Cosmic Muon Experiment Intro & Analytical Tasks

BNL Muon Storage Ring

Cosmic Muon Experiment

I. Cosmic muons and μ-decay electrons as relativistic particles
  - Relativistic notation energy/momentum, time dilation effect (F&S exp't).
  - Range of GeV-muons in metals (Cu, Fe) and plastic.
  - Mean range of μ-decay electrons in plastic

II. ANSEL cosmic-ray experiment setup
  - Pulse-height calibration of telescope detectors (3mm thick) and AT(120mm thick) with γ-ray sources
  - Muon beam definition by telescope: fast timing (disc. $\Delta t \backsimeq 20$ns, $\delta t \backsimeq 2$-3ns)
  - Efficiency of 4-fold coincidence requirement (true vs. random)

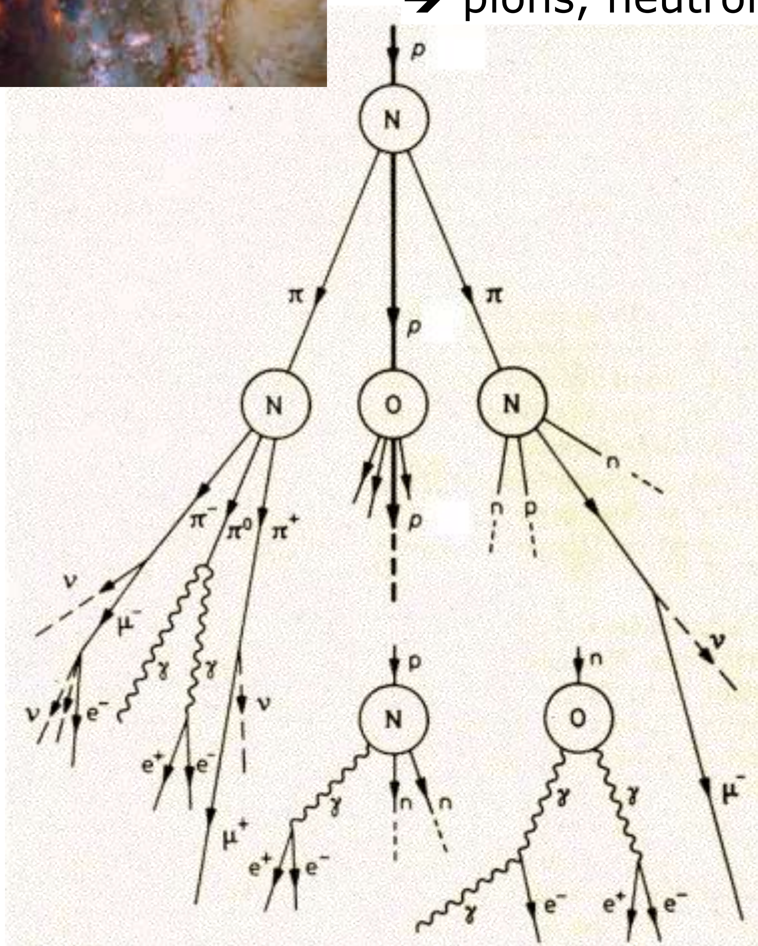
III. Energy deposition of cosmic muons in active target
  - Traversing muons
  - Stopped muons plus decay electrons

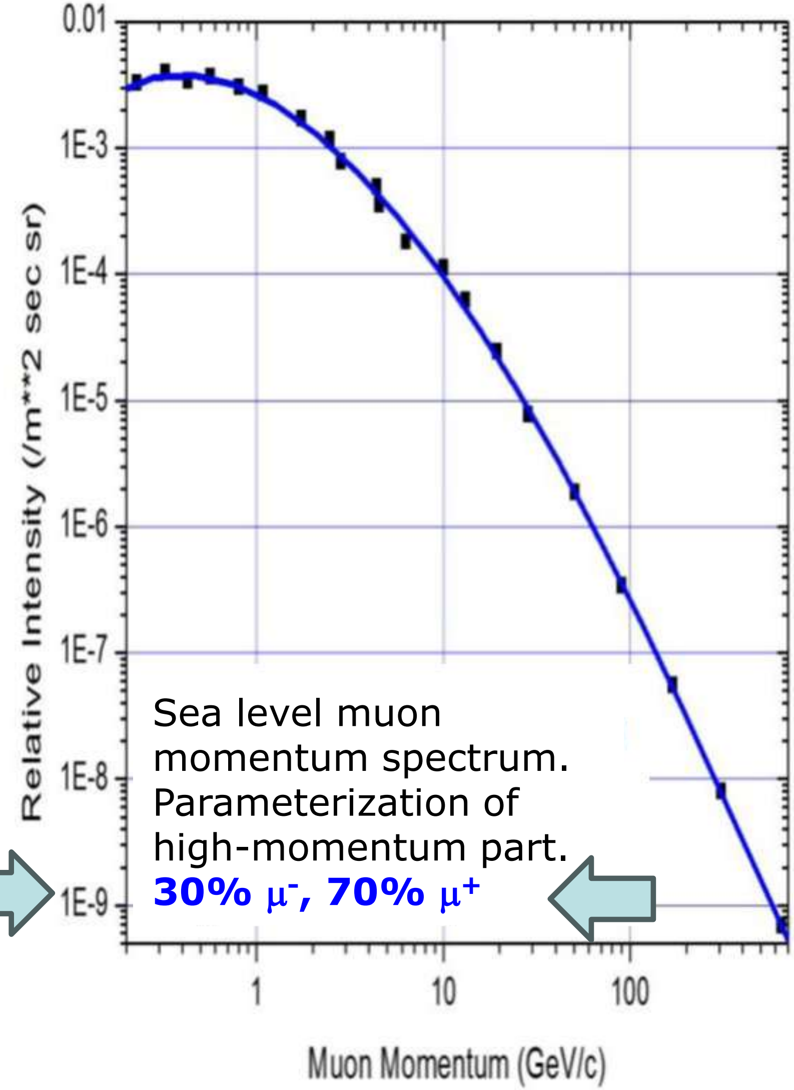
IV. Lifetime of cosmic muons in active target
  - Time calibration for decay lifetime measurement
  - Fit time spectrum.

