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

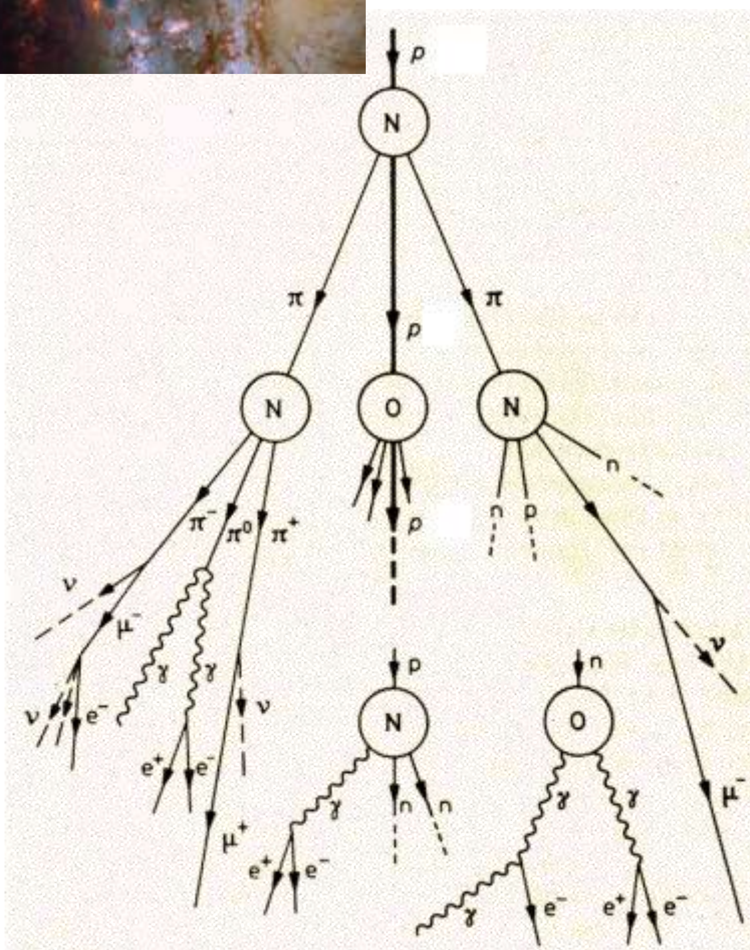
II. ANSEL cosmic-ray experiment setup
   - Pulse-height calibration of telescope detectors (3mm thick) and AT(120mm thick) with γ-ray sources
   - Muon beam definition by telescope: fast timing (disc. $\Delta t \backsimeq 20$ns, $\delta t \backsimeq 2$-3ns)
   - Efficiency of 4-fold coincidence requirement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

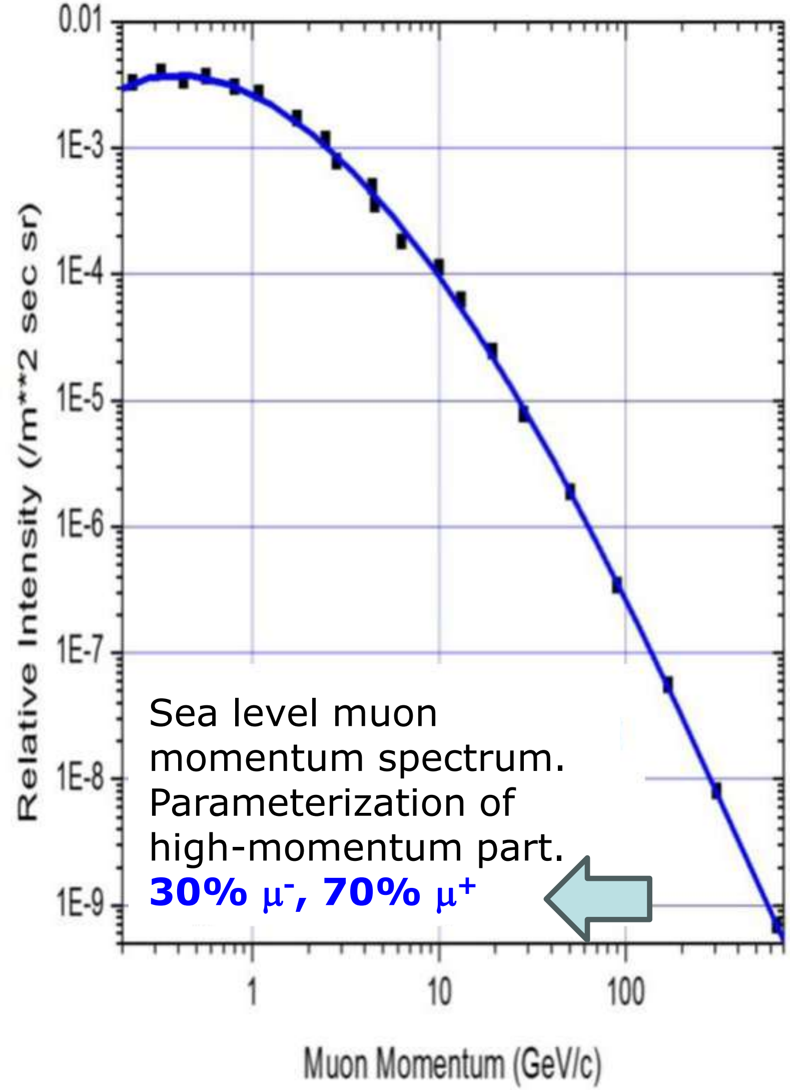
III. Energy deposition of cosmic muons in active target
   - Traversing muons
   - Stopped muons plus decay electrons

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

Muons in Cosmic Ray Showers

Discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936. Muons produced in energetic p-induced reactions. Cosmic ray shower in the upper atmosphere generated by primary cosmic protons.





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

Direct Measurement of Muon Lifetime

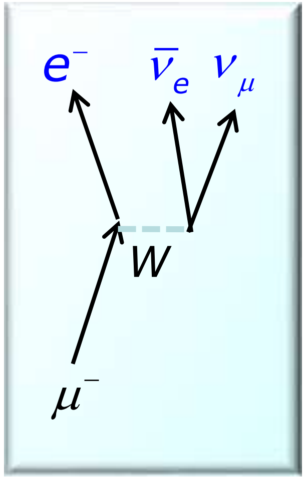
Measure survival of energetic muons (1907m/c=6.8μs), compare to stopped muon decay at base of mountain.

David Frisch and James Smith, AJP 31, 342 (1963).

Images from the 1962 documentary "Time Dilation".

