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Progress Report 2013

Study of Muon Capture for Muon to Electron Conversion Experiments

The AlCap Experiment

PSI Experiment R-13-03, spokespersons P. Kammel and Y. Kuno

AlCap Collaboration

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Figure 1: Members of AlCap at PSI in December 2013

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1 Overview

The Mu2e [1] (FNAL) and COMET[2] (J-PARC) experiments seek to determine the branching ratio for the charged lepton flavor violating process $\mu^- N \to e^- N$ to better than 10^{-16}, which is a factor of 10,000 improvement compared to the current best limit established by SINDRUM II [3] (PSI). The AlCap experiment is a combined effort of the Mu2e and COMET collaborations to study important background reactions from muon capture in candidate target materials (Al, Ti), which are required to optimize the new muon-electron conversion experiments.

In 2013 the AlCap collaboration performed its first run at PSI, focusing on work package WP1: "Charged Particle Emission after Muon Capture". Protons emitted after nuclear muon capture in the stopping target dominate the single-hit rates in the tracking chambers for both the Mu2e and COMET Phase-I experiments. The goal of WP1 is a measurement of the rate and spectrum of these protons, both of which have never been measured in the relevant low energy regime of 2.5 to 15 MeV.

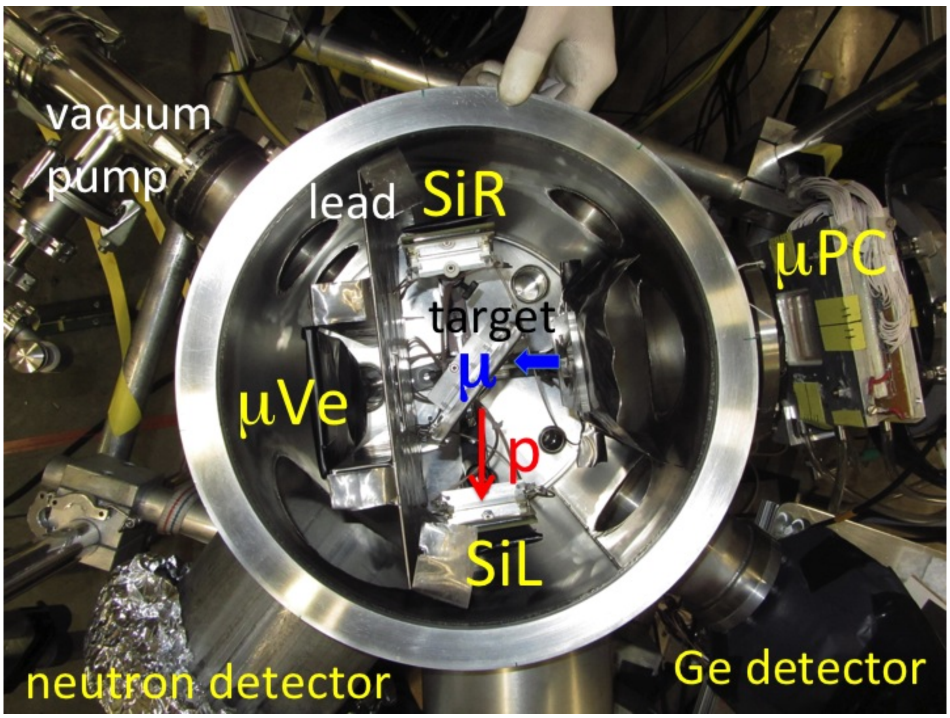


Figure 2: AlCap detectors inside target vacuum vessel.

The first run, denoted R2013, was performed at the πE1.2 beam line area from November 26 to December 23, 2013. Low energy muons were stopped in 50 and 100 μm Al targets and detected by silicon detector packages, labeled **SiL**eft and **SiR**ight according to their position relative to the muon beam. Several other detectors including muon beam counters, a germanium detector to observe muonic X-rays, plastic scintillators to detect electrons and neutron detectors completed the system.

As the run ended very recently, we can only present a very preliminary report here. Still, we wanted to inform the committee about our progress and plans. As the run heavily relied on the work of seven Ph.D. students, most of which had not worked on accelerator experiments before, we chose a picture of the team for the cover page to emphasize the fertile training ground PSI can provide for a new generation of young nuclear/particle physicists.