Muons in Cosmic Ray Showers

Discovered in 1936 by Carl D. Anderson and Seth Neddermeyer at Caltech: Muons produced in energetic p-induced reactions. Cosmic ray showers in the upper atmosphere initiated by cosmic protons →

➔ pions, neutrons,…

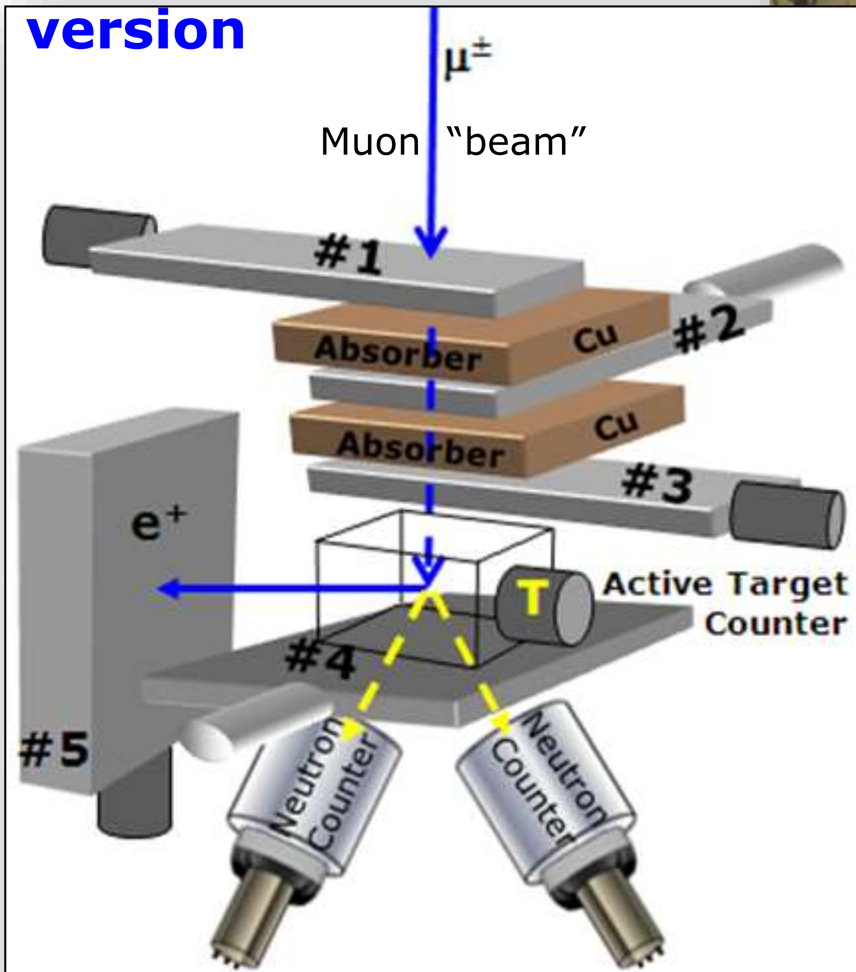




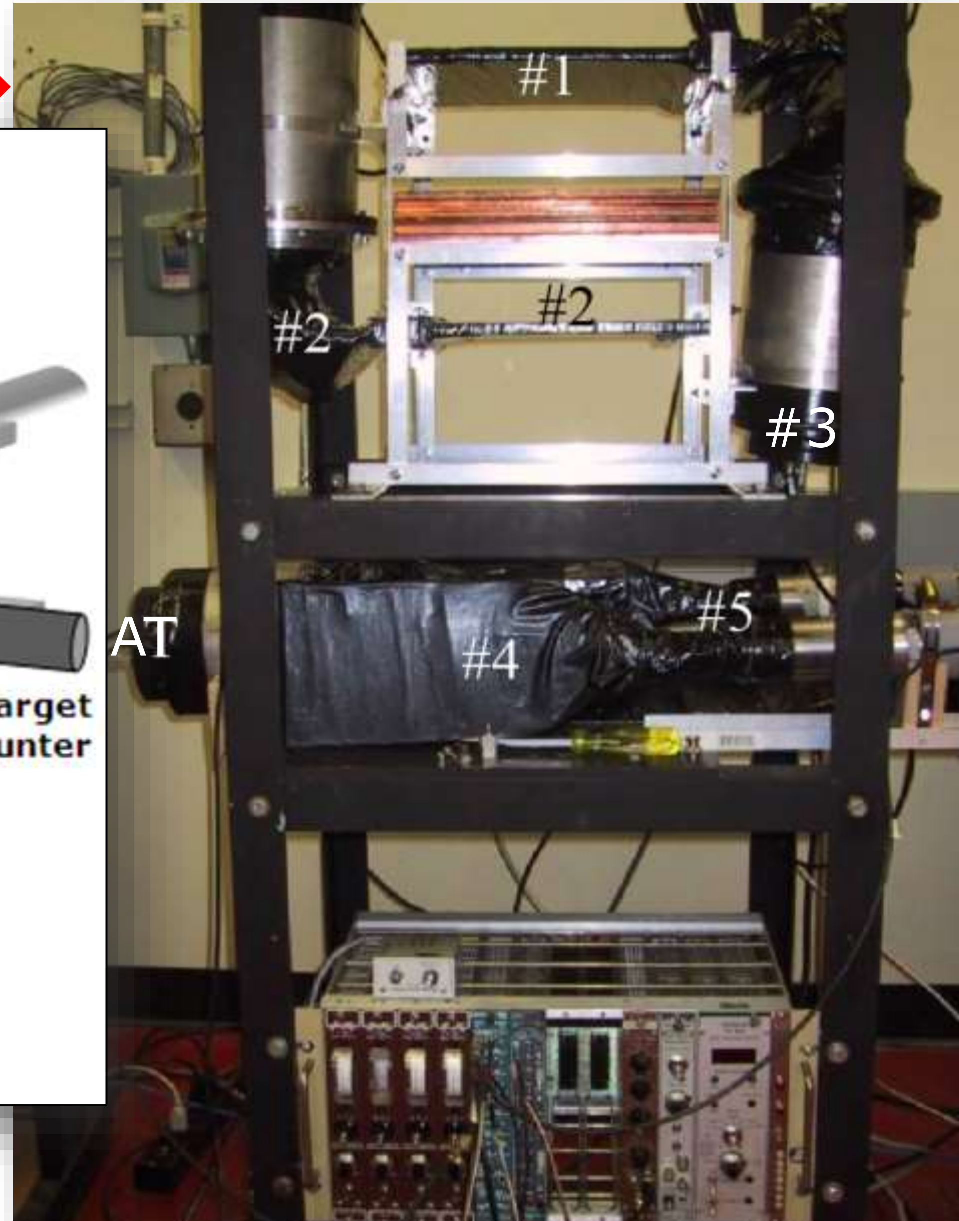
Sea level muon momentum spectrum. Parameterization of high-momentum part.
30% μ^-, 70% μ^+