Properties of Electrons and Muons

Muon Decay

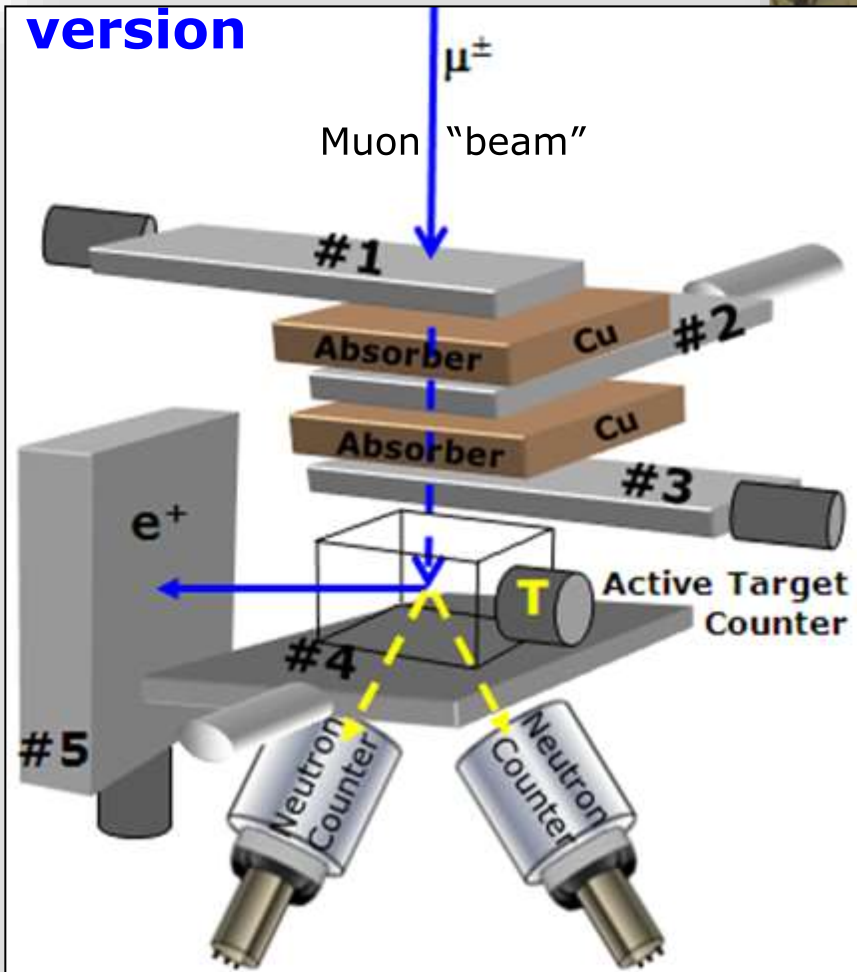


Property	e^-	e^+	μ^-	μ^+
Mass *m* (MeV/c²)	0.511	0.511	105.658	105.658
Charge (|e|)	-1	+1	-1	+1
Spin *S* ($\hbar$)	½	½	½	½
Magneton ($\mu = e\hbar/2m$)	$\mu_B = 5.788 \cdot 10^{-11}$ MeV T^{-1}	$\mu_B = 5.788 \cdot 10^{-11}$ MeV T^{-1}	$\mu_B = 2.800 \cdot 10^{-13}$ MeV T^{-1}	$\mu_B = 2.800 \cdot 10^{-13}$ MeV T^{-1}
Bohr Radius *a* (nm)	5.292	N/A	$2.56 \cdot 10^{-2}$	N/A
Rydberg Energy R_H (eV)	13.6	N/A	$2.81 \cdot 10^{3}$	N/A
Weak Inter - actions	β^- decay e^- capture	β^+ decay	μ^- decay μ^- capture	μ^+–decay

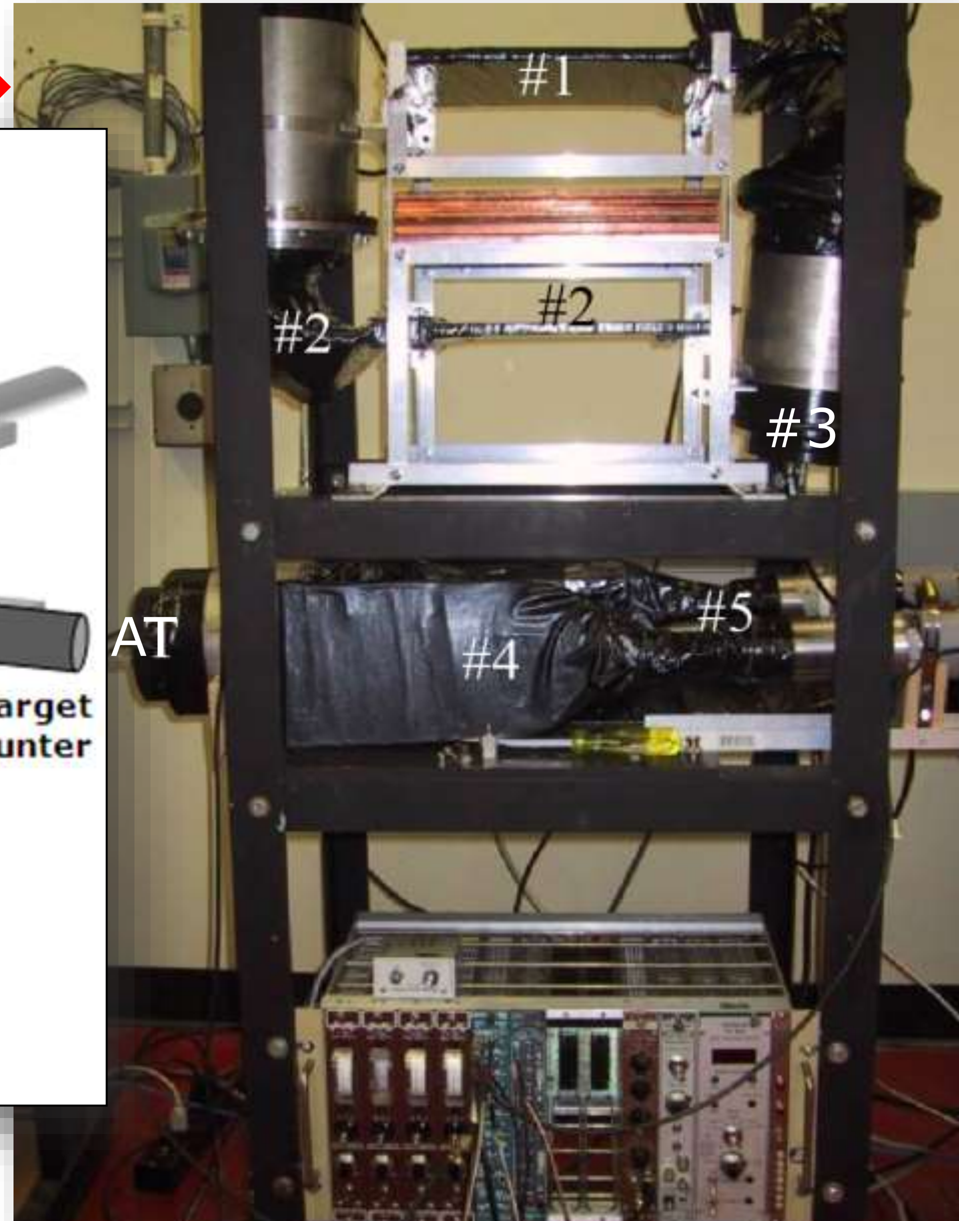
Electromagnetic interactions via charge and spin magnetic moment.
Weak muonic interactions: $\mu^\pm$ decay and μ^- capture (≙EC)