2 Report on First AlCap Run R2013

2.1 Development and Performance of Subsystems

2.1.1 Vacuum Chamber

The main silicon detectors for the R2013 measurement are located inside a vacuum vessel as shown in Fig. 2 and 3. The side walls and bottom flange of the vessel provide several vacuum-feedthroughs for the high voltage and signal cables for the silicon and scintillator detectors inside the chamber. In addition, the chamber is equipped with several lead collimators to quickly capture muons that do not stop in the actual target. For operation of the system, a vacuum of $< 10^{-4}$ mbar was necessary. At the beginning of our setup phase, significant effort went into establishing good enough pumping speed to reach this pressure within less than an hour, in order to minimize downtime after a target change or other detector work inside the chamber. As can be seen in Fig. 2, several components inside the chamber acted as an outgassing source so that our intial pump stand connected by a bellow from below the chamber was not quite sufficient. With the help of the vacuum group at PSI, several changes provided

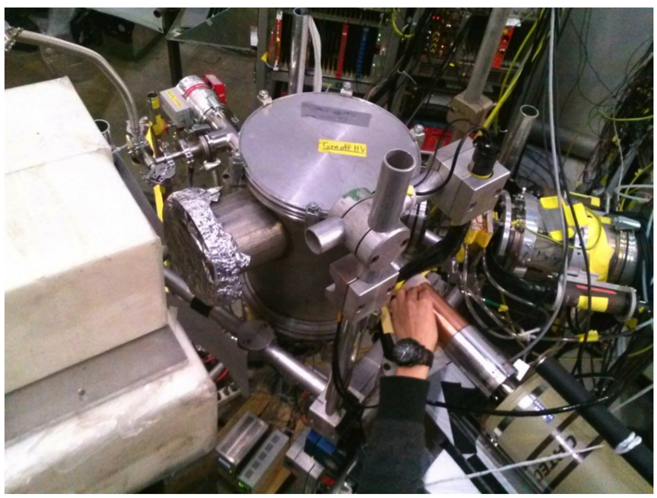


Figure 3: Vacuum chamber in beam line

the necessary improvement to maintain high pumping speed. These included the usage of a better suited, larger port on the side, a better optimized arrangement of the two pumps, elimination of some leaks and the addition of flushing with dry nitrogen during venting of the chamber. In the final arrangement, we consistently reached 10^{-4} mbar within 45 minutes after closure of the chamber's top flange.

2.1.2 Beam

Fig. 2 shows the experimental setup. The muon beam enters from the right of the image and hits the target, which is placed at the center of the vacuum chamber and orientated at 45 degrees to the beam axis.

In order to define stopped muon events, four muon counters are used: a 500 μm thick scintillator muon trigger counter (μSC); a muon anti-coincidence counter (μSCA) surrounding the trigger counter with a hole of 35 mm diameter to define the beam radius; and a multiwire proportional chamber (μPC) that uses 24 X wires and 24 Y wires with at 2 mm intervals. This detector system belongs to the MuSun experiment and was well tuned in advance. A muon veto counter (μVe) is placed at the downstream end of the chamber and is used to reject muons that pass through the stopping target.

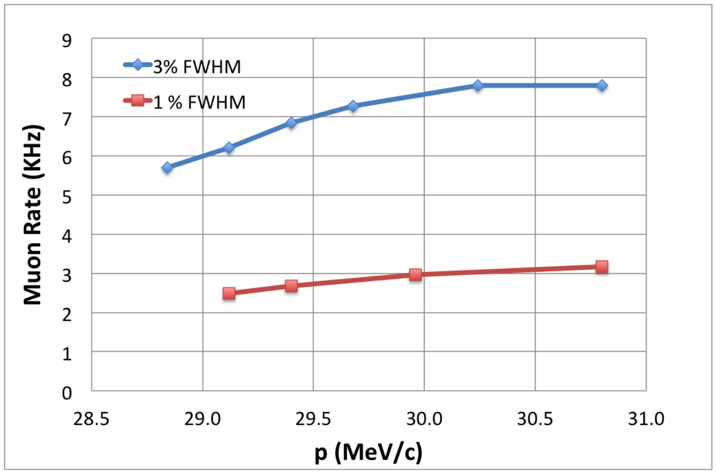


Figure 4: Measured muon rate (kHz) at low momenta. Momentum bite of 3 and 1 % FWHM, respectively.

One of the main requirements of the AlCap experiment was a muon beam with narrow momentum bite in order to achieve a high fraction of stopping muons in the very thin targets. For part of the experiment the target was replaced with one of the Si detector packages which allowed an accurate momentum and range calibration (via range-energy relations) of the beam at the target. Fig 4 shows the measured muon rates as a function of momentum for two different momentum bites. Fig. 5 shows an example of the resulting energy spectra.

