Search for MUonium TO Neutrinos

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Outline

Topics of my thesis

- Search for the standard model (SM) process $e\mu \rightarrow \nu_\mu \nu_e$ (MUonium TO Neutrinos, *MUTON*). The signal of this process can be enhanced by some models beyond the SM (e.g. mirror matter or heavy neutrinos).
- Search for invisible decay channels of positronium (Experiment on Positronium Invisible Channels, *EPIC*). Test of mirror matter as a possible dark matter candidate, as well as other beyond–SM physics (e.g. milli-charged particles).

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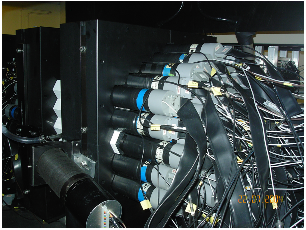
My specific task

- Construction of a 4π calorimeter with BGO crystals to search for rare processes with zero energy deposition signal. This calorimeter will be used for both MUTON and EPIC experiments.



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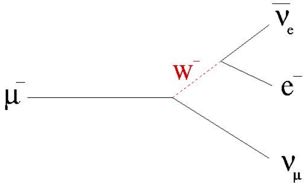
The muon

- Lepton from the second family discovered in 1936.
- ∼200 times heavier than the electron, lifetime 2.2 µs.
- Purely electroweak decay process $\mu \rightarrow e\nu_\mu\nu_e$ through charged currents.
- Three canonical processes connected by crossing symmetry:
  - Standard μ decay: $\mu \rightarrow e\nu_\mu\nu_e$ (1936)[1]



[1] C. D. Anderson, 1936

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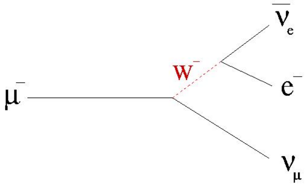

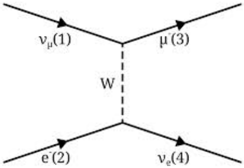

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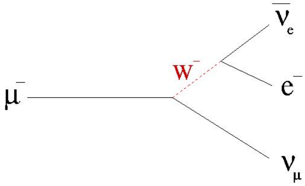
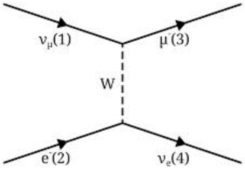
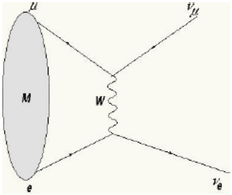
  - μ - e annihilation $e\mu \rightarrow \nu_\mu\nu_e$ (not yet observed)







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The $\mu^+ e^- \to \nu_\mu \nu_e$ decay mode

- At low energy $\mu^+ e^-$ can form the atomic bound state muonium (Mu).
- Muonium is bounded by electromagnetic forces and can self-annihilate through CC.
- Branching ratio predicted to be $Br(Mu \to \nu_\mu \nu_e) = 6.6 \times 10^{-12}$.[3]
- Current limit is $Br(Mu \to \mathrm{inv.}) < 5.7 \times 10^{-6}$ extracted from MuLan.

Experimental signature

- No measurement of neutrinos from $\mu^+ e^- \to \nu_\mu \nu_e$.
- Instead search for no energy deposition: $\mu^+ e^- \to \mathrm{invisible}$.

Beyond-SM physics can be addressed

- Mirror matter oscillations, similar to $n \to n'$ and $Ps \to Ps'$ oscillations.[4]
- $\mu \to \mathrm{inv.}$: charge non-conserving process which might hold in models with infinite extra dimensions (current limit $Br(\mu \to \mathrm{inv.}) < 5.2 \times 10^{-3}$).[4]
- Heavy neutrino oscillations which might explain the LSND/MiniBooNE anomaly.[5]

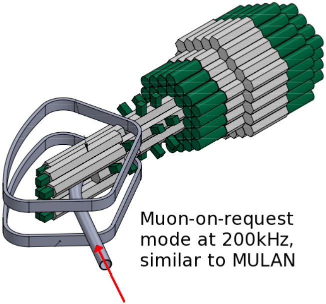
[3] A. Czarnecki, G.P. Lepage, and W. Marciano, Phys. Rev. D 61, 073001 (2000)
[4] S.N. Gninenko, N.V. Krasnikov, and V.A. Matveev, Phys. Rev. D 87, 015016 (2013)
[5] S.N. Gninenko, Phys .Rev. D 76, 055004 (2007)
[6] S.N. Gninenko, Phys. Rev. D 83, 093010 (2011)

LOI submitted in 2012, encouraged to submit detailed proposal in 2013.

