PROCEEDINGS OF SCIENCE

Status of the AlCap experiment

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COMET (J-PARC) and Mu2e (Fermilab) are two experiments currently under construction that aspire to discover the neutrino-less muon to electron conversion BSM process. As a cooperation between the two experiments, AlCap was created to measure low energy particle emission spectra after nuclear muon capture in target materials aluminium and titanium. These measurements are important for understanding noise hit rates and radiation damage in COMET and Mu2e's detector systems. AlCap also explored muonic x-ray measurement methods that could be used for muon normalization. This talk will report the preliminary results collected at the Paul Scherrer Institut(PSI) in Switzerland during the 2015 run.

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1. Introduction

Nuclear muon capture on aluminium

$$\mu^- + ^{27}_{13}Al \rightarrow \nu_\mu + X + \{n,p,d,t,\alpha\} \tag{1.1}$$

is a dangerous background process for μ^- to e^- conversion experiments COMET[1] and Mu2e[2]. Their tracking detectors may have to be shielded depending on the rate and energy spectrum of the emitted protons after nuclear muon capture. This deteriorates the momentum resolution, while emitted neutrons can induce noise and electronic damage. Proton emission rate data for Al would be able to conclusively determine the need for such shielding but unfortunately, muon capture studies that were done in the past[3] had much higher energy threshold. Nuclear activation experiments[4] gave estimates of proton emission rates but with large errors. The best estimate so far was from charged particle emission spectra for silicon[5] as an approximate replacement for Al but Hungerford[6] notes that ^{27}Al would have much less charged particle emission. Therefore the urgent need for new measurement.

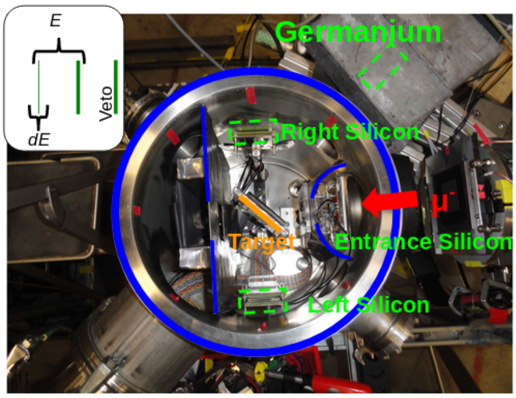


Figure 1: Experimental layout

Type	Thickness [μm]	DAQ run time [hr]
Al	50	25.2
Al	100	25.6
Si	52	8.4
Ti	50	10.4

Table 1: Run time of other target materials.

The AlCap experiment ran with ~26 MeV/c muons at a rate of 6-8 kHz from the PSI πE1 beam line. The setup consists of a high-purity germanium (HpGe) detector for muonic x-ray energy and time measurement along with two silicon detectors located perpendicular to the beam direction and labelled left- and right-silicon in Figure 1. The left(right) silicon detector consists of a thin, 52(53) μm and thick 1.535(1.545) mm sub-detector and for the right, a working veto[1] of 1.5 mm thickness. Muons pass through a silicon entrance detector, then a collimator before hitting the target. The analysis here use data from the Al 50 μm target. Other target data are shown in Table 1.

2. Analysis

Muons that enter through the entrance detector are defined by a 200 keV energy threshold cut to separate them from electrons. Muon pile-up events are those that occur within $\pm10\,\mu$s and they are rejected to prevent double counting of muonic x-rays and charged particles. Some muons scatter

[1]The left detector veto was under powered.

from the collimator and/or chamber walls but a vast majority reach the target. The muon beam was optimized for stopping muons in the center of the target by maximizing the x-ray count. Muons stopped in the Al atomic E-field emit x-rays of various energies before reaching the ground state. They can then either decay in orbit or be captured by the nucleus. Figure 2 shows the strongest