The ANSEL Cosmic Muon Telescope

Extended version



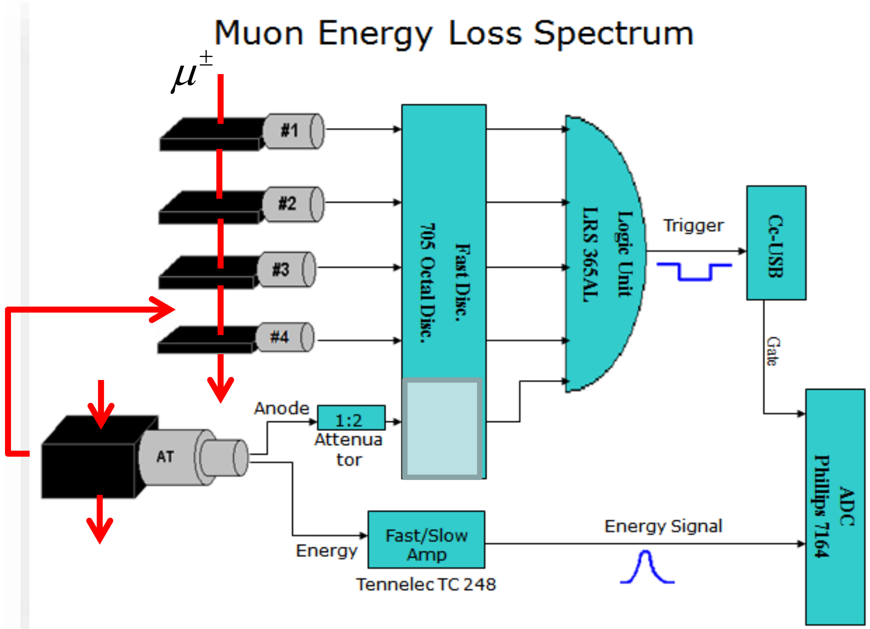
Actual →



Telescope scintillators 3 mm thick

AT=12 cm → Calibrate response

Electronics for ANSEL Muon Experiment

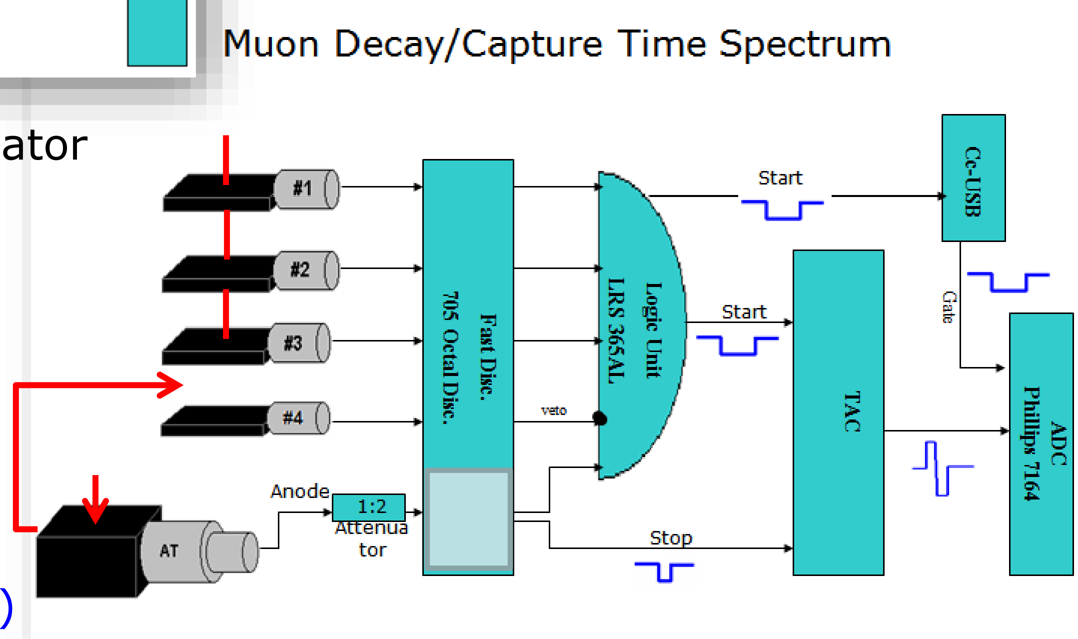


Active target AT= plastic scintillator
Placed between telescope
counters #3 and #4

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



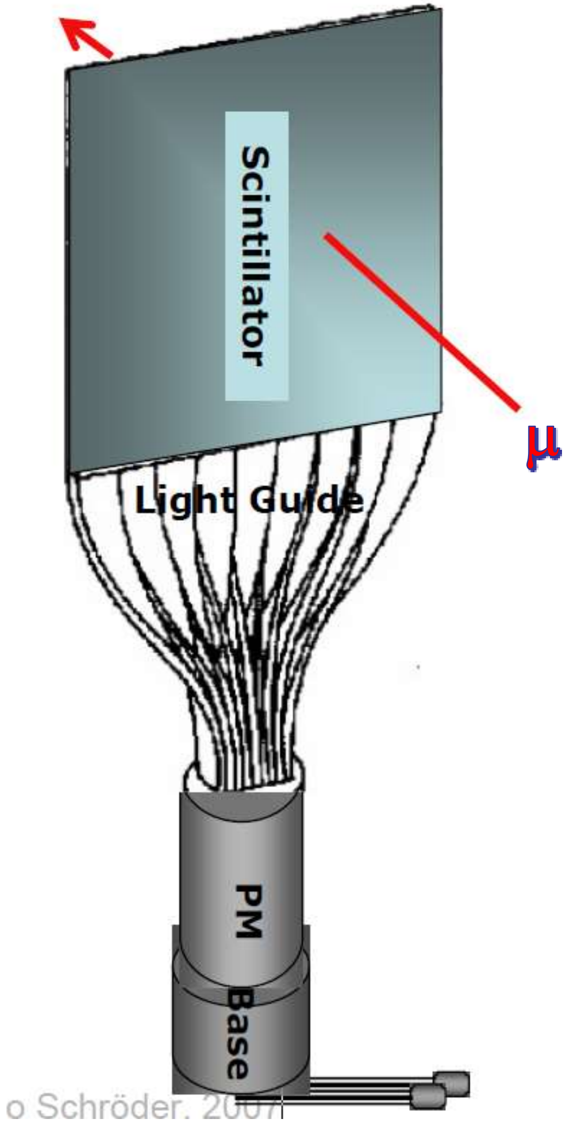
Active target AT= plastic scintillator
between #3 and #4
stops muon → decay

