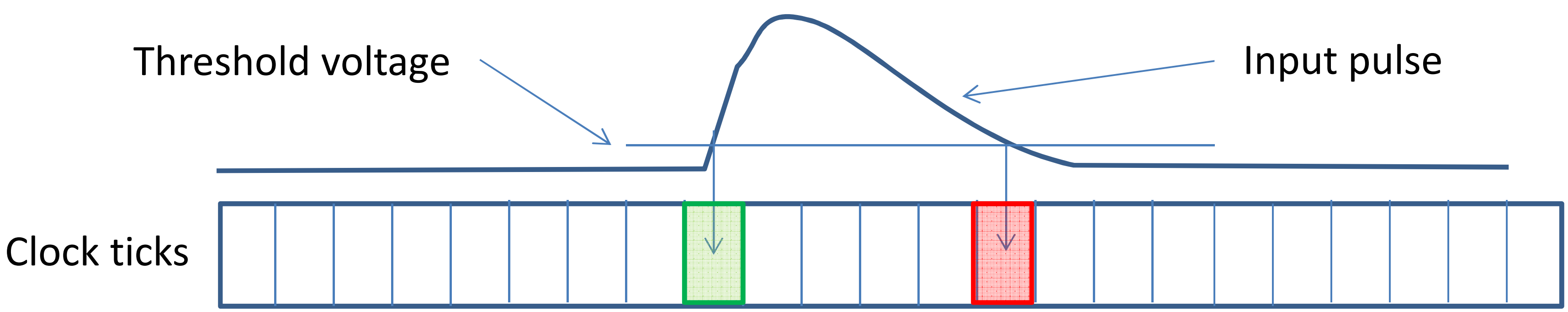
Example



- Once you have a digital logic pulse, you can analyze it using digital electronics (a "computer").

Detector Electronics

- Measures the times of the leading and trailing edge of the discriminator pulses.
  - The difference is called “Time Over Threshold”
  - Larger pulses have a larger time-over-threshold
  - We don’t measure the pulse height directly
- The electronics has an internal clock that “ticks” every 1.25 ns
  - This determines how precisely times can be measured

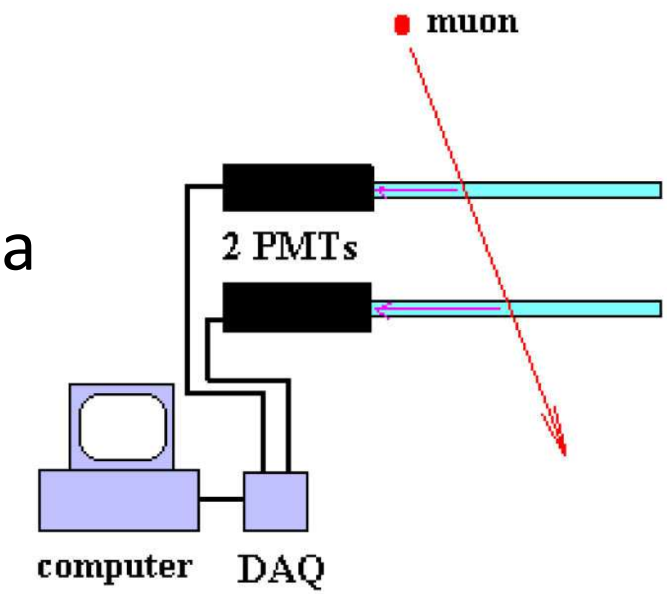


What Can We Measure So Far?

- Two main types of measurements:
  - Count rates: how many leading edges in a fixed period of time (eg, 1 minute, 5 minutes, etc…)
  - Times of leading and trailing edges
- Important problem:
  - Do you know that each pulse is from a cosmic ray?
  - It might be from noise in the PMT…
  - How can we tell the difference?
- We can’t read every pulse and analyze all the data fast enough.
- Solution: ***a coincidence trigger!***

Coincidence Triggers

- Suppose we stack two scintillators on top of each other.
- A cosmic ray will go through both.
- It is unlikely that both will have a noise pulse simultaneously.
- Even less likely to have three simultaneous noise pulses in a stack of three scintillators.
- But… do the pulses really arrive at ***exactly*** the same time?