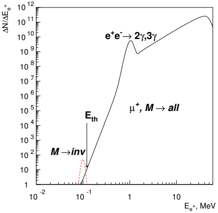
Principle of measurement

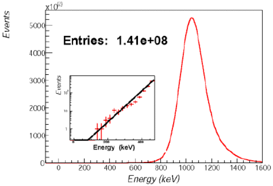
Goal: detect $\mu e \rightarrow \text{invisible}$ at a level of $\sim 10^{-12}$.

1. Stop a μ^+ in a Mu formation target (fused quartz) surrounded by a 4π hermetic calorimeter.
2. Look for missing energy from the decay positron and the annihilation photons within a time gate $t_G \sim 60\,\mu s \rightarrow P = e^{-\frac{t_G}{\tau_\pi}} = 1.43 \times 10^{-12}$.



Muon-on-request mode at 200kHz, similar to MULAN





$P_{2\gamma \rightarrow \text{inv.}} < 10^{-8}$

A. Badertscher, P. Crivelli et al., Phys. Rev. D 75, 032004 (2007)

My contribution: measurement of background.

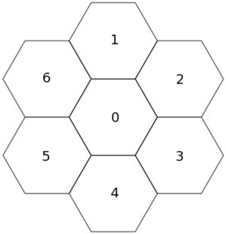
Background definition.

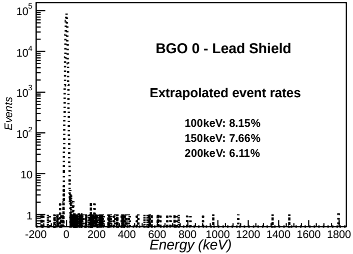
Goal: detect zero-energy events → define individual energy threshold E_{th}.
Zero-energy event definition: no crystal shows energy deposition above E_{th}.
Background: energy deposition above E_{th} uncorrelated with a μ^+ decay.

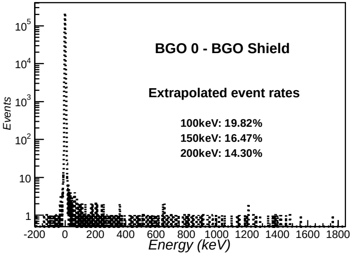
- Lower E_{th}: better sensitivity reachable.
- Larger E_{th}: less background.

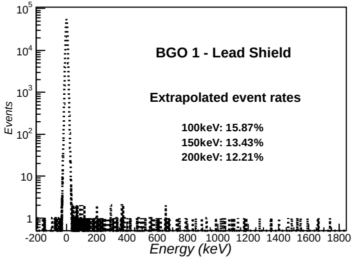
Measurement setup.

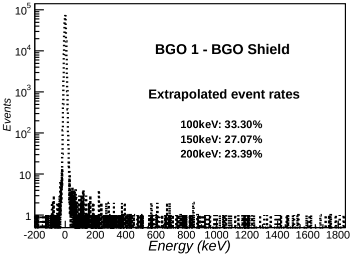
- 7 BGO used.
- Tests performed at ETH and PSI.
- Crystal position and lead shielding effects tested.