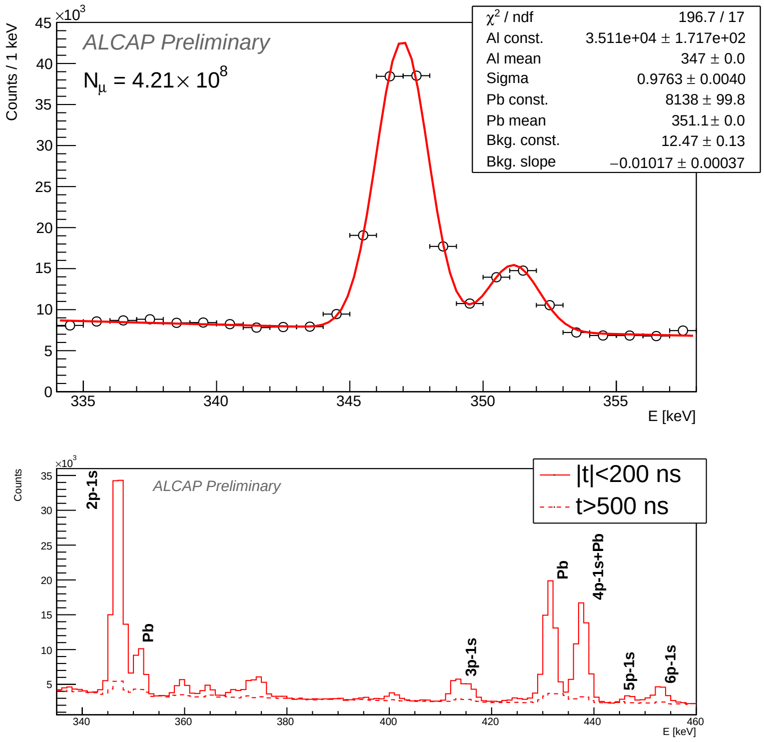


Figure 2: (top) Energy spectrum in the vicinity of the μAl 2p-1s transition. Pile-up protection time cut is used to prevent double counting. (bottom) Other μAl x-ray peaks that transition down to the 1s orbital.

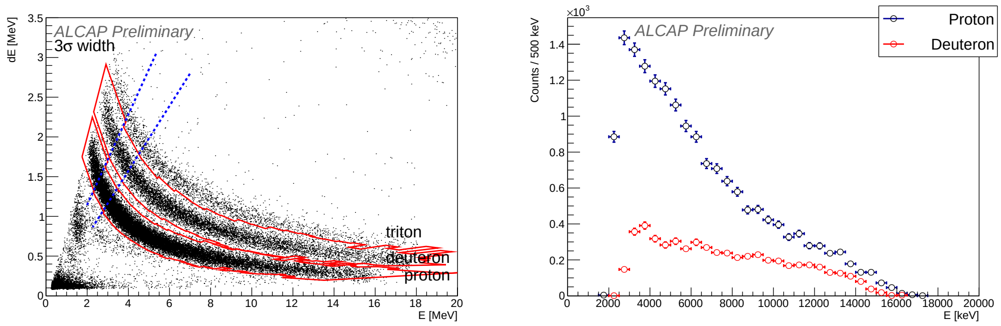
peak from μAl 2p-1s transition with an emission probability per muon stop, $P = 0.798 \pm 0.008$[7]. A background from μ^{206}Pb at about 351 keV can also be accounted for by performing a fit with a double Gaussian(with shared σ) and approximate the Compton background with an exponential function. The number of detected 2p-1s x-rays from Figure 2 is 85337 ± 1766 obtained by taking the integral of the Gaussian. The number of stopped muons is then $N_{stop} = (161 \pm 4) \times 10^6$ from Equation 2.1.

$$N_{stop} = \frac{C}{\varepsilon \times P} \tag{2.1}$$

where the HpGe detector acceptance at 347 keV is $\varepsilon = 6.63 \pm 0.10 \times 10^{-4}$ obtained from ^{152}Eu efficiency calibration. For charged particles, we start from the energy loss plot drawn by taking the energy deposit of the silicon thin detector, dE against total energy deposit, E. Figure 3 shows the plot for the right detector with proton and deuteron selection bands. The selection bands are constructed by first rotating the $\log_{10}$ of both axes 45° counterclockwise

$$(E, dE) \rightarrow (\frac{1}{\sqrt(2)}(\log_{10} E - \log_{10} dE, \frac{1}{\sqrt(2)}(\log_{10} E + \log_{10} dE)) \quad (2.2)$$

and then applying a triple Gaussian and a constant fit. (μ, σ) from the fit results for all the y_{trans} slices can be used for varying the PID cut tightness. Figure 3 is obtained with selection cuts from Table 2.