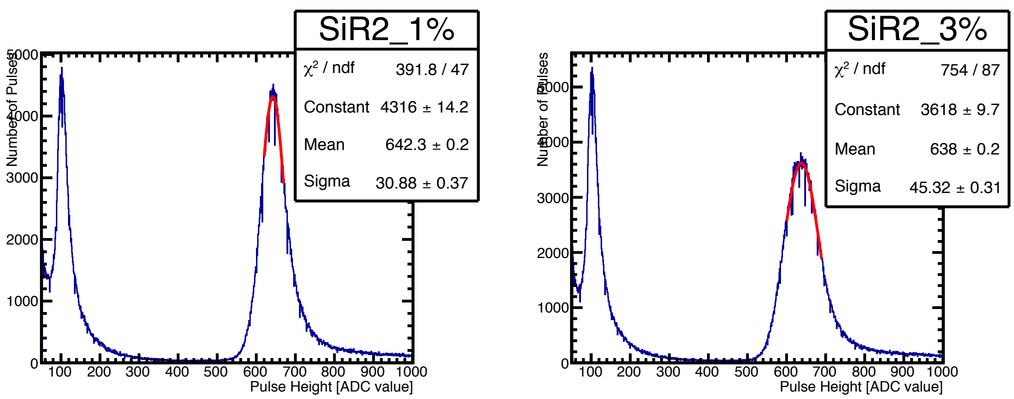


Figure 5: Energy deposition at 36.4 MeV/c incident muon beam in SiR detector in target position. The peak at low energy is due to beam electrons, the peaks at higher energies are due to muons. Momentum bite of 1 and 3 % FWHM on left and right hand side, respectively.

2.1.3 Silicon Detectors

Charged particles emitted from the target are measured with two detector packages located symmetrically at 90 degrees of the target, SiL and SiR in Fig. 2. Each arm consists of: one ΔE counter, a 65 μm thick silicon detector, divided into 4 quadrants; one E counter made from 1500 μm thick silicon, and one plastic scintillator to identify electrons or high energy protons that pass through the silicon. The area of each of these silicon detectors and the scintillators is 50×50 mm^2.

Achieving good energy resolution was particularly challenging for the thin silicon detector, as each quadrant had a large capacity of 1 nF. Both noise and pickup suppression had to be carefully optimized in the real PSI accelerator environment which differed significantly from a more benign lab environment. Optimization of the fast timing signals proved another challenge. After improving the feed-through flanges during the set-up phase of the experiment with isolated ground connections, good electronic resolution of 55 - 76 keV FWHM was achieved in the thin silicon detectors. In future runs we would improve the shielding and cable quality of the critical preamplifier connections to increase the stability of the system.

2.1.4 Ge and Neutron Detectors

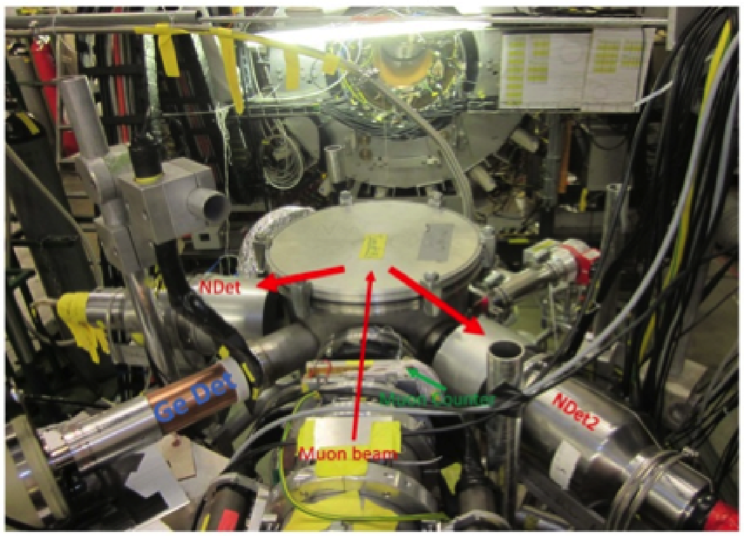


Figure 6: Setup of two liquid scintillators outside the vacuum envelope for neutron detection.