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

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

Measure decay lifetime
in plastic AT (negligible capture)

ANSEL Cosmic Muon Telescope Detectors



- Scintillator *(q (ΔE) → hν → hν*)*
- Light guide (*collect, average, direct*)
- Photomultiplier (*hν* → e^- → n e^-*)
- Base (*power PM dynode chain, readout*)

Scintillating Materials

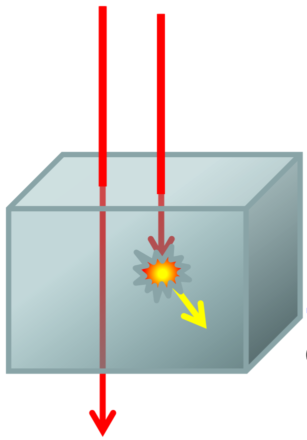
Inorganic { *gas (Ar, Xe,...)*; *liquid (He, Xe,...)*; *solid (NaI, CsI, BGO, BaF_2..)* }

Organic { *liquid (xylene, benzene,..)*; *solid (polystyrene,..)* }

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

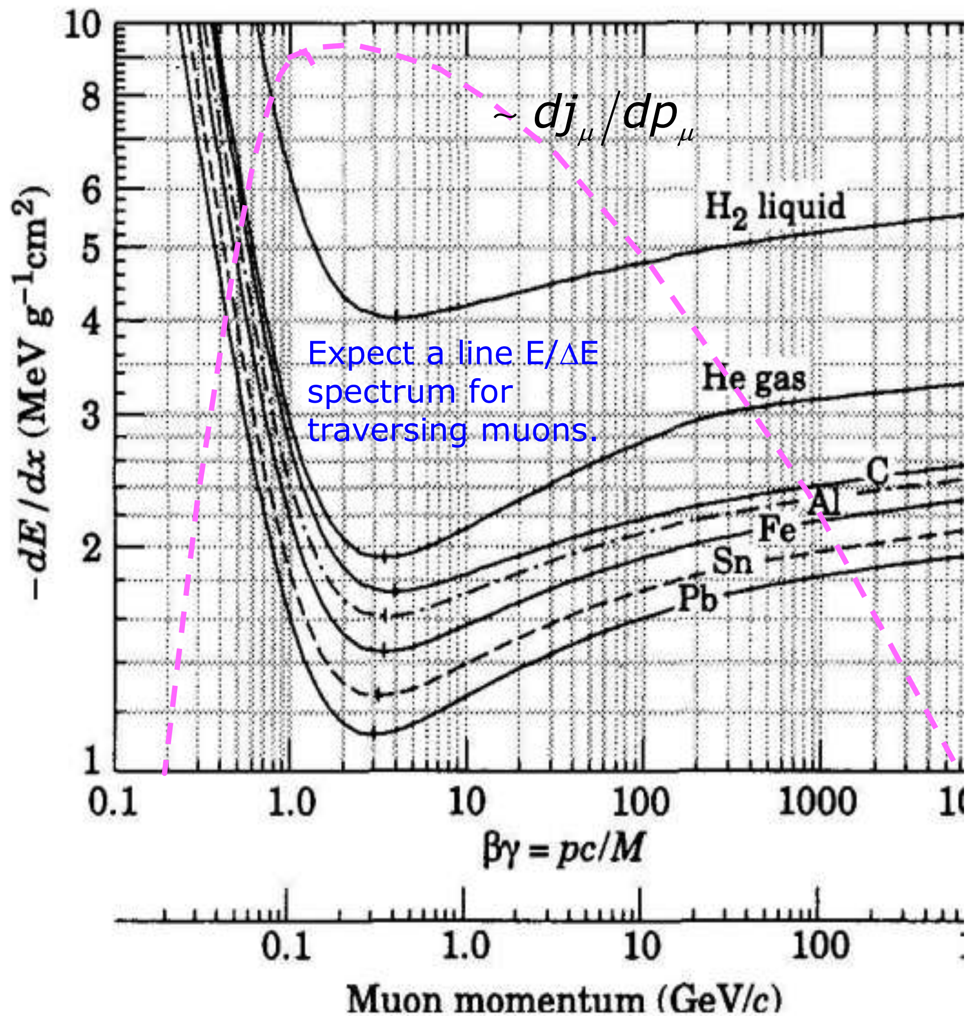
Stopped, muon decay following

Transmitted

Plexiglas Plastic:
C_nH_m polymer
([*H*]/[*C*]≈1.11),
ρ_T =*1.03 g/cm*^{3} *IE=64.7 eV*.

Cosmic ray muons = mostly minimum ionizing particles (mips)

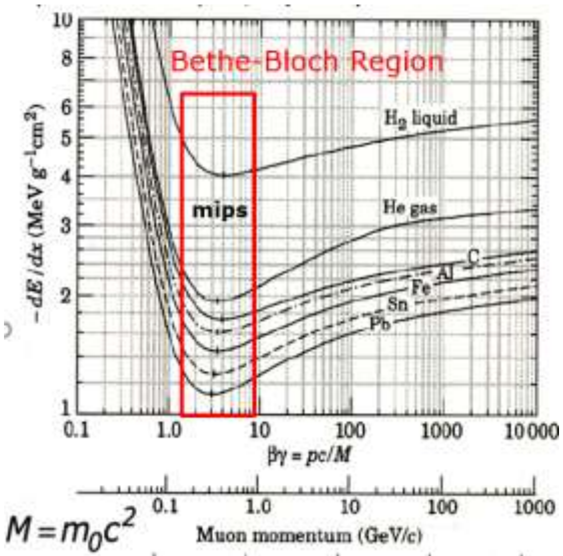
For plastic: ΔE ≈ 2 MeV/cm



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

Stopping Power For Leptons (Electrons & Muons)