The ANSEL Cosmic Muon Telescope

Extended version



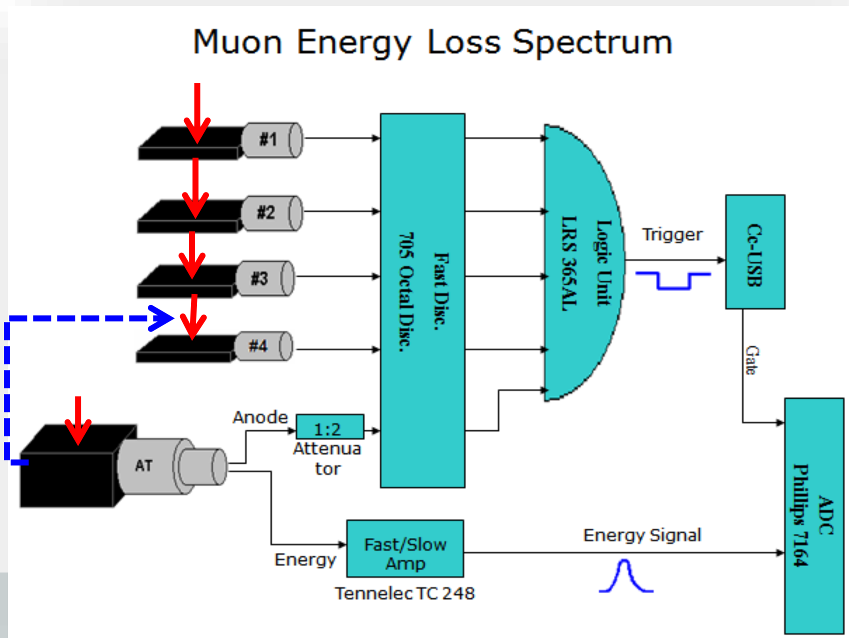
Actual →



Telescope scintillators 3 mm thick

AT=12 cm → Calibrate response

Electronics for ANSEL Muon Experiment



Active target AT= plastic scintillator
Placed between telescope
counters #3 and #4

Muon transmission $1 \wedge 2 \wedge 3 \wedge AT \wedge 4$

Muon stop in AT $1 \wedge 2 \wedge 3 \wedge AT \wedge \overline{4}$

Measure energy deposit in both modes

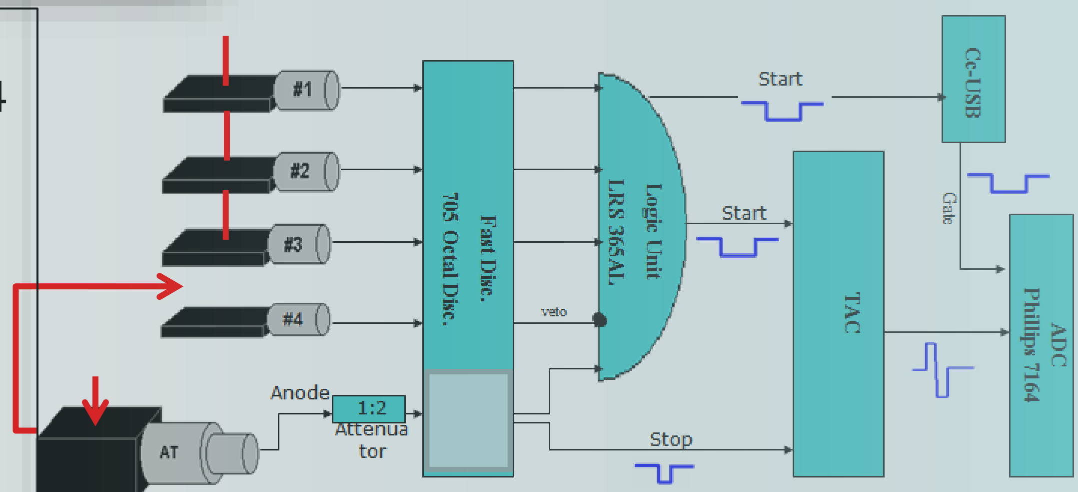
Muon Decay/Capture Time Spectrum

Active target AT= plastic scintillator between #3 and #4 stops muon → decay

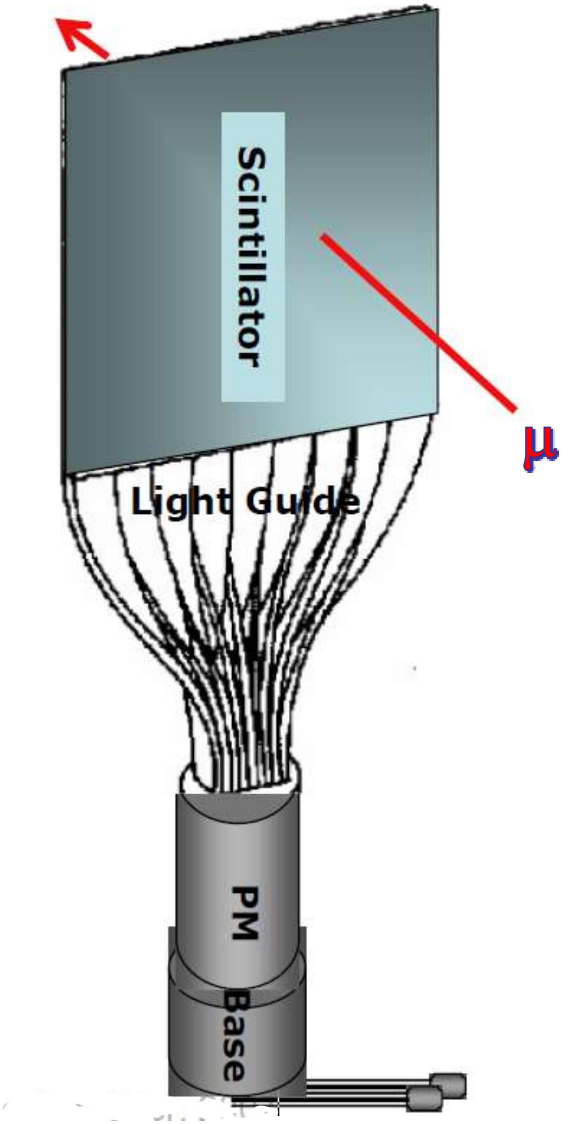
$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

Measure decay lifetime in plastic AT (weak capture)



ANSEL Cosmic Muon Telescope Detectors



- Scintillator $(q\ (\Delta E) \rightarrow h\nu \rightarrow h\nu*)$
- Light guide (*collect, average, direct*)
- Photomultiplier ($h\nu* \rightarrow e^- \rightarrow n\ e^-$)
- Base (*power PM dynode chain, readout*)

Scintillating Materials

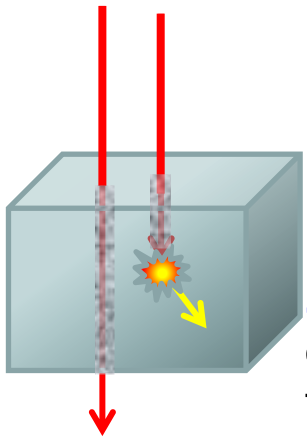
$$\text{Inorganic} \begin{cases} \text{gas } (Ar, Xe, \ldots) \\ \text{liquid } (He, Xe, \ldots) \\ \text{solid } (NaI, CsI, BGO, BaF_2 ..) \end{cases}$$

$$\text{Organic} \begin{cases} \text{liquid } (xylene, benzene, ..) \\ \text{solid } (polystyrene, ..) \end{cases}$$

