MUON LIFETIME

Determination of the Fundamental Weak Coupling Constant
Muons are produced in the outer atmosphere mainly by reactions of cosmic protons with air, yielding pions and kaons which decay into muons $\mu_-$, antimuons $\mu_+$ and related neutrinos. Because of their high speed and the involved time dilatation muons reach the earth’s surface despite of their short lifetime of about 2.2 $\mu$s and can be detected in a scintillation detector. The energy loss and the decay of the muon can be measured in the same detector as two well separated events and the time interval between both is the individual decay time. Collecting the decay of many muons leads to the decay curve and the nominal decay time $\tau$. The decay of negative muons is enhanced in matter because a further decay channel opens up depending strongly on the Z of the material. In an organic scintillator as used in this experiment this effect is small. From the decay time $\tau$ and the muon mass the coupling constant of the weak interaction can be derived.
The Muon is unstable and decays into an electron, a neutrino and an antineutrino:

\[
\begin{align*}
\mu^+ & \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\mu^- & \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{align*}
\]

The lifetime of the muon is of order 2.2 \(\mu\text{s}\) and its mass is \(m_\mu = 105.65\ \text{MeV}/c^2\). The neutrinos from the muon-decay are not detected, only the electron or positron, the maximum energy is observed when the two neutrinos recoil against the electron, the corresponding energy being:

\[
E_e (\text{max}) \cong \frac{1}{2} m_\mu c^2 = 53 \ \text{MeV}
\]

The energy spectrum of the decay-electrons is shown in the next slide; it is difficult to separate from all other events in the big detector used. The spectrum is continuous because the decay involves 3 resp. 4 ‘bodies’. Because of the high energy deposit one has to work with low amplification and therefore the high voltage is set to only -1300 Volts. Important are also the threshold settings of the two constant fraction discriminators, scale 250 for the start signal and 050 for the stop. Because the start and the stop signal are derived from the same detector and signal line one has to make sure that no stop pulse will be on the stop line when the start arrives; for this purpose the start signal is delayed by about 60 ns using a delay cable. The TAC is set to the \(10\mu\text{s}\) range and it has to be calibrated by using the Ortec time calibrator. Random coincidences are determined from a fit to the background line and have to be subtracted from all channels.
Simple set-up for the measurement of the muon decay time
The Fermi Weak Interaction Constant $G_F$

The decay of the muon proceeds through the weak interaction, only leptons being involved in this process. Therefore one can calculate the weak interaction constant $G_F$, one of the fundamental constants, from the measured muon lifetime:

\[
\frac{1}{\tau} = \frac{1}{\hbar} \frac{G_F^2}{(\hbar c)^6} \frac{(m_{\mu}c^2)^5}{192 \pi^3}
\]

The measured lifetime has to be corrected for a small effect: When negative muons are stopped in matter they can be captured by protons of a nucleus opening thus a further decay channel, which shortens the lifetime of negative muons to some extent:

\[
\mu^- + Z \rightarrow (Z-1)^* + \nu_{\mu}
\]

The effective mean life $\tau_e$ for negative muons becomes:

\[
\frac{1}{\tau_e} = \frac{1}{\tau_\mu} + \frac{1}{\tau_c}
\]

where $1/\tau_\mu$ and $1/\tau_c$ are the rates for decay and capture, respectively. For a plastic scintillator (carbon in the hydrocarbon) this effect of shorter lifetime is about 4%.
Calculated and idealized muon-decay spectrum

(a) $e^-$  $\bar{\nu}_e$  $\nu_\mu$

(b) $\frac{dN_\nu}{dE}$

$\frac{m_\mu c^2}{2} = 53$ MeV

End point

$E_\nu$

25  50 MeV
The measurement of the energy spectrum of the muon decay products is more difficult because one has to consider only events that have shown a decay, e.g. one selects after a true coincidence the second event with its amplitude. The selection is made by a single channel analyzer (SCA) after the TAC, choosing the range of about 1 – 6 μs. The other difficulty is, that the linear pulses have to be quite short to avoid pileup with the first event, the stopping of the muon in the scintillator. Therefore the linear pulses are prepared in a very unconventional manner: The linear signal is prepared in a timing filter amplifier to be very short. But the decision whether it is a valid pulse comes after the sequence of the TAC, e.g. after a few microseconds and therefore the linear pulse has to be delayed before the gate which is opened by a logic pulse after a true decay event. The other problem is the high energy range of the signals of about 50 MeV and their calibration. The highest energies of radioactive sources are in the range of 2 – 3 MeV and they are therefore nearly invisible in this setup. But γ transitions in the range of 8 – 10 MeV can be produced by using our Am-Be neutron source and a neutron capture reaction, for example the 7.3 MeV n-capture line of iron.
Set-up for the measurement of the muon-decay energy spectrum