Electronic collisions most important for kinetic energies T_e< 10 MeV.
For kinetic energies $T_e \approx$ 100 MeV, collision loss ≈ radiative loss ($\sim 6\cdot 10^{-4}\cdot Z_{abs}\cdot T_e$)



$M = m_0 c^2$

$$\left(-\frac{dE^{\pm}}{dx}\right)_{coll} = 5.08\cdot 10^{-31}\frac{N_e}{\beta^2}\left[G^{\pm}(\beta) - Ln I_e\right] MeV/cm$$

$$G^{\pm}(\beta) := Ln\left(3.61\cdot 10^5 \tau\cdot\sqrt{2+\tau} + F^{\pm}(\beta)\right); \qquad \tau := T_e/m_e c^2$$

$$F^{-}(\beta) := \frac{1-\beta^2}{2}\left[1 + \frac{\tau^2}{8} - (2\tau+1)Ln2\right]$$

$$F^{+}(\beta) := Ln2 - \frac{\beta^2}{24}\left[23 + \frac{14}{\tau+2} + \frac{10}{(\tau+2)^2} + \frac{5}{(\tau+2)^3}\right]$$

Example: *stopping power of water* *for* $T_e = 1 MeV$ *electrons*

$$\tau = 1MeV/0.511MeV = 1.96;\ \beta = 0.941;\ \beta^2 = 0.886;\ N_e(water) = 3.34\cdot 10^{29} m^{-3}$$

$$F^{-}(0.941) := \frac{1-0.886}{2}\left[1 + \frac{1.96^2}{8} - (2\cdot 1.96+1)Ln2\right] = -0.110$$

$$G^{-}(0.941) := Ln\left(3.61\cdot 10^5 1.96\cdot\sqrt{2+1.96} + F^{-}(0.941)\right) = 14.0$$

$$\rightarrow \text{Stopping power}\ \left(-\frac{dE}{dx}\right)_{coll} = 1.86\, MeV/cm\,(water)$$

J.E. Turner, *Atoms, Radiation, and Radiation Protection*; Wiley-VCH, Weinheim, 2007

Muon Energy Loss in Compounds

Index of tables for selected high polymers. Densities from Sternheimer et al., Atomic Data and Nuclear Data Tables 30, 261–271 (1984). Material composition from S. M. Seltzer & M. J. Berger, Int. J. Appl. Radiat. 33, 1189{1218 (1982), or on the web at http://pdg.lbl.gov/AtomicNuclearProperties.

Compound or mixture	$\langle Z/A \rangle$	ρ [g/cm^3]	$\langle -dE/dx \rangle_{\min}$ [MeV cm^2/g]	$E_{\mu c}$ [GeV]
Bakelite $[C_{43}H_{38}O_7]_n$	0.52792	1.250	1.889	1110.
Nylon (type 6, 6/6) $[C_{12}H_{22}O_2N_2]_n$	0.54790	1.180	1.973	1156.
Polycarbonate $[OC_6H_4C(CH_3)_2C_6H_4OCO]_n$	0.52697	1.200	1.886	1104.
Polyethylene $[C_2H_4]_n$	0.57034	0.890	2.079	1282.
Polymethylmethacrylate (acrylic)	0.53937	1.190	1.929	1107.
Polystyrene $[C_6H_5CHCH_2]_n$	0.53768	1.060	1.936	1183.
Polytetrafluoroethylene (Teflon) $[C_2F_4]_n$	0.47992	2.200	1.671	853.
Polyvinylchloride (PVC) $[CH_2CHCl]_n$	0.51201	1.300	1.779	696.
Polyvinyltoluene $[2\text{-}CH_3C_6H_4CHCH_2]_n$	0.54141	1.032	1.956	1194.

For plastic counters $\Delta E_\mu / \Delta x \approx 2\, MeV/cm$

Cosmic Muon Experiment

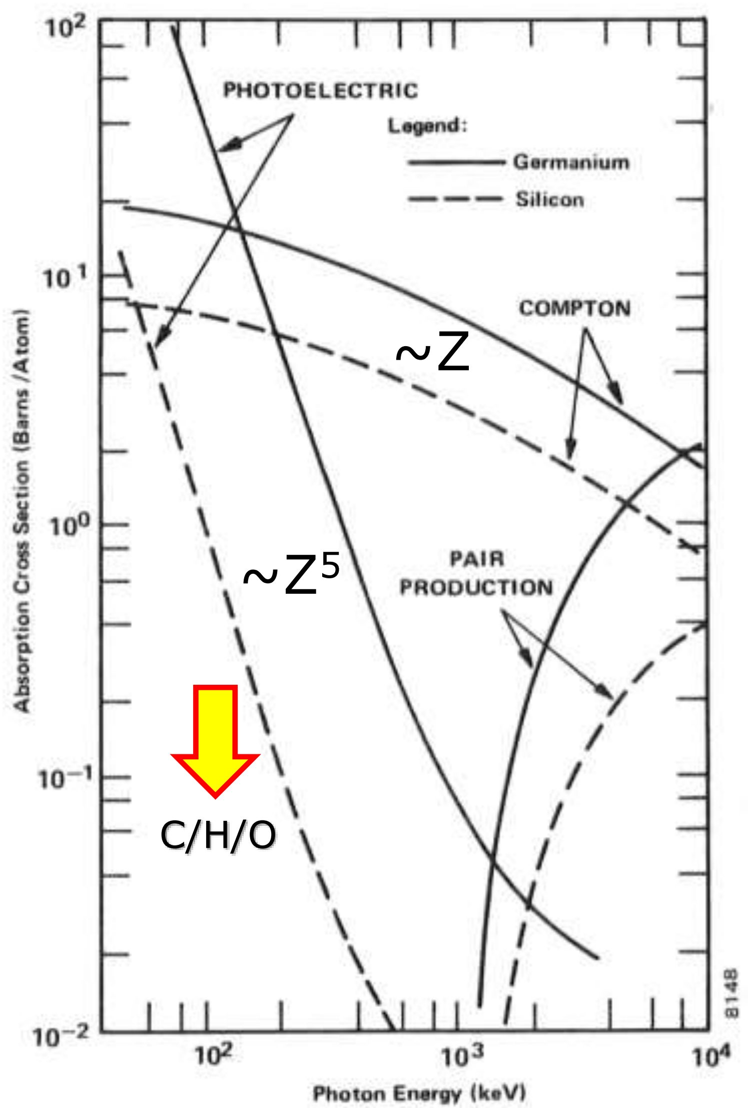
I. Cosmic muons and μ-decay electrons as relativistic particles
   - Relativistic notation energy/momentum, time dilation effect (F&S exp't).
   - Range of GeV-muons in metals (Cu, Fe) and plastic.
   - Mean range of μ-decay electrons in plastic