Protect scintillator + light guide against external light (→ wrap in black tape/plastic)

Telescope scintillators 3 mm thick AT=12 cm → Calibrate response

Electronic Interactions of Muons with Matter



Plastic AT Target:
→ Monitored in experiment

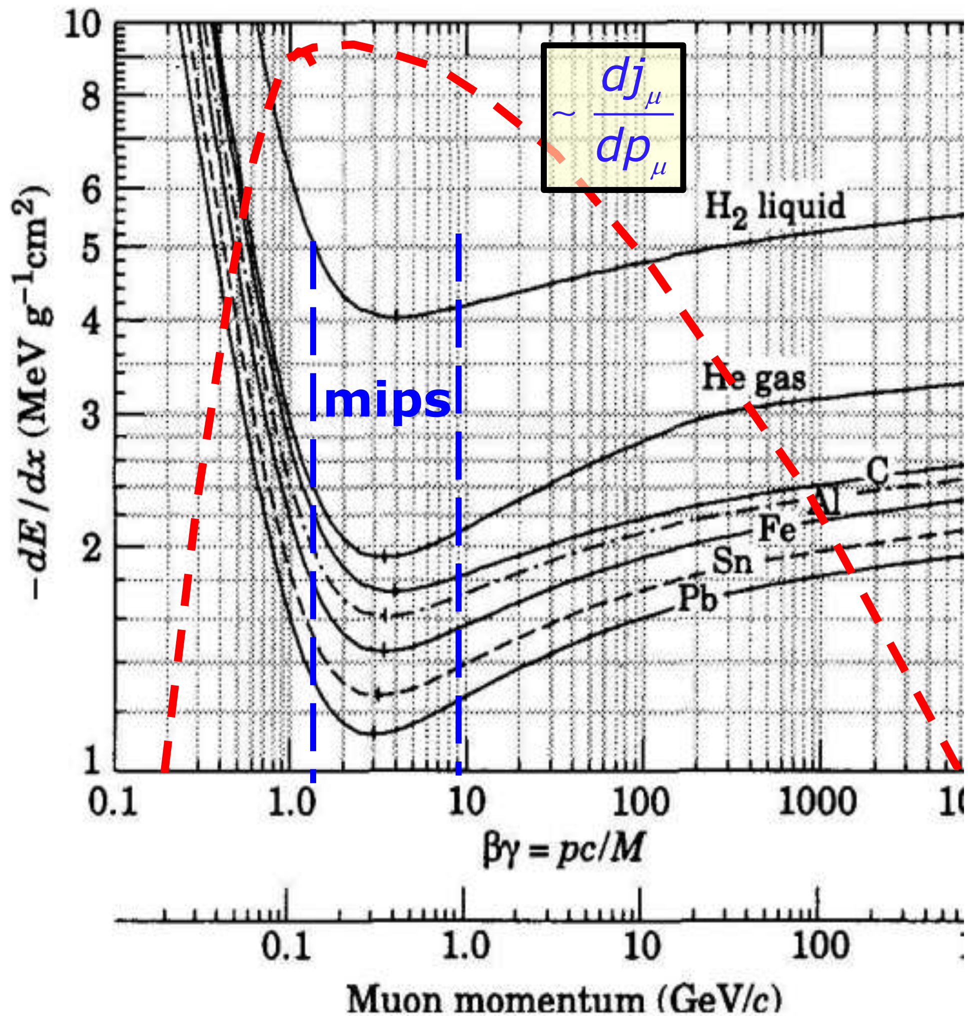
Stopped, muon decay or capture following

Transmitted

Plexiglas Plastic:
C_nH_m polymer ($[H]/[C] \approx 1.11$),
$\rho_T = 1.03\ g/cm^3$ $IE = 64.7\ eV$.

Cosmic ray muons = mostly minimum ionizing particles (mips)

For plastic: $\Delta E \approx 2$ MeV/cm



Muon energy spectrum → Spectrum of energy deposits.
Most probable energy deposit:
Characteristic deposit by mips muons.

Cosmic Muon Experiment

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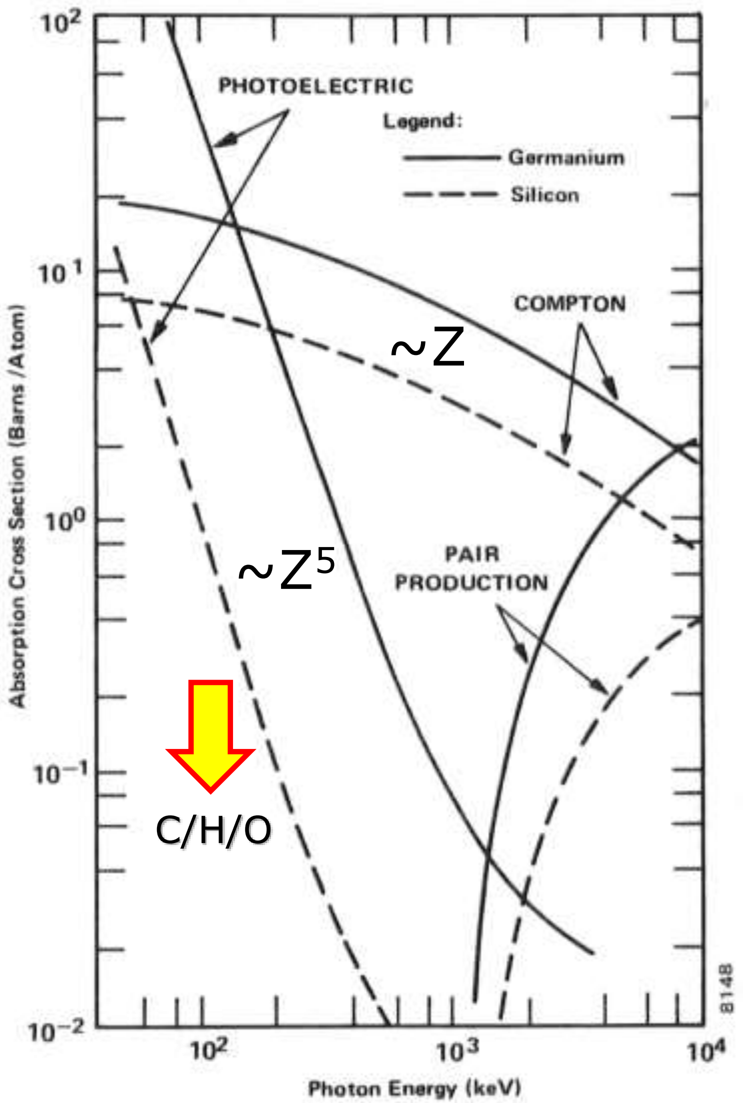
Detector Calibration: Response to γ-Rays



Different processes are dominant at different γ energies and for different materials: (1b = 10^{-24} cm^2)

Photo absorption at low E_γ

Pair production at high E_γ > 5 MeV

Compton scattering at intermediate E_γ.