In order to normalize the number of stopped muons, an n-type, coaxial germanium detector was used to measure the muonic X-rays (see Fig. 6). This detector is equipped with a transistor reset preamplifier so that it can work in a high count rate environment. The energy resolution is better than 2 keV for all peaks of a calibrated Eu-152 source. The detector was installed outside of the vacuum chamber, about 30 cm from the target. The absolute efficiencies for the K_α lines of aluminium (346.8 keV) and silicon (400.2 keV) were determined to be 3.56×10^{-4} and 3.16×10^{-4} respectively, see Fig. 7.

We also were able to perform preliminary measurements of neutron emission. Two BC501 neutron counters (12.5 cm diameter and 12.5 cm depth) were borrowed from the MuSun experiment, and placed outside the target chamber on both sides of the muon beam. The counter on the beam left (right) was placed at approximately 4 (7) cm from the outer surface of vacuum vessel, see the Fig. 6. The detectors were calibrated with Co-60 and Cs-137 radioactive sources, and tuned for an energy range of approximately 2 to 10 MeV. The counters were read by 12-bit 170-MHz FADCs. Neutron data were collected for Al-l00, Al-50, SiR and Si16 targets using the MIDAS framework and were stored in MIDAS banks. Data analysis is now beginning, starting with neutron/gamma separation based on pulse shape discrimination.

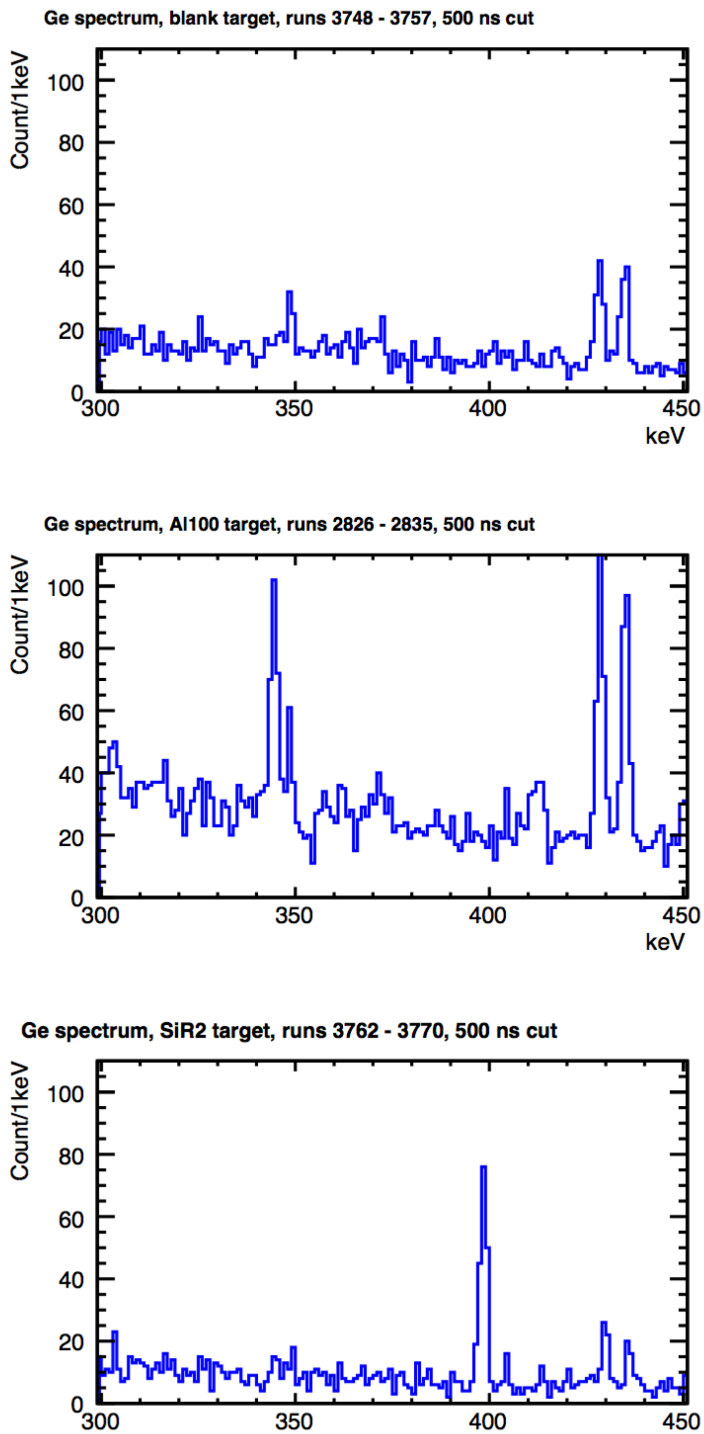


Figure 7: Germanium detector spectra in the range of 300 - 450 keV with different targets: no target, silicon 65 µm, and aluminium 100 µm. The K_α of aluminium (346.8 keV) and silicon (400.2 keV) are clearly visible, the double peaks at 431 and 438 keV are from the lead shield.