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,

Detector Calibration: Efficiencies of γ-Induced Processes



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

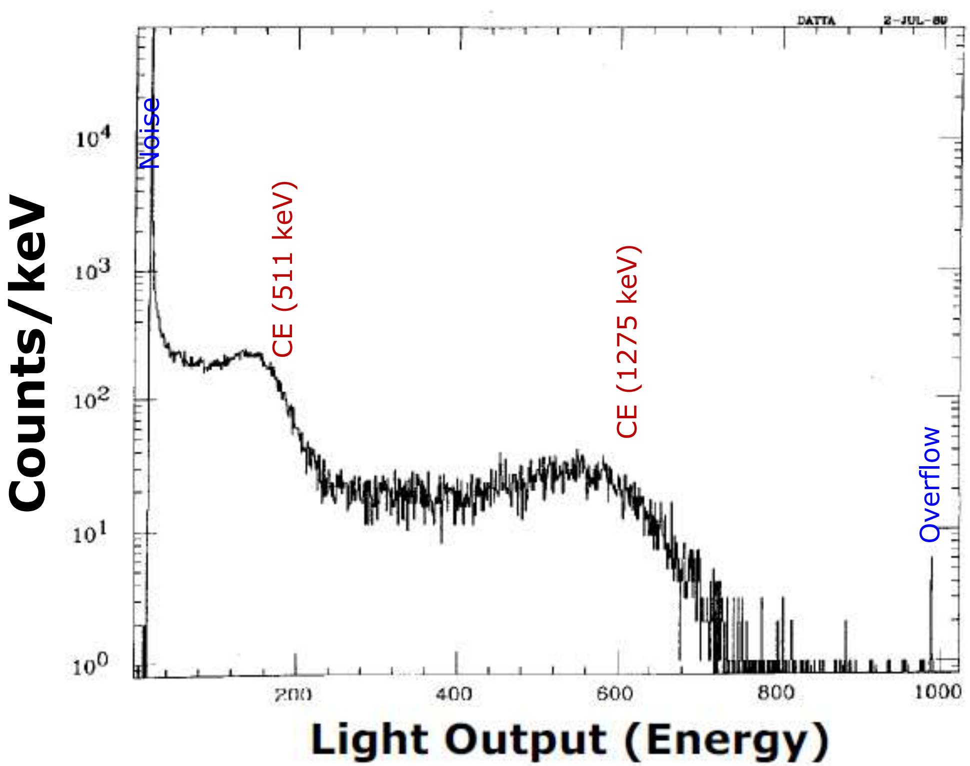
Response of detector depends on

- detector material
- detector shape
- E_γ

Muon Telescope: AT Pulse-Height Calibration

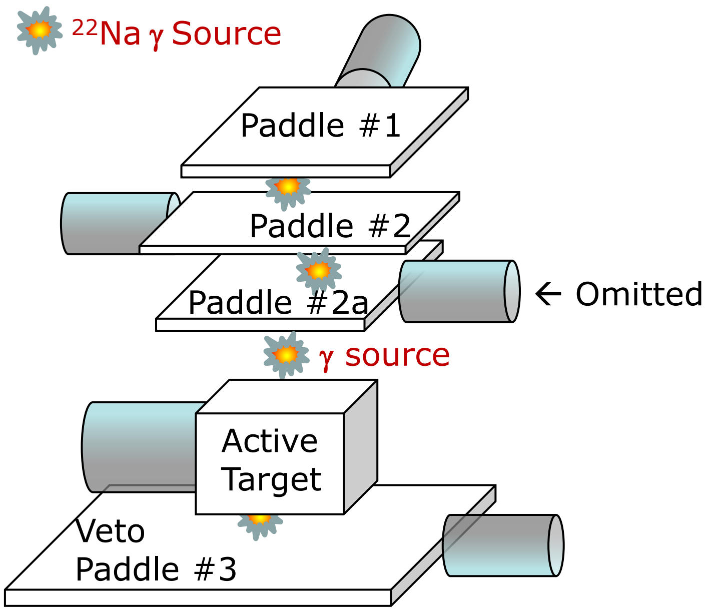
Task: Pulse-height calibration of AT(120mm thick) with γ-ray sources

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.



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

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.