Z dependence important: Ge(Z=32) has higher efficiency for all processes than Si(Z=14). Take high-Z for large photo-absorption coefficient

C/O/H: small photo-absorption coefficient → Most significant: Compton scattering

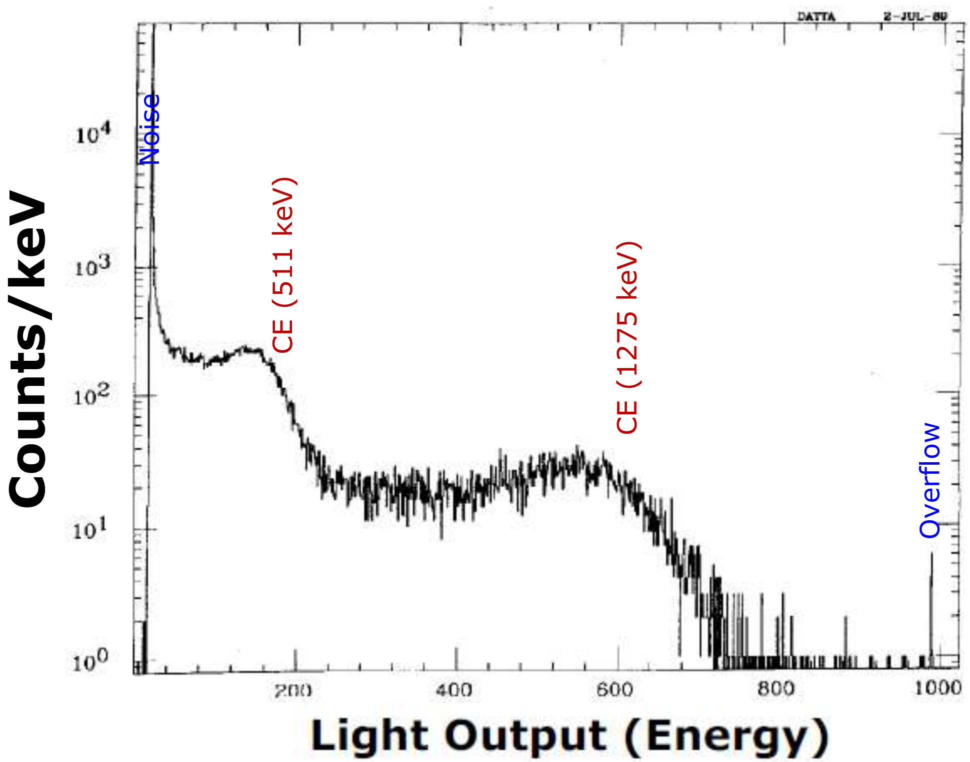
Response of detector depends on

- detector material
- detector shape
- E_γ

Muon Telescope: AT Pulse-Height Calibration

Task: Pulse-height calibration of AT(120mm thick) with γ-ray sources

a) Identify the processes responsible for the main features in pulse height spectra of AT for various γ-ray sources.
b) Specify the energies of the charged-particle groups associated with structures
c) Perform an energy calibration of DDC-8 channel numbers with 2 γ sources. For the AT, use Na-22 and Cs-137 for calibration of μ energy deposits.
d) Extend calibration to ~25 MeV with pulser fence (Amp coarse gain).

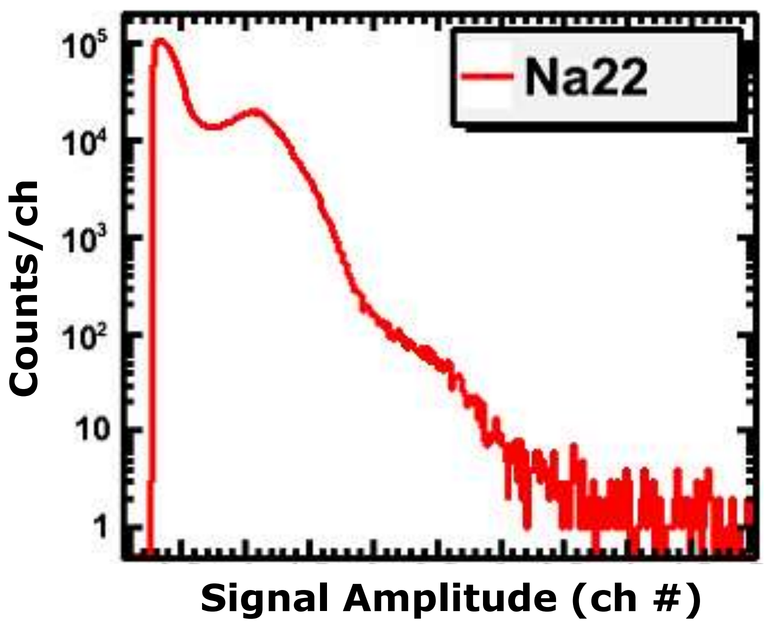


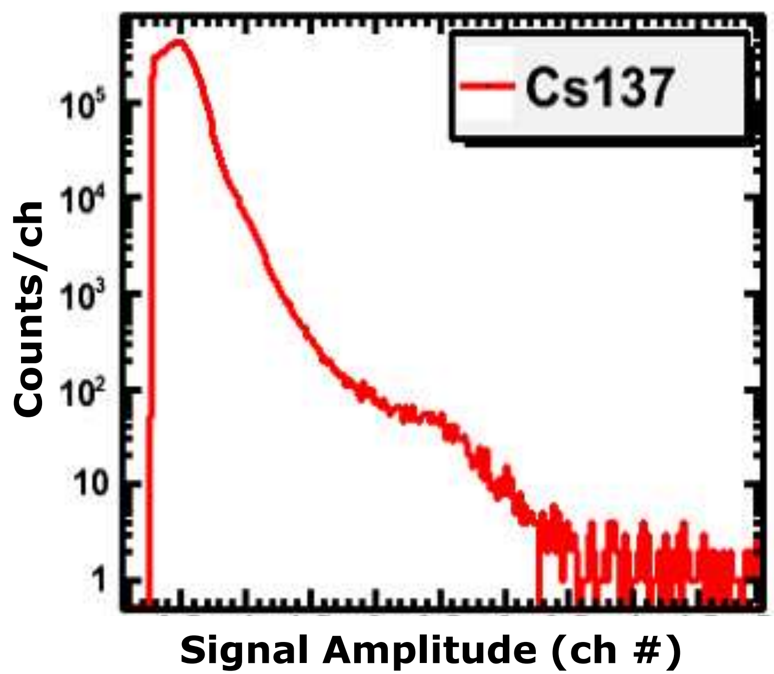
Example of a Na-22 spectrum measured with a high-resolution, optimized organic (NE-213) liquid-scintillator detector