HV Canberra 3002 D

Pre-Amp Ortec 113

Timing Filter Amplifier Canberra 2110

Delay Amp Ortec 427A

( Biased Amp Ortec 408 )

Linear Gate Ortec 426

Computer (PC)
IBM ThinkCentre

ADC +MCA
Canberra Multiport II

Voltage Divider
Photonis VD105k/01

Photomultiplier
Photonis XP4572B

Scintillator
Saint-Gobain
BC 400

CFD Ortec 473A

Fixed Delay

Start

TAC Canberra 2044

Stop

Single Channel Analyzer Ortec 488

modules in (...) are optional
Muon Lifetime Experiment: Required Knowledge

- Basic elementary particle physics
- The Standard Model of elementary particles
- Lepton families
- Lepton number conservation
- Weak interaction
- Relativistic time dilatation
- Decay characteristics of the muon
- Scintillation detectors
- Properties of plastic detectors
- Fast photomultipliers
- Fast timing techniques
- Basic nuclear electronics
- Multichannel analyzer
- Neutron capture and $\gamma$-transition production
Muon Lifetime Experiment: Tasks and Goals

- Prepare setup for lifetime measurement (block scheme Nr. 1)
  - HV=-1300 Volts, TAC-range 10μs, MCA→1000 channels, thresholds: scale 250 (start) and 050 (stop)
- Use oscilloscope to watch and understand all signals
- Measure lifetime → overnight or overweekend run
- Calibration of the TAC and the time-axis with Ortec time calibrator

- Prepare set-up for measurement of the energy spectrum according to block-scheme Nr. 2
- The linear pulses have to be very short, else one obtains summing up of the incoming muon energy and the decay product energy
- The exact timing of all pulses is very important (→ oscilloscope)
- Calibration of the energy spectrum using n-capture γ-rays, get help with handling of the neutron source
Muon lifetime experiment, first run

\[ \tau = 2.2 \pm 0.2 \, \mu s \]
Energy spectrum of decay products of muon decay. The broad red distribution shows a maximum energy of about 53 MeV which corresponds to the muon decay.

Energy calibration of the muon detector using capture gamma rays from slow neutron capture at iron. A standard Am-Be neutron source was positioned behind a polyethylene moderator and a wall of iron bricks. The compton spectrum from the 7.3 MeV transition in iron is observed: red area of the spectrum (blue being background).
# The Muon

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muon Mass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in eV, $m_{\mu}c^2/{e}$</td>
<td>$1.8835327(11)$</td>
<td>$10^{-28}$ kg</td>
</tr>
<tr>
<td></td>
<td>$0.113428913(17)$</td>
<td>u</td>
</tr>
<tr>
<td></td>
<td>$105.658389(34)$</td>
<td>MeV</td>
</tr>
<tr>
<td><strong>Muon-Electron Mass Ratio</strong></td>
<td>$m_{\mu}/m_e$</td>
<td>$206.768262(30)$</td>
</tr>
<tr>
<td><strong>Magnetic Moment</strong></td>
<td>$\mu_{\mu}$</td>
<td>$4.4904514(15)$</td>
</tr>
<tr>
<td>Anomaly, $[\mu_{\mu}/(e\hbar/m_{\mu})] - 1$</td>
<td>$a_\mu$</td>
<td>$1.1659230(84)$</td>
</tr>
<tr>
<td>g-Factor, $2(1 + a_{\mu})$</td>
<td>$g_{\mu}$</td>
<td>$2.002331846(17)$</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>$\tau_{\mu}$</td>
<td>$2.19703 \pm 0.00004$</td>
</tr>
<tr>
<td><strong>Half-Life</strong></td>
<td>$T_{1/2} = \tau \ln 2$</td>
<td>$1.52287 \pm 0.00003$</td>
</tr>
</tbody>
</table>
### The Electron