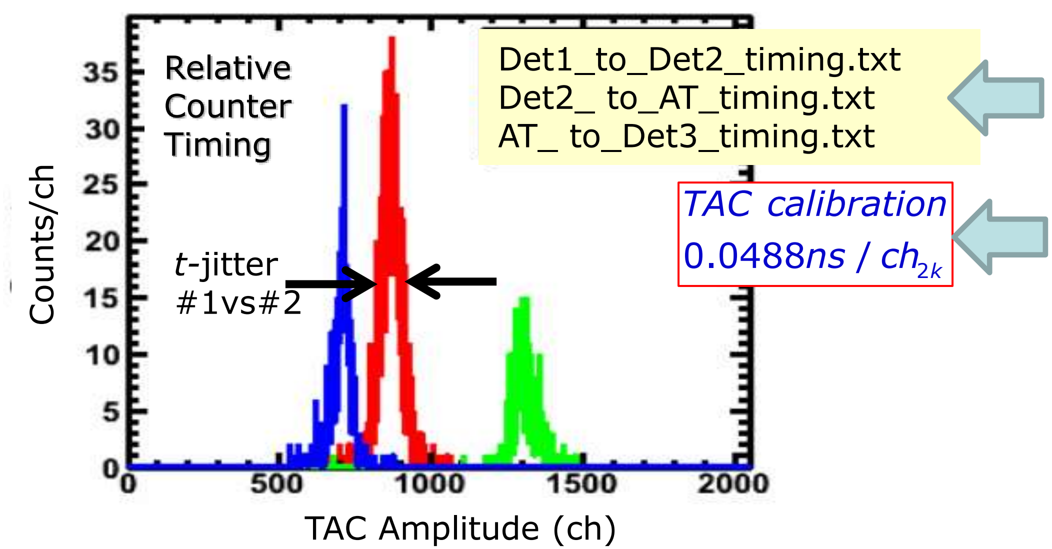
Make plot of safe timing diagram

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

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

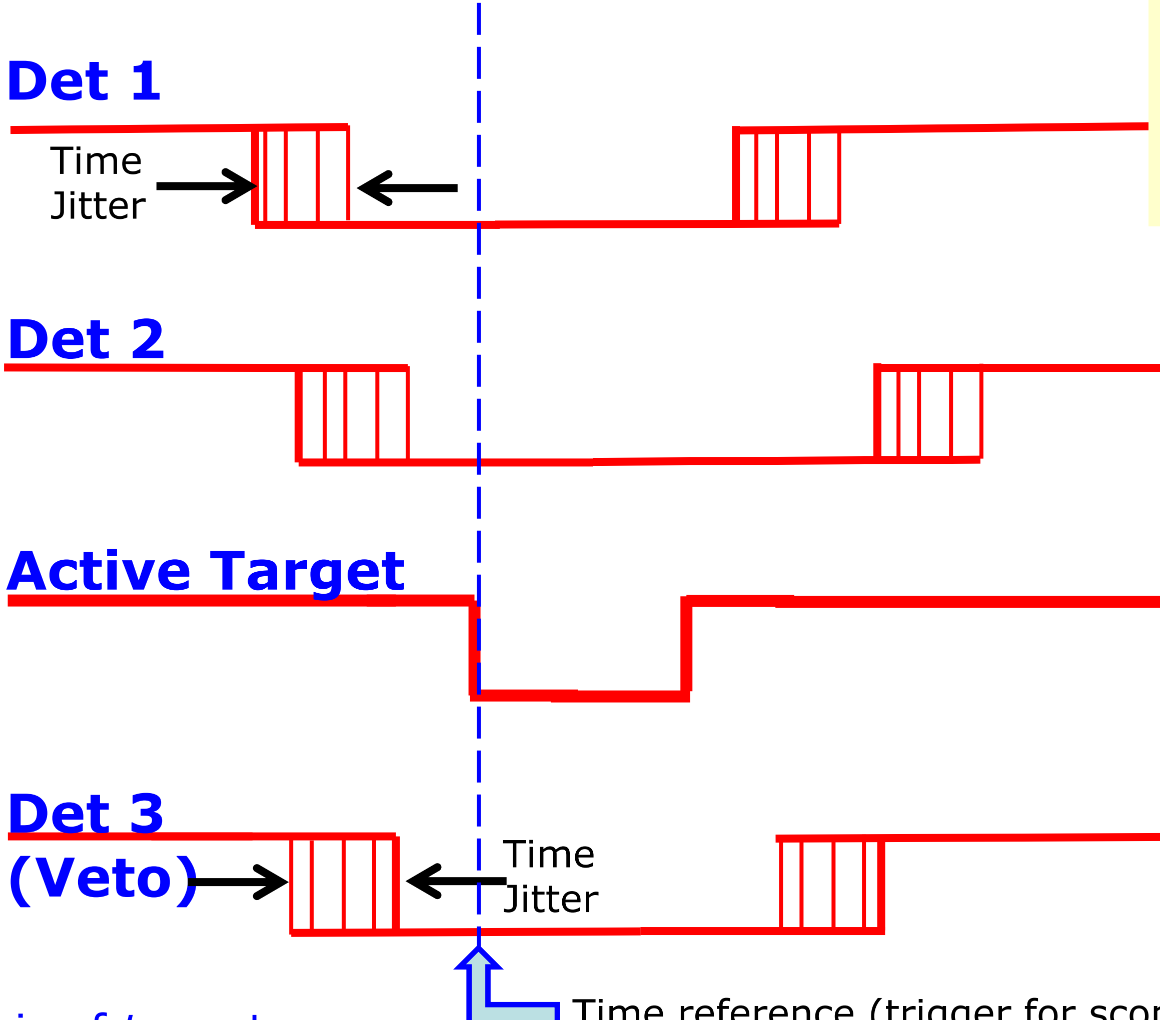
Cosmic ray muons = mostly minimum ionizing particles (mips)

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

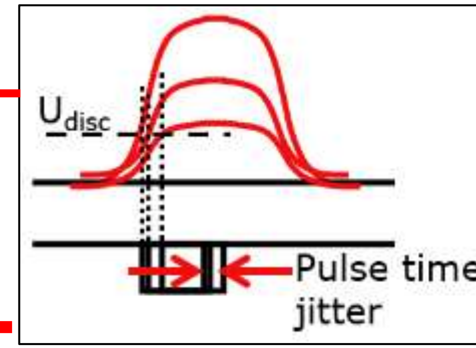


Cosmic Muons

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.

Analysis of *t* spectra

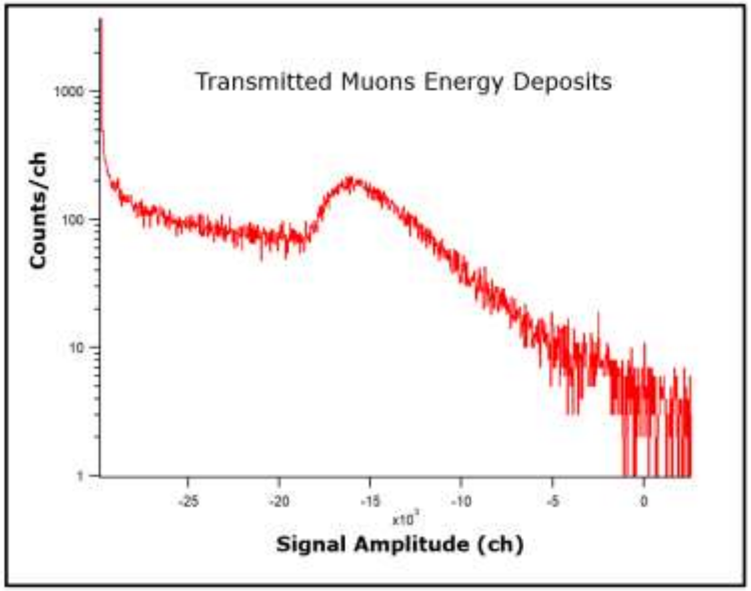
→ best paddle for defining t(muon) → your ideal timing diagram.