Coincidence Triggers

- Signals don't necessarily arrive at ***exactly*** the same time because:
  - Discriminator thresholds on different channels might not be ***exactly*** equal
  - Signal cables might not be ***exactly*** equal length
  - PMT's might not be at the same voltage
    - Different acceleration of secondary electrons leads "transit times" that are not ***exactly*** the same
  - Scintillators are not at ***exactly*** the same position
    - Cosmic rays are travelling at about 1 foot per ns
- Instead, we relax what we mean by "coincident"…

Coincidence Triggers

- We call two or more pulses “coincident” when the arrive within a certain time interval.
  - This is called the **GATE WIDTH**
- We can delay all the pulses by a certain time interval so that we can read out the leading edge of the first pulse.
  - This is called the **PIPELINE DELAY**
- When we see a coincidence we can read out the times of all leading and trailing edges in this interval or just count triggers.

“Accidental” Rate

- Consider a 2-fold coincidence with two counters
  - a gate width of “T” (eg, T=100 ns)
  - singles rates of R_1 and R_2 (eg, 20 Hz)
- What is the rate of accidental coincidences?
  - Probability that the gate is open due to a signal in the first channel:

$$P = T R_1$$

  - Rate at which the second channel has a signal while the gate is open:

$$R_{acc} = T R_1 R_2$$

- With these numbers we get:

$$R_{acc} = 4 \times 10^{-5} Hz$$

- There are similar formulas for 2-fold coincidence with 3 counters, 3-fold coincidence with 4 counters, etc…

Examples of Triggers

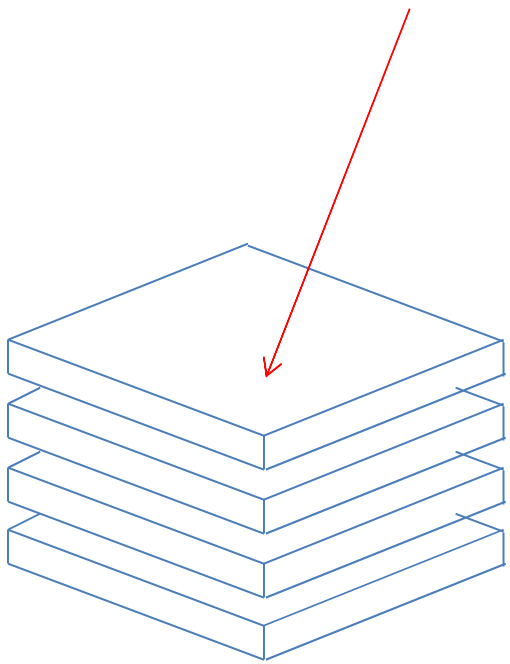
- Counting cosmic rays with a stack of four scintillators...

  Require 3-fold coincidence

  GATE WIDTH = 100 ns

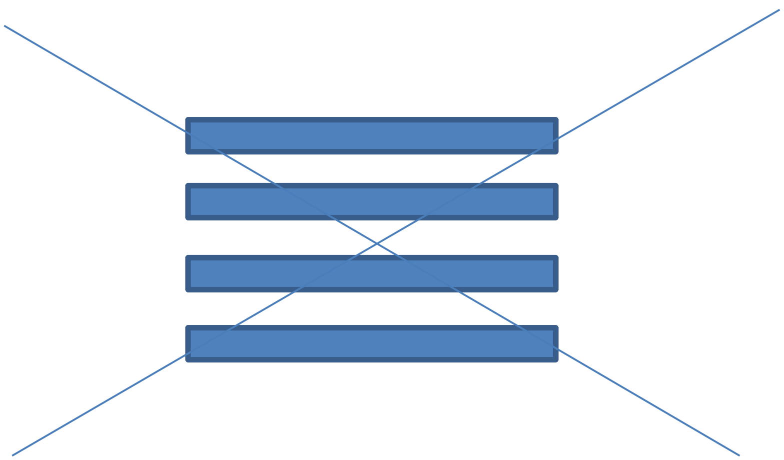
  PIPELINE DELAY = 20 ns

- Very unlikely to have three noise pulses within 100 ns
- Could also use 4-fold coincidence
- What difference would this make?