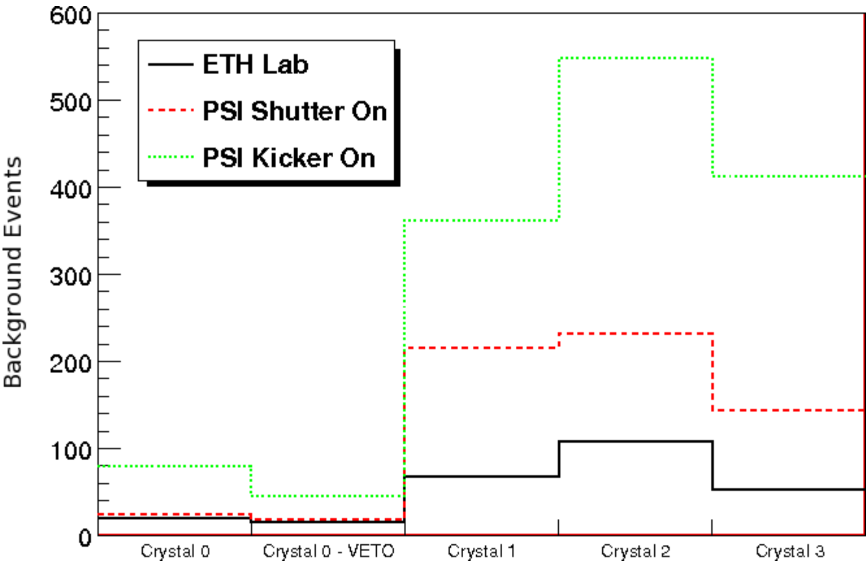



BGO 0 - Lead Shield
Extrapolated event rates
100keV: 8.15%
150keV: 7.66%
200keV: 6.11%
Events
Energy (keV)


BGO 0 - BGO Shield
Extrapolated event rates
100keV: 19.82%
150keV: 16.47%
200keV: 14.30%
Events
Energy (keV)


BGO 1 - Lead Shield
Extrapolated event rates
100keV: 15.87%
150keV: 13.43%
200keV: 12.21%
Events
Energy (keV)


BGO 1 - BGO Shield
Extrapolated event rates
100keV: 33.30%
150keV: 27.07%
200keV: 23.39%
Events
Energy (keV)



600
500
400
300
200
100
0
Background Events
ETH Lab
PSI Shutter On
PSI Kicker On
Crystal 0
Crystal 0 - VETO
Crystal 1
Crystal 2
Crystal 3

Conclusions

- Lead shielding found to be necessary to reduce environmental background.
- Shielding requirements at PSI are higher due to beam environment.
- Expected inefficiency after shielding and beam collimation $\sim 10\,\%$.

Proposal submitted and positively received. However beam time was not granted due to huge load in μ^+ line.

We are now studying the feasibility of using a π^+ beam line instead to get preliminary results. The target sensitivity for these results is 10^{-9}, which can be achieved in 2 weeks of beam time.

Principle of measurement

Goal: detect $Mu \to \text{invisible}$ at a level of $\sim 10^{-9}$.

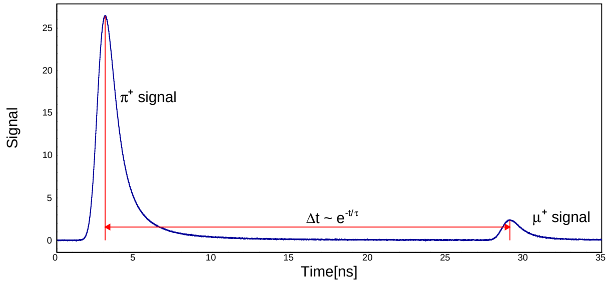
1. Stop a π^+ in an **active** target surrounded by a 4π hermetic ECAL.
2. Detect the $\pi^+ \to \mu^+\nu_\mu$ decay.
3. Form Mu in the stopping target.
4. Look for missing energy from the decay positron and the annihilation photons within a time gate $t_G \sim 45\,\mu\text{s} \to P = e^{-\frac{t_G}{\tau_\pi}} = 1.31 \times 10^{-9}$.

Main challenge: target

- Efficiently form Muonium
- Active material (otherwise introduces great energy losses)
- Fast material to tag the π^+ and μ^+ decay within tens of ns.

Trigger Principle

- Use the double signal of π^+ arrival and π^+ decay to trigger the μ^+.
- Two clear energy depositions (π^+ and μ^+ kinetic energies) within a short time gap ($\tau_{\pi^+} = 26\,\text{ns}$).
- Time and energy cuts applied to suppress fake triggers due to inelastic processes and in-flight decays (65 % efficiency expected).