III.1 Muon Telescope: Muon Energy Loss 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)

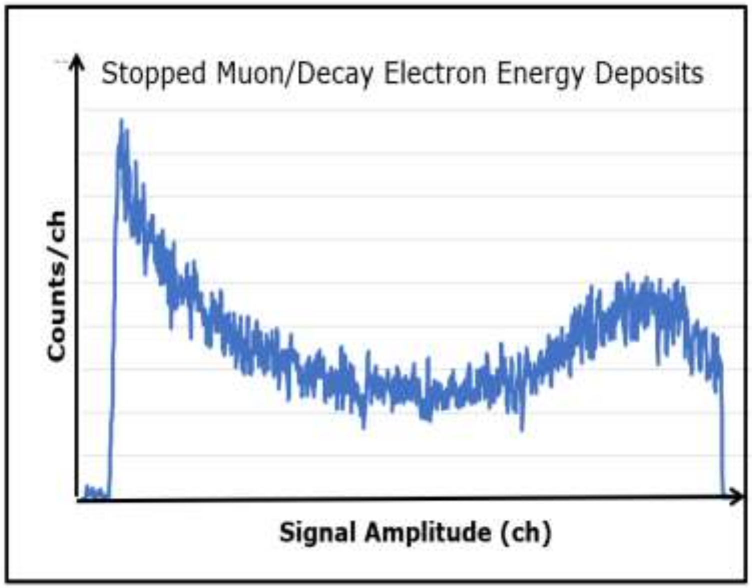


- Discuss shapes and probable origins of various spectral components.
- What effect does room background have on the measured energy deposits? (Use your experience from prior experiments)

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

III.2 Muon Telescope: Stopped Muon & Electron Energy

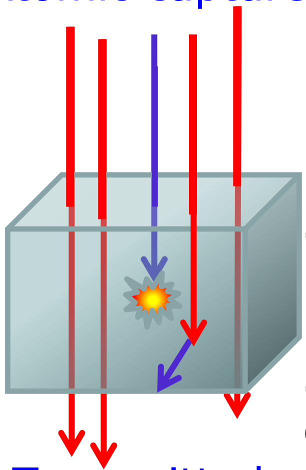
3. Measure, analyze, and discuss the energy deposition spectrum for muons stopped in the AT and its decay electrons. (Analyze File EnergyStoppedMuonAT.txt)



- 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)



Muons stopped in AT disappear by a "disappearance rate Λ_d

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

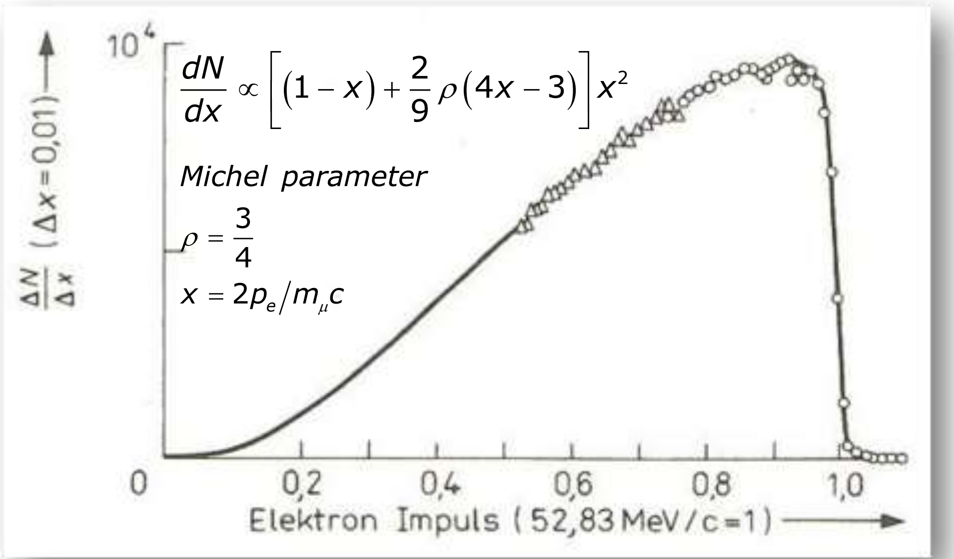
$$\Lambda_{cap}\left(\mu^+\right) = 0 \ (\mu^+ \ \textit{are not captured by atoms})$$

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

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

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

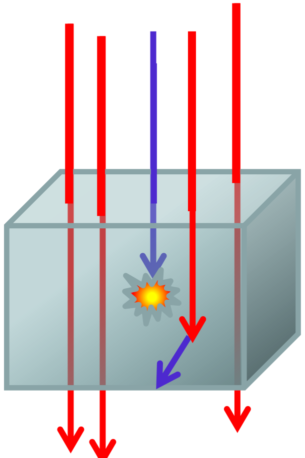
Light nuclei (Li, Be, …C, O,..): long partial capture muon life times (τ_{cap} ~ 100 μs » τ_d)



Stopped Muon Decay: E Deposit and Lifetime

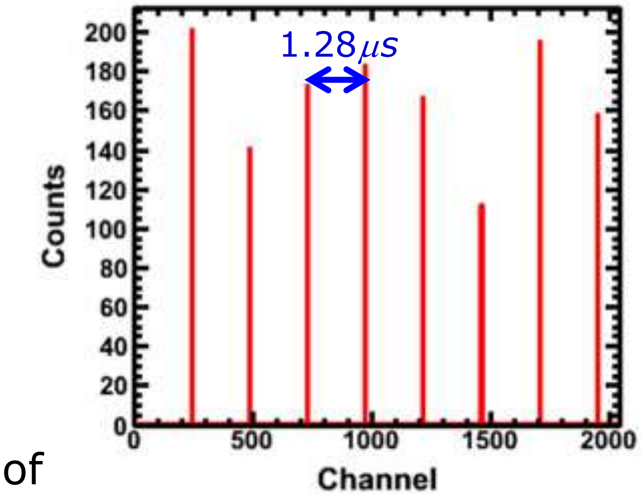
1. Set tight timing conditions for muon telescope, choose paddle detector with best time resolution (small jitter) to start TAC.

   Connect (delayed) AT disc signal to TAC stop.

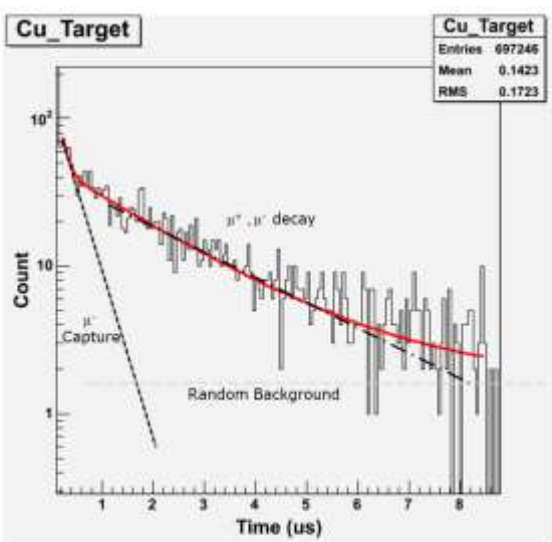


2. Set TAC range several μs. Calibrate TAC (Analyze t calibration spectrum)
3. Briefly measure time spectrum of AT events $t_{TAC} = t(AT) - t(\mu - stop)$

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