2.1.5 Data Acquisition System

The Data Acquisition System (DAQ) of the AlCap experiment provided the readout of frontend electronics, event assembling, data logging, hardware monitoring and control, and the run database of the experiment. It was based on MIDAS framework and consisted of two circuits, *i*) a "fast" circuit for synchronous data readout from the frontend electronics instrumenting detectors, and *ii*) a "slow" circuit for asynchronous periodic hardware monitoring (vacuum, Ge detector filling with liquid nitrogen, etc.). The fast circuit consisted of three computers, two frontend computers and one computer serving both as a frontend and as a backend processor. The slow circuit consisted of one computer. All computers were running Linux operating system and connected into a private subnetwork.

Where possible, the AlCap experiment recycled the computers and electronics from MuCap and MuLan experiments. The detectors were read out using waveform digitizers and flash analog-to-digital converters (FADCs). Suitable sampling frequencies were used to digitize fast and slow signals from detectors. Si detectors were read out by 12-bit 170-MHz FADCs custom built for the MuCap experiment. FADC boards feature network-based data readout interface. To maximize the data throughput, each of the four FADC boards was read out through separate network adapter. Two new digital electronics modules, a 14-bit 32-MS/s CAEN VME digitizer (model 1724) and a 12-bit 250-MS/s CAEN desktop digitizer (model DT5720), were used to read out the Ge detector (timing and energy, slow signals) or scintillator detectors (fast signals). For redundancy, all beam monitors (μSC, μSCA and μPC) were also read out by the CAEN time-to-digital converter (TDC) model V767 which was "available for free" as a part of the beam detector package kindly provided by the MuSun experiment.

The data were collected as dead-time-free time segments of 110 ms followed by about 10-ms-long time intervals used to complete data readout and synchronize the DAQ. Such data collection approach was chosen to maximize the data readout efficiency. A similar approach was successfully used in MuLan, MuCap and MuSun experiments at PSI. During each 110-ms-long data segment all detector data were first written into on-board memories of frontend electronics and either read out in a loop (CAEN TDCs and CAEN digitizers) or streamed (FADCs) into the computer memories. Signals from each detector were digitized independently by threshold crossing. The thresholds were adjusted as low as possible and individually for each detector. The time correlation between detectors will be established in the offline analysis. The clock signals for digital electronics modules were derived from a single master clock unit.

2.1.6 Analysis Framework

The analysis framework consists of two separate programs. A MIDAS based analyzer framework, `alcapana`, processes the raw data and passes its ROOT data output to a second stage, `rootana`, where most of the physics analysis is performed. Because the MIDAS analyser is intended to be usable as an real-time component of a MIDAS DAQ, this approach allowed us to develop analysis modules that could also be used online to generate plots quickly.

The DAQ system generated MIDAS files which stores the data as a stream of MIDAS 'banks'. In the AlCap DAQ, each bank corresponds to a single channel on a digitizer and was named according to a predefined convention. The first step of the analysis framework is to convert this data into so-called `TPulseIslands`, which contain the bank name, the ADC values of the digitized samples and the time stamp of the first sample. This conversion is performed using `alcapana` and the resulting objects are stored in a ROOT output file as a TTree.

The next step of the analysis is to obtain summary parameters of the pulses from the digitized samples. The parameters of primary interest are the amplitude and time of the peak and the integral of the pulse. This conversion is done by a `rootana` module, which also allows some flexibility in the exact algorithm that is used to calculate these parameters. The objects produced by this stage are called `TAnalysedPulse`s. At this point in the analysis chain, it is also possible to perform individual pulse finding which is for example important to detect muon pile-up in the target. A first iteration of this was developed late on in the run and so further development is still required.

As well as storing the raw data in a ROOT file, `alcapana` also stores information from the MIDAS online database (ODB), such as a map between detector channels and MIDAS bank names, timing offsets for each channel, and energy calibration constants. These can then be accessed by both `alcapana` and `rootana` for either online or offline analysis.