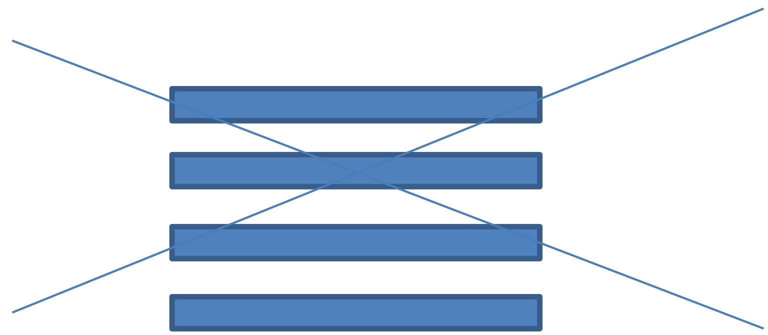


Trigger Acceptance

- The coincidence level and the geometry of the scintillators affects the trigger rate:



Narrower range of angles

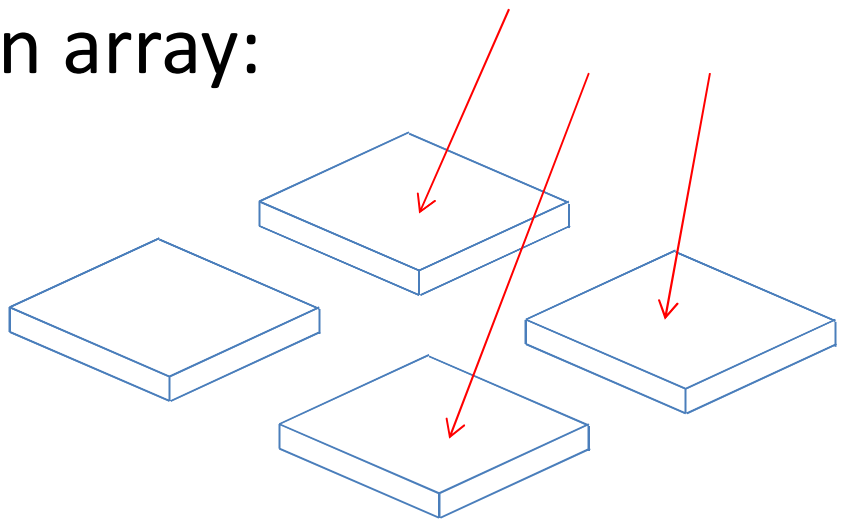


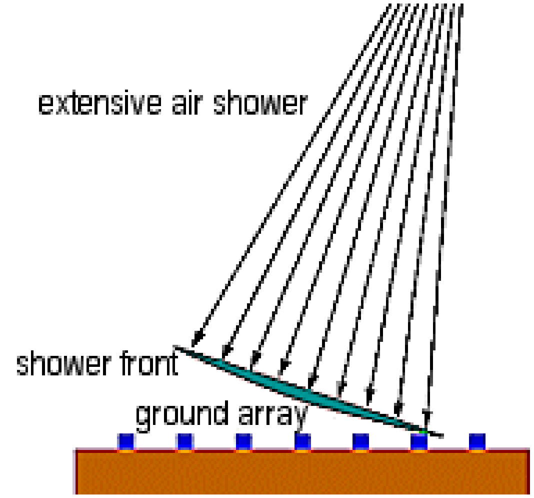
Wider range of angles

- Typical counting rate for 3-fold coincidence:
  – about 10 Hz at typical elevations in the Midwest

Examples of Triggers

- Extensive air showers: put the scintillators in an array:



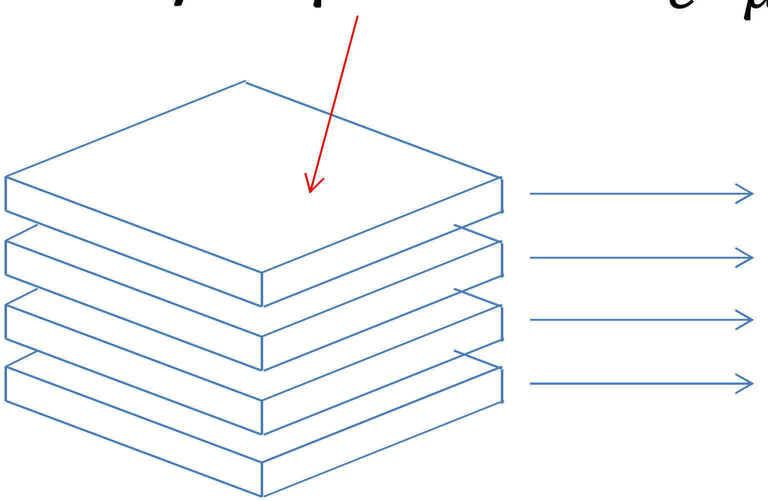


- The arrival times could be more spread out.

Require 3-fold coincidence
GATE WIDTH = 200 ns
PIPELINE DELAY = 20 ns

Muon Decay Trigger

- We want to identify events where a muon stops in one of the scintillators and then decays… $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ with $\tau = 2.2\ \mu s$



Pulse from muon entering stack

Pulse from muon passing through stack

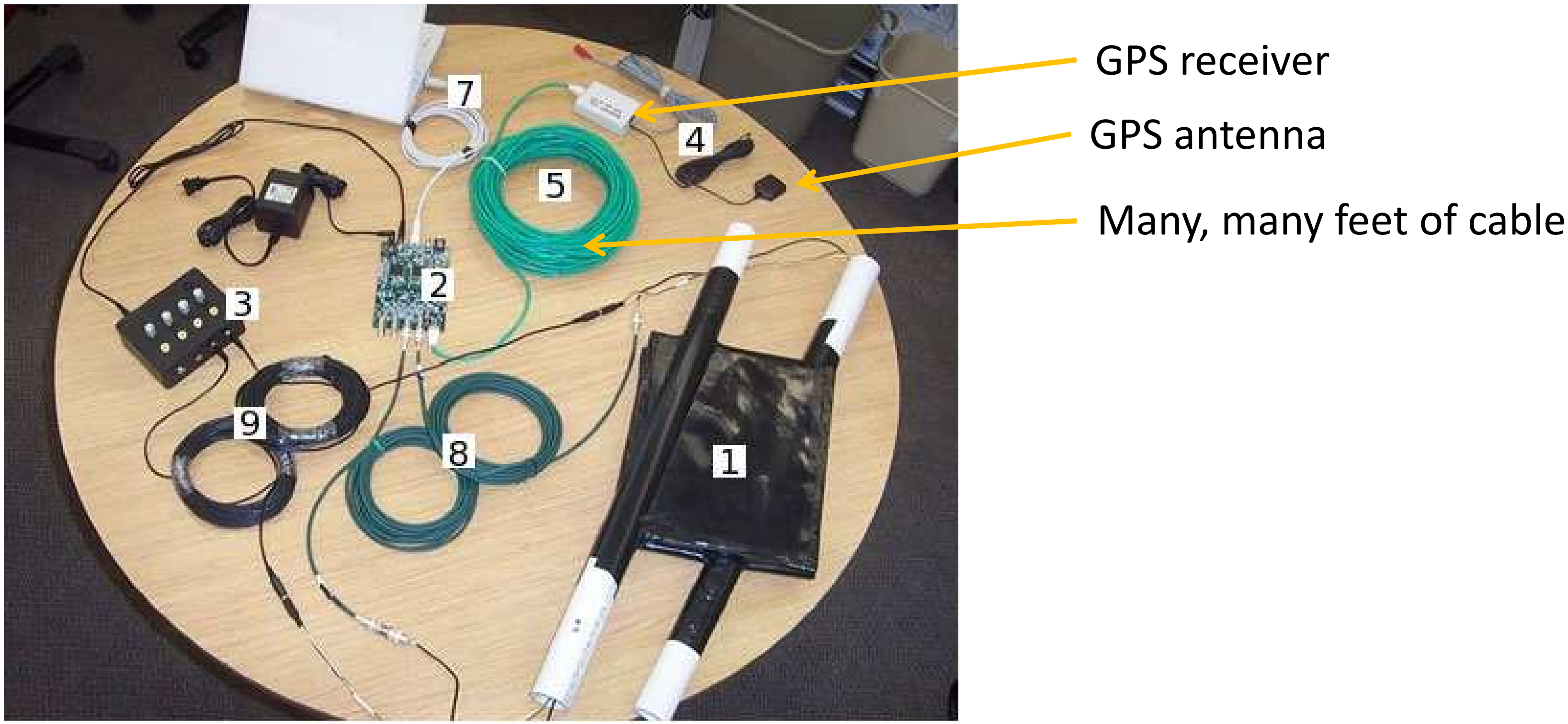
Pulse from muon stopping, another from the decay