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Mass in eV, $m_e c^2/{e}$</td>
<td>$m_e$</td>
<td>$9.1093897(54)$</td>
<td>$10^{-31}$ kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5.48579903.(13)$</td>
<td>$10^{-4}$ u</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.51099906(15)$</td>
<td>$1$ MeV</td>
</tr>
<tr>
<td>Compton Wavelength, $h/m_e c$</td>
<td>$\lambda_c$</td>
<td>$2.42631058(22)$</td>
<td>$10^{-12}$ m</td>
</tr>
<tr>
<td>$\lambda_c / 2\pi = \alpha a_0 = \alpha^2 / 4\pi R_\infty$</td>
<td>$\lambda_c^-$</td>
<td>$3.86159323(25)$</td>
<td>$10^{-13}$ m</td>
</tr>
<tr>
<td>Classic Electron Radius, $\alpha^2 a_0$</td>
<td>$r_e$</td>
<td>$2.81794092(38)$</td>
<td>$10^{-15}$ m</td>
</tr>
<tr>
<td>Thomson Cross Section, $(8\pi/3) r_e^2$</td>
<td>$\sigma_e$</td>
<td>$0.66524616(18)$</td>
<td>$10^{-28}$ m$^2$</td>
</tr>
<tr>
<td>Magnetic Moment of the Electron in Bohr Magneton</td>
<td>$\mu_e$</td>
<td>$928.47701(31)$</td>
<td>$10^{-26}$ J T$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\mu_e / \mu_B$</td>
<td>$1.001159652193(10)$</td>
<td>-</td>
</tr>
<tr>
<td>Magnetic Moment of the Electron Anomaly, $(\mu_e / \mu_B) - 1$</td>
<td>$a_e$</td>
<td>$1.159652193(10)$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>g-factor, $2(1 + a_e)$</td>
<td>$g_e$</td>
<td>$2.002319304386(20)$</td>
<td>-</td>
</tr>
</tbody>
</table>
The Moon's cosmic ray shadow, as seen in secondary muons detected 700m below ground, at the Soudan II detector.
## 130 mm (5”) tubes

<table>
<thead>
<tr>
<th>Key features</th>
<th>XP4500B</th>
<th>XP4508B</th>
<th>XP4512B</th>
<th>XP4572B</th>
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</thead>
<tbody>
<tr>
<td>Dynode structure / number of stages</td>
<td>focused/10</td>
<td>focused/10</td>
<td>focused/10</td>
<td>b.i./10</td>
</tr>
<tr>
<td>Cathode luminous sensitivity (µA/lm)</td>
<td>typ. 70</td>
<td>typ. 65</td>
<td>typ. 70</td>
<td>typ. 70</td>
</tr>
<tr>
<td>Cathode blue sensitivity (µA/lmF)</td>
<td>min 6</td>
<td>min 6</td>
<td>min 6</td>
<td>min 6</td>
</tr>
<tr>
<td>Cathode radiant sensitivity (mA/N)</td>
<td>typ. at (nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>typ. 2x10⁸</td>
<td>typ. 2x10⁸</td>
<td>typ. 2x10⁸</td>
<td>typ. 2x10⁸</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>typ. 1500</td>
<td>typ. 1500</td>
<td>typ. 1500</td>
<td>typ. 1500</td>
</tr>
<tr>
<td>max. (V)</td>
<td>typ. 2500</td>
<td>typ. 2500</td>
<td>typ. 2500</td>
<td>typ. 2500</td>
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<tr>
<td>Anode dark current</td>
<td>typ. (nA)</td>
<td>typ. 90</td>
<td>typ. 90</td>
<td>typ. 90</td>
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<tr>
<td>max. (nA)</td>
<td>typ. 400</td>
<td>typ. 400</td>
<td>typ. 400</td>
<td>typ. 400</td>
</tr>
<tr>
<td>Anode dark counts</td>
<td>typ. (cps)</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>max. (cps)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Max. anode pulse current for linearity 2% (mA)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Time response</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PHR (%)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Maximum ratings</td>
<td>supply voltage (V)</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>gain</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

### Accessories
- **Voltage divider**: VD105K, VD305K, VD105K, VD305K, VD105K, VD305K
- **Socket**: FE1120, FE1120, FE1120, FE1120
- **Mu-metal shields**: MS175, MS175, MS175, MS175
Muon Lifetime Experiment

Determination of the Fundamental Weak Coupling Constant