Pulse-Height Calibration of Telescope Detectors

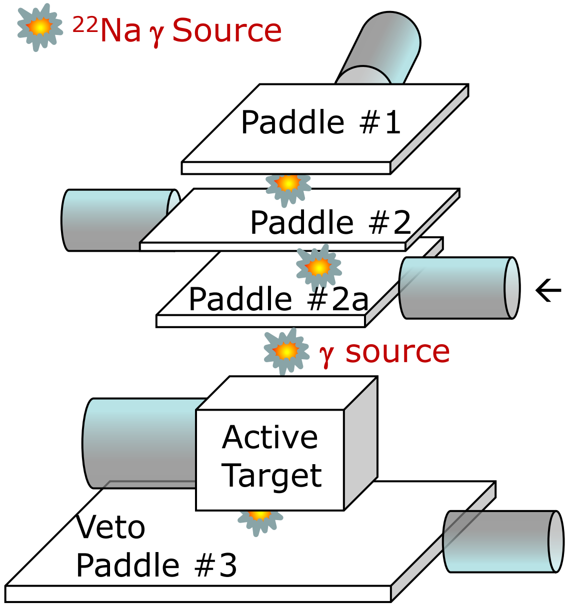
4. Pulse-height calibration of telescope detectors (3mm thick) and AT(120mm thick) with γ-ray sources

a) Identify the processes responsible for the main features in pulse height spectra of AT for various γ-ray sources.
b) Specify the energies of the charged-particle groups associated with the structures.
c) Perform an energy calibration of channel numbers.





Telescope Counter Discriminator Timing



Experimental Tasks Define the muon "beam" by Telescope.

a: Set discriminator thresholds on PM signals for Paddles and AT with γ-sources.

b: Measure rel. timings with time-to-amplitude converter (TAC).

Analyze t-data

Which detector defines the time of arrival of a muon the best?

Choose width (20ns ≤ ΔT ≤200 ns) and relative delay times of detectors.

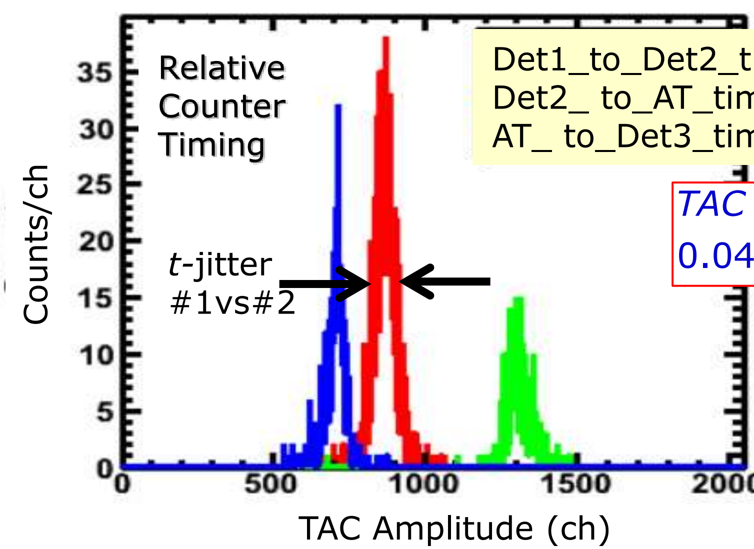
Make plot of safe timing diagram

Discuss Paddle #3 veto efficiency $\mathbf{e}_{V3}$<1.

Paddles & AT: Plexiglas Plastic C_nH_m polymer ($[H]/[C]\approx1.11$), $\rho_T = 1.03\ g/cm^3$ $IE=64.7\ eV$.

Cosmic ray muons = mostly minimum ionizing particles (mips)

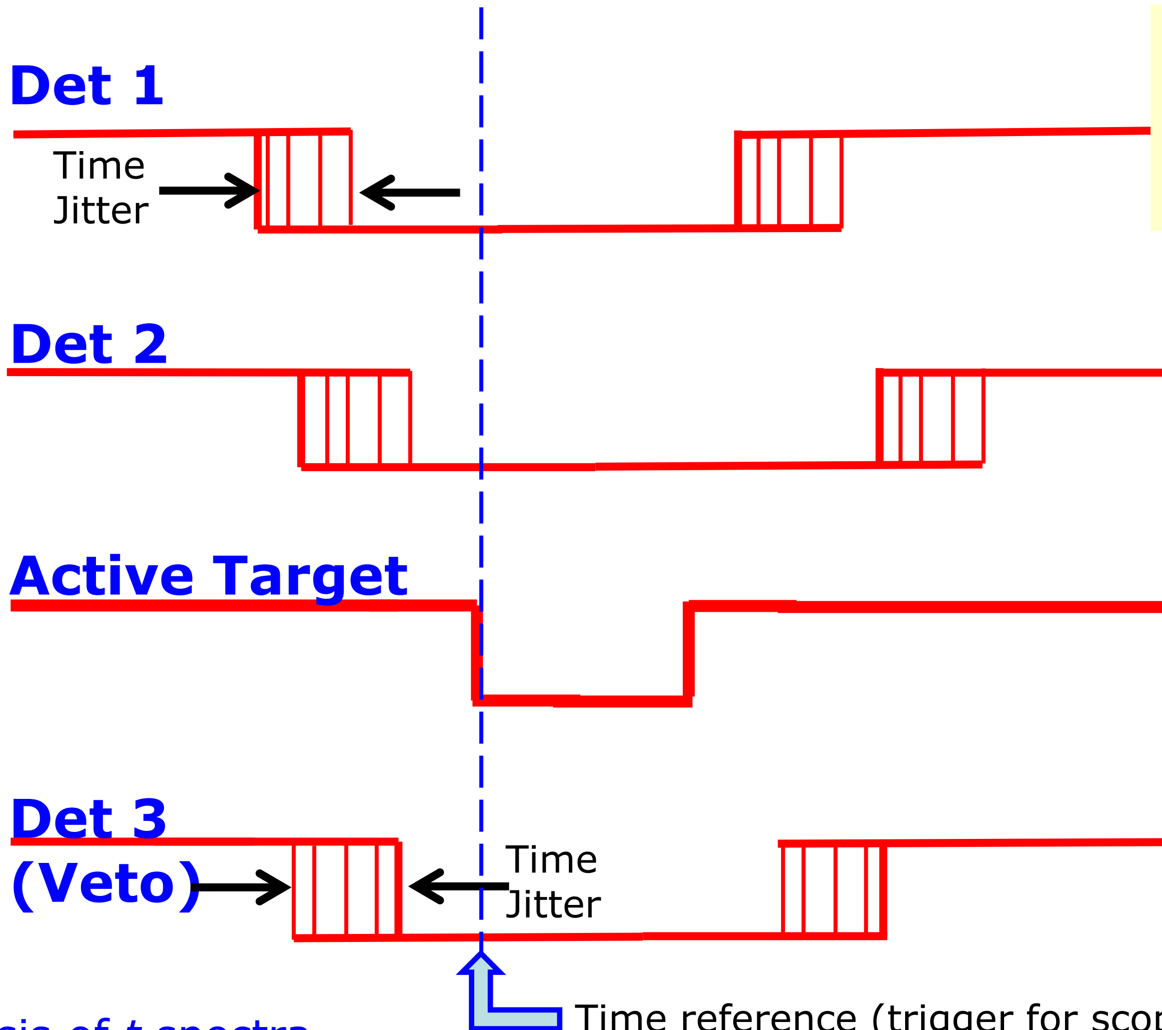
For plastic: $\Delta E_{mips} \approx 2$ MeV/cm