No pulse

Require 3-fold coincidence
GATE WIDTH = 10,000 ns
PIPELINE DELAY = 20 ns

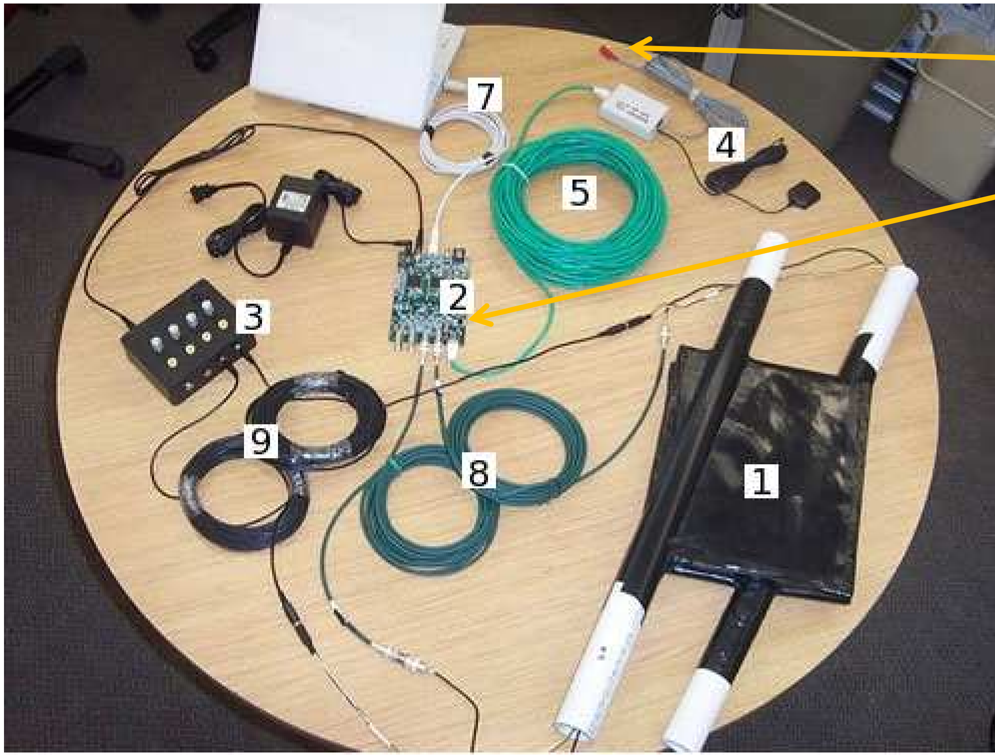
This isn't *exactly* what we want because it triggers on any 3 channels, but the trigger rate is low enough that we can examine each event to see if it is just the top three channels with pulses.

