Precision measurements of rare pion decays with the PIONEER experiment

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PIONEER Collaboration

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Pion decays back then

Theory of the Fermi Interaction

R. P. Feynman and M. Gell–Mann
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

Experimentally[16] no $\pi \rightarrow e + \nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

Pion decays now

$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

$$= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$
$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$

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- One of the most precisely known observable involving quarks in the SM!
- Experimental uncertainty 15x larger than theoretical!

A new experiment

Physics cases for a new R^{π} measurement:

- Testing Lepton Flavor Universality
  - Several tensions in flavour sector
  - μ g-2, B decays, CKM unitarity

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  - R^π extremely sensitive to new (pseudo)scalar couplings (e.g. charged Higgs, heavy neutrinos, ...)

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Physics cases for a new π beta decay measurement:

- Testing CKM unitarity via V_{us}/V_{ud}
- Direct determination of V_{ud}

PIONEER

Goals:

- measure R^{μ} to 0.01 % relative precision (Phase I)
- measure BR($\pi^{+} \rightarrow \pi^{0} e^{+} \nu$) to 0.2 % (Phase II)
- measure BR($\pi^{+} \rightarrow \pi^{0} e^{+} \nu$) to 0.06 % (Phase III)

PIONEER

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Needs high intensity π^+ beam (Phase 1: $3 \times 10^5\,\mathrm{s}^{-1}$, Phases II/III: $2 \times 10^7\,\mathrm{s}^{-1}$)

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Phase I approved to run at PSI
(Proposal: https://arxiv.org/abs/2203.01981)

$$R^{\pi} = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow \mu\nu(\gamma)}$$: how is it measured?

$\mu \rightarrow e\nu\bar{\nu}$

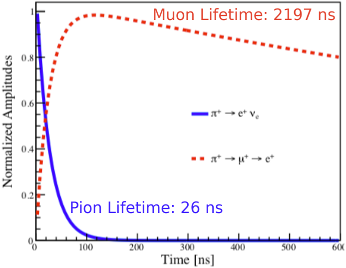
What π decay to “normally”: $B(\pi^+ \rightarrow \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$

Helicity suppressed decay: $B(\pi^+ \rightarrow e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

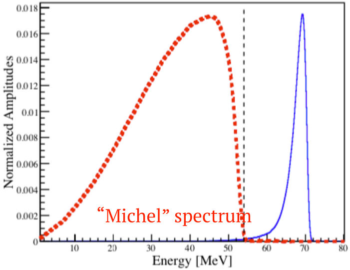
Pion β decay: $B(\pi^+ \rightarrow e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

Measure precisely e^+ energy spectrum and $t_{e^+} - t_{\pi^+}$

$\Longrightarrow$ different time and energy spectra - discrimination between the two decays



Time spectrum



e^+ energy spectrum

C. Malbrunot

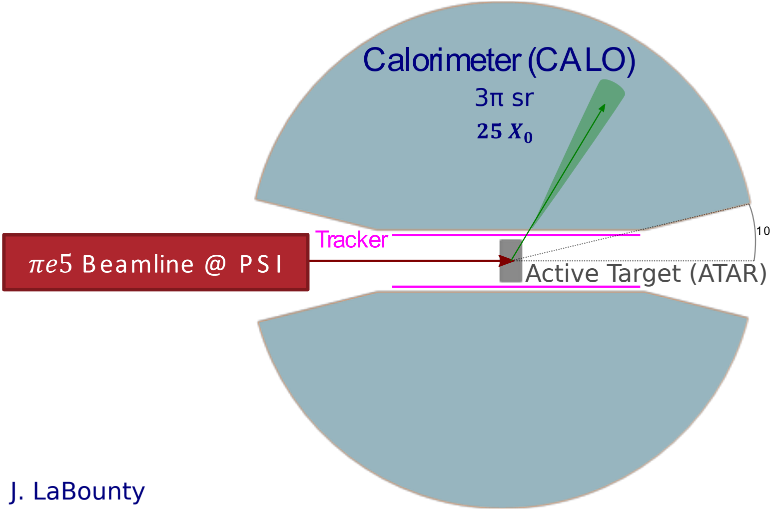
The low energy tail

Main systematic effect:
Low energy tail of positron spectrum from $\pi \rightarrow e\nu$

Caused by:

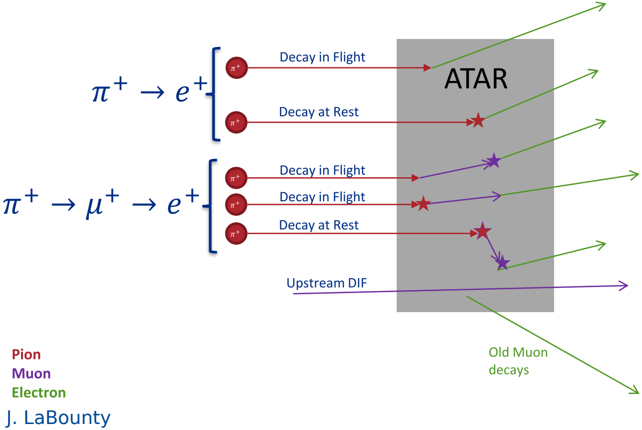
- finite energy resolution
- energy loss in dead material
- shower leakage
- geometrical acceptance
- radiative decays
- PIENU experiment: photo-nuclear interactions (^{127}I(γ,n))
- ...

Apparatus overview



J. LaBounty

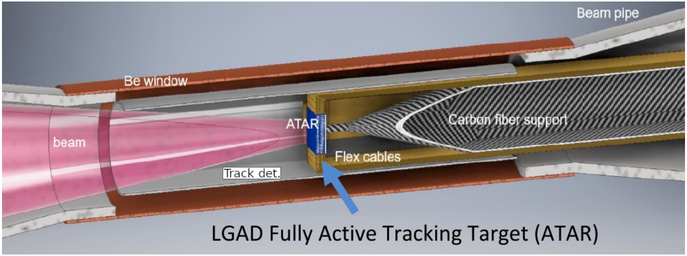
ATAR



- High longitudinal segmentation
- As little material as possible
- Fast collection time
- Large dynamic range

ATAR Hardware (preliminary)

- Stack of low gain avalanche diodes (LGADs)
- 48 layers, 120 µm thickness per layer
- 100 strips per layer, 20 mm length, 200 µm pitch
- 20 mm x 20 mm area
- read out using flex cables to the side, then back
- Development led by UC Santa Cruz

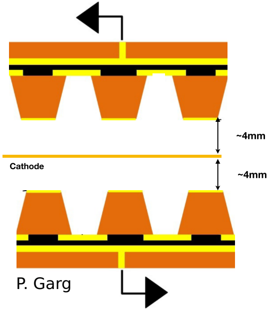


Tracker

- Correlation of ATAR hit to CALO shower
- High speed
- As little material as possible

Preliminary concept:

- Cylindrical 2-layer Resistive Micro Well (μRWELL)
- Development led by Stony Brook University



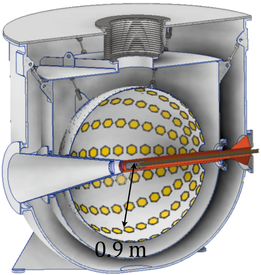
P. Garg

CALO

25 X_0, 3π sr calorimeter

High energy resolution, fast, symmetric → Much better tail suppression

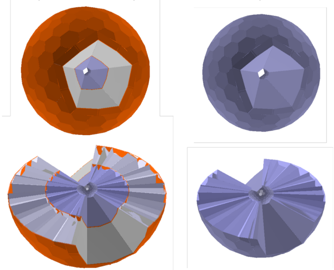
Option 1: LXe



Advantages:
- uniform/homogeneous volume
- fast response
- Excellent energy resolution

Question marks
- (un)known issues with VUV SiPM
- handling pileup
- cost

Option 2: LYSO or combined LYSO/CsI



Advantages:
- Not cryogenic
- fast response
- “natural segmentation”

Question marks
- energy resolution
- possible to make long crystals?
- cost

C. Malbrunot

PIONEER Collaboration

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more collaborators welcome!

Summary

- Pion decay: long history of challenging the SM
- PIONEER: Major new pion decay experiment pushing state of the art technology into low energy precision physics
- Goals:
  - R^{π} at 0.01 %
  - Pion beta decay at 0.06 % (in 2 steps)
- Approved to run at PSI, first test beam time just finished
- Time scale: 10-15 years
- New collaborators welcome!