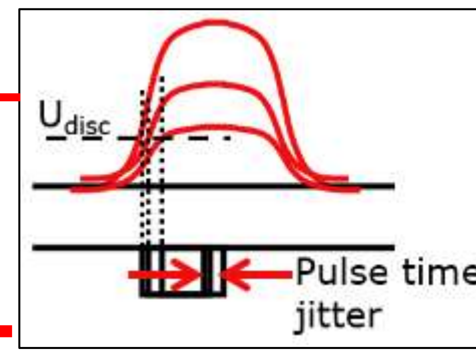
Det1_to_Det2_timing.txt
Det2_ to_AT_timing.txt
AT_ to_Det3_timing.txt

TAC calibration
0.0488*ns / ch$_{2k}$*

Example: Telescope + AT Timing Diagram



Goals are to make telescope as fast and coincidence/veto as effective as possible.



"Time jitter" is due to pulse height dependent response of discriminator threshold.

Time reference (trigger for scope), here: AT signal.

Analysis of *t* spectra

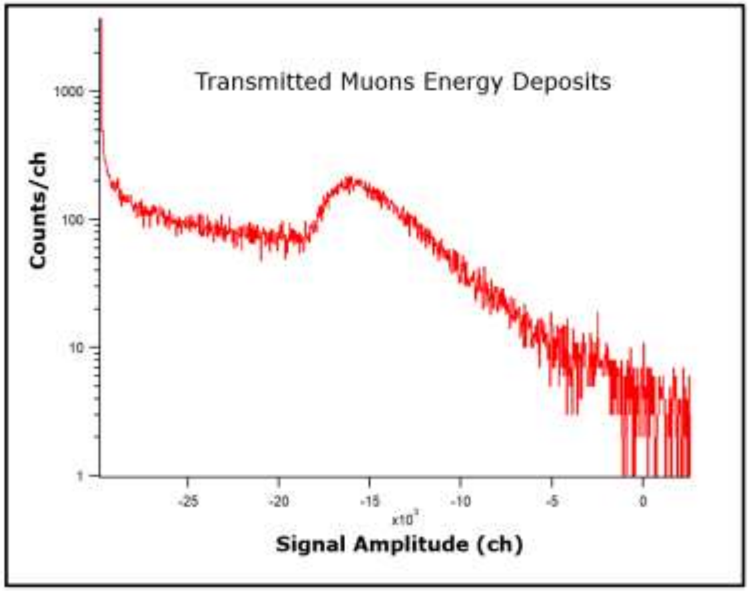
→ best paddle for defining t(muon) → your ideal timing diagram.

III.1 Muon Telescope: Muon Energy Deposit in AT

III.1. Pulse-height calibration of AT and measurement of energy deposit by charged particles (muon and electrons)

a) Perform an energy calibration of DDC-8 channel numbers for the AT with 2 γ sources Na-22 and Cs-137.(Similar Files Cs137_AT.txt and Na22_AT.txt,). Referring to known muon decay-electron spectra, discuss what DDC-8 range is likely needed for energy deposited for transmitted and for stopped muons.

b) Measure and analyze the spectrum of energy depositions (energy loss) for muons traversing the AT. (Analyze File EnergyTransmittedMuonAT.txt)

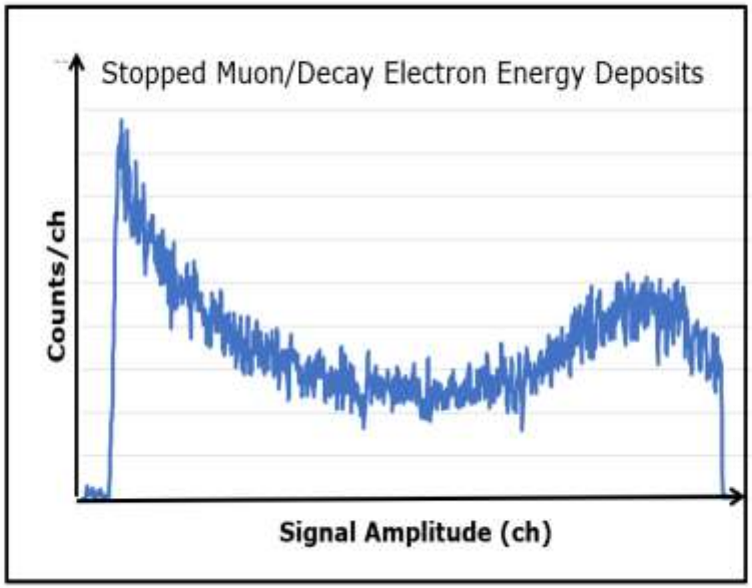


- Discuss shapes and probable origins of various spectral components.
- What effect does room background have on the measured energy deposits? (Use your experience from prior experiments)

Sample AT deposit spectrum for muons transmitted, large energy range. Use as illustration of spectral shape.

III.2 Muon Telescope: Stopped Muon (& Electron) Energy

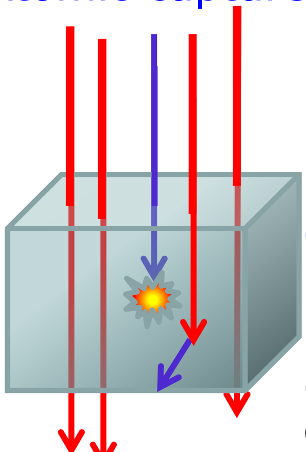
3. Measure, analyze, and discuss the energy deposition spectrum for muons stopped in the AT and its decay electrons. (Analyze File EnergyStoppedMuonAT.txt)



- Compare the experimental energy deposit spectra associated with muons transmitted through the AT and that of deposits by muons stopped (and decayed) in the AT.
- Discuss shapes and probable origins of various spectral components.
- What effect do the decay electrons have on the energy spectrum? Are these electrons also stopped in the AT?
- What would be the effect of the finite #4-veto efficiency on the energy spectrum?
- What effect does room background have on the measured energy deposits? (Use your experience from prior experiments)
- What can you conclude about the mean depth of stopped muons?