GPS Antenna and Receiver



- Measures latitude, longitude, elevation
- Measures absolute time very precisely
  - Internal clock synchronized to satellites
  - Uses UTC (Coordinated Universal Time, or Greenwich Mean Time)
- Allows you to correlate time measurements at different locations

Thermometer and Barometer



Temperature sensor

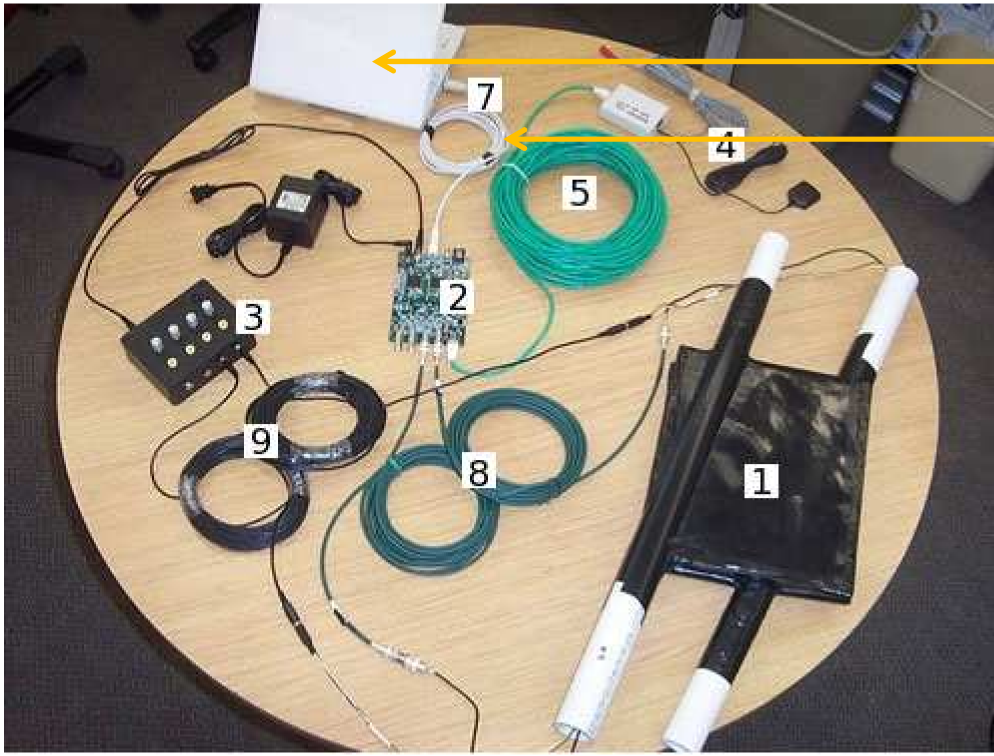
Barometer mounted on printed circuit board

- Why?
  - Why not?
- Why might measurements depend on temperature or atmospheric pressure?

Less Well Advertised Features

- Electronic pulser:
  - Injects electronic pulses directly into discriminator inputs
  - Amplitude of pulses can be adjusted
  - Pulses can go to single channels or to groups of multiple channels
- Why?
  - Very controlled and predictable.
  - Lets you test most features of the electronics without any scintillators attached.

Data Interface



Computer

USB cable

- The data is read out using a computer over a USB cable.
- The USB driver emulates a serial port (COM port)
- The data format is ASCII text… you can read it.
  - But you probably don't want to…

Data Interface

- Programs for interfacing with the serial port:
  - Windows XP: Hyperterm
  - Windows 7: No more free Hyperterm… try PuTTY.
  - Linux: minicom
- In case you need to know:
  - Baud rate: 115200 bps
  - 8 data bits, 1 stop bit, no parity
  - No flow control
- Windows may need a driver from Silicon Labs, Inc.
  - Linux usually has it by default