BaF_2 crystal

- Dense enough to stop π^+.
- Fastest inorganic crystal available.
- Muonium formation observed in the past[6]. This will be checked by μSR technique within 2014 at PSI, as well as other possible materials (e.g. $PbWO_4$ and BrilLanCe).

[6] J.H. Brewer, S.R. Kreitzman et al., Phys. Rev. B 33, 7813 (1986)

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Current status

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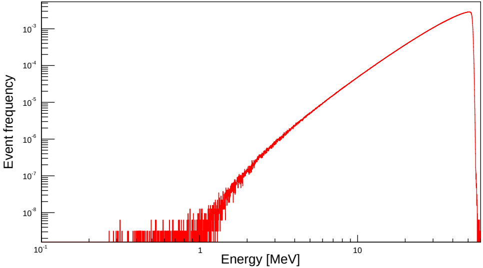

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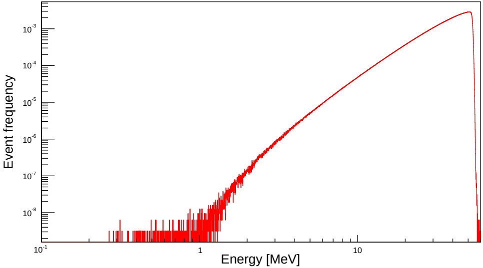
- Ongoing tests with πM1 beam line at PSI on the trigger scheme to test efficiency.



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- Inefficiency due to background can be as low as 10 %.
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Modification for π^+ beam line

- Sensitivity reduced to 10^{-9}, still great improvement to current limit (5.2×10^{-3}).
- BaF_2 and fast inorganic scintillators are candidates for active target.
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Next Steps

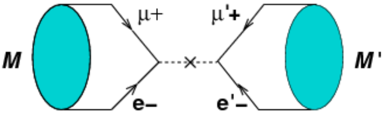
- Carry on full measurement with complete ECAL
- Design, construct and test ECAL injection for EPIC experiment (vacuum pipe).

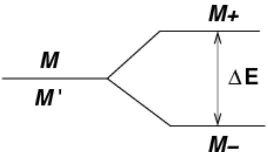
Thank you for your attention!

Questions?

Mirror Matter Oscillations

- Phenomenology is similar to matter – anti-matter and other mirror oscillations (M–$\bar{M}$, Ps–Ps', n–n').
- New mass eigenstates $M^{\pm} = \frac{M \pm M'}{\sqrt{2}}$.
- Energy splitting $\Delta E = 1.5 \times 10^{-12} \cdot \left(\frac{G_{MM}}{G_F}\right)^2$ [eV]
- Oscillation probability $P(M\text{–}M')(t) = 2.56 \times 10^{-5} \cdot \left(\frac{G_{MM}}{G_F}\right)^2$





Other charge non-conserving processes have very strong experimental limits

$\tau\left(e^- \to \text{inv}\right)$	$> 2.4 \times 10^{24}$y	DAMA '99
$\tau\left(p^+ \to \text{inv}\right)$	$> 9.2 \times 10^{34}$y	SuperK '03
$\text{Br}\left(n \to p^+\nu\nu\right)$	$< 8.0 \times 10^{-27}$	Solar ν exp. '96
$\tau\left(n \to \text{inv}\right)$	$> 5.8 \times 10^{29}$y	KamLand '06

No direct experimental limits for μ and τ

$\text{Br}(\mu \to \text{inv})$	$< 5.2 \times 10^{-3}$	from comparison of G_F and Γ_μ[5]
$\text{Br}(\tau \to \text{inv})$	$< 1.6 \times 10^{-3}$	MuLan at PSI vs. (indirect) LEP

[5]S.N. Gninenko, N.V. Krasnikov, and V.A. Matveev, Phys. Rev. D 87, 015016 (2013)

- Mixing between ν_μ and a heavy neutrino ν_h might be able to explain the anomalies in LSND and MiniBooNe experiments.
- If $m_{\nu_h} < 40\,\text{MeV}$ MUTON can be sensitive to this mixing.
- Experimental signature: energy deposition by the monoenergetic γ in an outer layer.