Stopped Muon Decay: E Deposit and Lifetime

Plastic AT: Measures energy deposit of all charged particles:
Positive & negative muons, electrons from muon decay or from X rays and γ-rays
Atomic capture of μ^- → decay from μ^- orbital or by nuclear capture ($E_\gamma < 1$ MeV)



Stopped μ^- nuclear capture

Stopped μ^+, μ^- decay follows

Transmitted

Muons stopped in AT disappear by a "disappearance rate Λ_d

$$\Lambda_{dis} = \Lambda_{dec} + \Lambda_{cap} = 1/\tau_{dec} + 1/\tau_{cap}$$

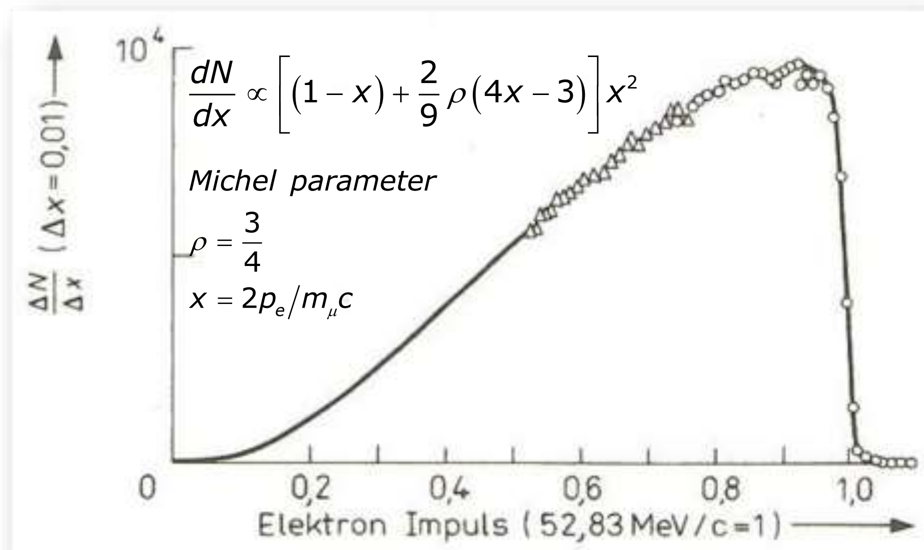
$$\Lambda_{cap}\left(\mu^+\right) = 0 \ (\mu^+ \text{ are not captured by atoms})$$

$$N_\mu(t) = N_\mu(t=0)\cdot e^{-\Lambda_{dis}\cdot t}$$

Partial Activities $(i = d, c)$:

$$\Lambda_i \cdot N_{\mu^-}(t) = -\frac{\Lambda_i}{\Lambda_{dis}}\left(\frac{d}{dt} N_{\mu^-}(t)\right)$$

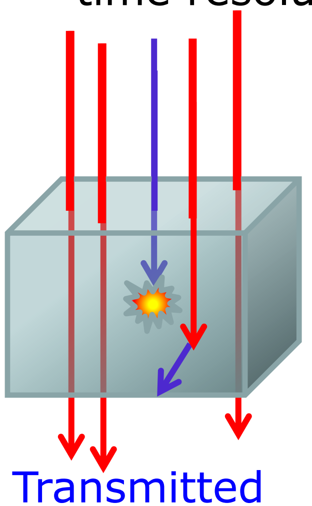
Light nuclei (Li, Be, …C, O,..): long partial capture muon life times ($\tau_{cap} \sim 100\ \mu s \gg \tau_d$)



Cosmic Muons

Stopped Muon Decay: E Deposit and Lifetime

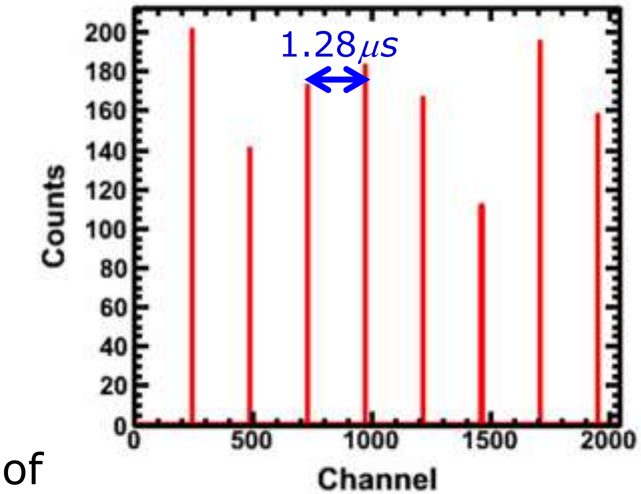
1. Set tight timing conditions for muon telescope, choose paddle detector with best time resolution (small jitter) to start TAC.



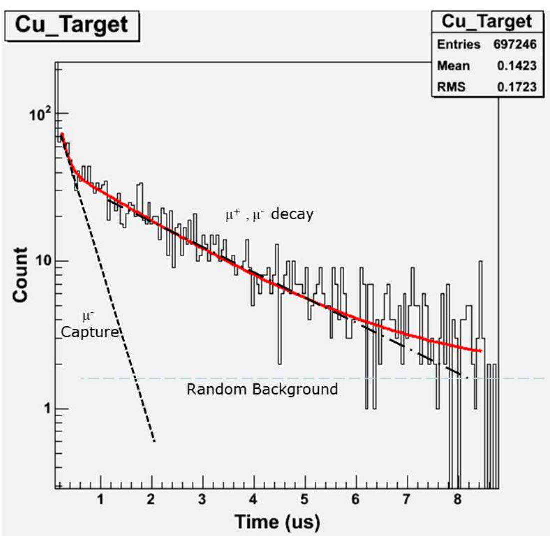
Connect (delayed) AT disc signal to TAC stop.

2. Set TAC range several μs. Calibrate TAC (Analyze t calibration spectrum)
3. Briefly measure time spectrum of AT events $t_{TAC} = t(AT) - t(\mu - stop)$

t Calibration for μ Decay



File *timing_calibration.txt*



4. Insert delay into TAC start to remove Accumulate delayed time data $dN(t_{TAC})/dt_{TAC}$.
5. Analyze TAC time spectrum with sum of one (or two) exponentials plus random background

$$N(t) = N_{BG} + N_{\mu}(t) \approx N_{BG} + N_{\mu}(0) \cdot e^{-\Lambda_{dec} \cdot t}$$

6. Estimate statistical and systematic errors, e.g. due to finite bin widths.

END
Cosmic Muons