(a) Energy loss distribution (b) Measured energy spectrum

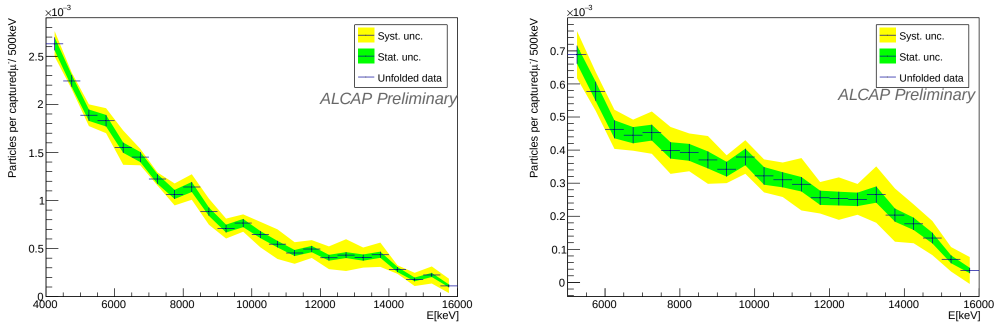
Figure 3: (left) Identification of the proton and deuteron bands in the left plot. A sample rotated-bin is indicated by dashed blue lines. (right) After the PID 3σ and other selection cuts are applied, the $E_{detector}$ spectrum for protons and deuterons are shown.

Reject pileup time	$t_{PP} < 10\,\mu s$
Accept coincidence time	$\lvert t_2 - t_1 \rvert < 100\,ns$
Accept lifetime	$t_2 > 500\,ns$
Accept PID	within 3σ
Reject veto	$e_3! = 0$

Table 2: Selection cuts for reducing accidentals and contamination from muonic lead capture. Cut efficiencies are close to 0.99.

3. Energy Unfolding & Systematic Errors

One of the challenges was due to charged particles of interest losing energy when traversing target material. It is necessary to employ unfolding techniques[8] to recover the initial energies. Using this method, a transfer matrix, M which is a map of probabilities relating $E_{detector}$ with E_{truth} is generated with Monte Carlo using GEANT4.10.03.p02 which also includes the Si detector acceptance. Muon stopping positions are inferred from active Si data which are assumed to be initial positions of emitted charged particles. Initial energies generated for protons are uniformly distributed from 0 to 20 MeV and up to 34 MeV for deuterons. The transfer matrix, M is generated from E_{truth} and $E_{detector}$ and used for unfolding. Figure 4 shows the unfolded results for protons and deuterons normalised to the number of muons captured by the Al nuclei (probability of muons captured from orbit[9] is 0.609.) and the lifetime cut is corrected with a factor of 0.56.



(a) Proton (b) Deuteron

Figure 4: The unfolded energy spectrum for protons and deuterons.

The systematic errors are calculated for each 500 keV bin. For Gaussian-like distributions like coincidence time and PID, the discrepancy between 1σ and 3σ after unfolding is regarded as systematic errors. Also, charged particle of different energies have different arrival time spreads and therefore the cuts need to be applied separately with 1 MeV bins. For lifetime cuts, the 300 ns (correction factor 0.71) and 500 ns cut results are compared. These are shown as yellow bands in Figure 4. Unfolding uncertainties are still under evaluation. Our detectors could measure energies down to 2 MeV but the energies of protons below 4 MeV and deuterons below 5 MeV could not be reliably unfolded due to missing entries in the transfer matrix so we do not show them.

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