Commands and Responses

- Example:

What you type

What it sends back

- But this looks complicated…
- Try typing "**H1**" for help…

```
SN
Serial#=6113
DG
 Date+Time: 18/07/12 01:28:18.026
 Status:    A (valid)
 PosFix#:   1
 Latitude:   40:25.819349 N
 Longitude: 086:54.786094 W
 Altitude:  216.670m
 Sats Used: 7
 PPS delay: +0078 msec  (CE=1 updates PPS, FPGA data)
 FPGA time: 00000000
 FPGA freq:        0 Hz (Cmd V3, freq history)
 ChkSumErr: 0
DC
DC C0=2F C1-70 C2=32 C3=00
DT
DT T0=00 T1=E3 T2=E8 T3=00
TL
TL L0=250 L1=250 L2=250 L3=250
DS
DS S0=00053C7A S1=0009CA86 S2=00064E57 S3=0004798E …
```

Reading Basic Data

- Reading scalars
  - counts on each channel and coincidence counts

```
DS
DS S0=00053C7A S1=0009CA86 S2=00064E57 S3=0004798E S4=0002E5F7 S5=00000000
ST 2 1
ST Enabled, with scalar data
ST 1021 -2882 +078 3359 013618 180712 A 07 00000000 107 6113 00E8E300 0032702F
DS 00054B93 0009E654 00066076 00048685 0002EE51
```

- Periodically reports scalar readings.
- Oh no!   Are those numbers hexadecimal?

Reading Basic Data

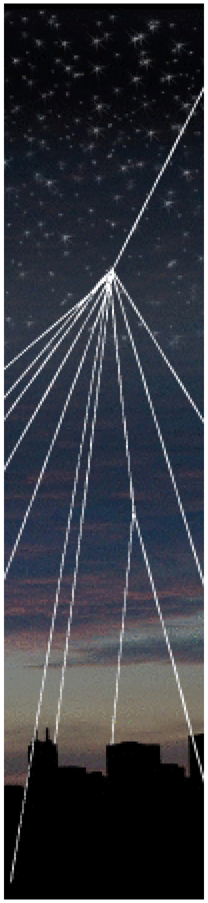
- Reading times of leading and trailing edges of triggered events:

```
CE
00033133 A7 00 22 00 24 00 00 00 00000000 014916.027 180712 A 07 8 +0077
00033133 00 00 00 00 00 00 2F 00 00000000 014916.027 180712 A 07 8 +0077
00033133 00 3C 00 3B 00 00 00 00 00000000 014916.027 180712 A 07 8 +0077
00033134 00 00 00 00 00 20 00 21 00000000 014916.027 180712 A 07 8 +0077
006A7A45 AC 00 2A 00 2D 00 00 00 00000000 014916.027 180712 A 07 8 +0077
006A7A45 00 00 00 00 00 00 35 00 00000000 014916.027 180712 A 07 8 +0077
006A7A45 00 00 00 3F 00 00 00 00 00000000 014916.027 180712 A 07 8 +0077
006A7A46 00 22 00 00 00 24 00 24 00000000 014916.027 180712 A 07 8 +0077
CD
```

- From this data you can calculate the time-over-threshold for each channel…
- ***Seriously?*** Do you really need to decode all this?

Two Ways to Process this Data

- Download all the data from the serial port into a file and upload it to the Cosmic Ray e-lab on the i2u2 web site.
  - More details later in the week.
- An *even better* way (IMHO), developed at Purdue:
  - The Cosmic Ray Detector Java Interface
  - Using the cosmic ray detector has never been easier!
  - This week, we hope to show you how to use and develop modules to explore many aspects of cosmic ray physics in your classroom…



Cosmic Ray Detector Java™ Interface
Version 2.00

Developers: M. Jones (Purdue University)
F. Roetker (Jefferson High School)

Built using: RXTX 2.1
JFreeChart 1.0.14
JCommon 1.0.17
freehep-jminuit 1.0

Please report bugs/crashes to
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NSF