At this stage, preliminary plots have been produced using `TAnalysedPulse`s as was done during the run. However, there are further enhancements that can be made to the analysis framework. Firstly, the pairing up of fast and slow pulses from the same detector needs to be implemented. This will entail looping through all fast and slow pulses from each detector and checking for coincident pulses. Once we have these paired pulses (provisionally called `TDetectorPulse`s), we can obtain more accurate pulse parameters, for example, using the time of the pulse from the fast channel but the amplitude information from the slow. This will also reduce the impact of pile-up on the amplitude measurement, by using the improved time resolution of the fast channels to separate the overlapping amplitudes in the slow.

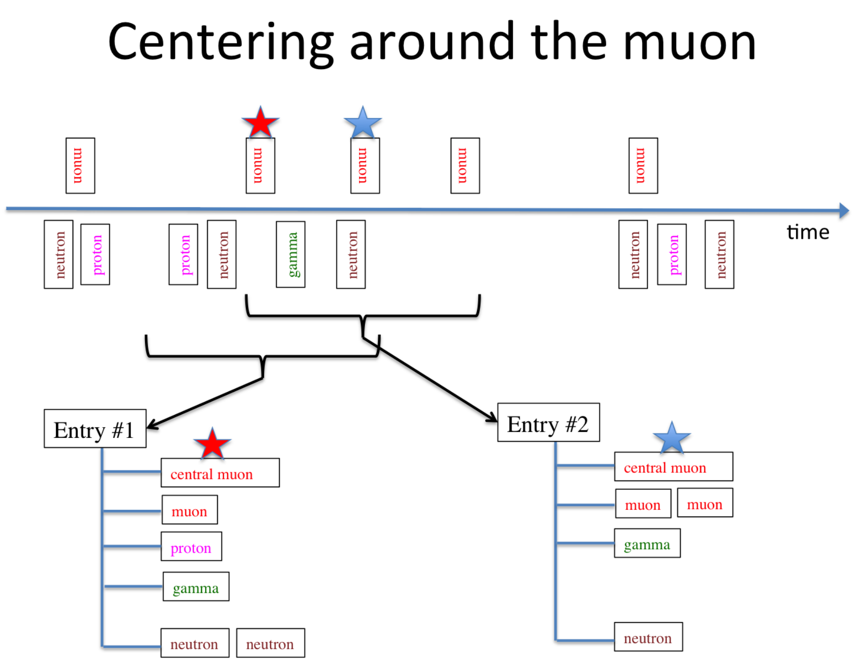


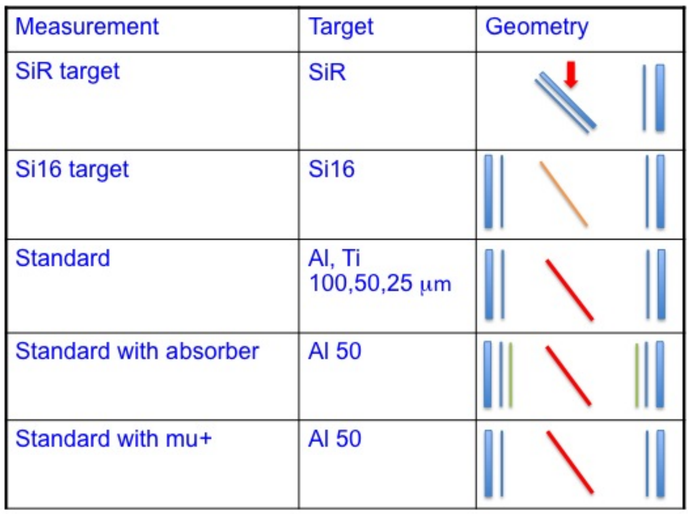
Figure 8: Figure showing the planned format of the ROOT tree for analysis.

Another feature we would like to implement is the reformatting of the ROOT tree to be centered around the muon. Currently, each entry in the tree corresponds to the 110 ms block length from the DAQ. The plan is to iterate through the tree to find stopped muons and to take any events within a certain window around this muon from every detector (see Fig. 8). This will make it much easier to look for coincidences and apply cuts, thereby bringing the end goal of particle numbers and momentum distributions within sight.

To conclude, the analysis framework is still very much a work in progress. However, a strong foundation has been developed during the run and it will continue to be built upon in the coming weeks and months ahead.

2.2 Summary of Measurements

After commissioning, tuning and calibrating the experiment, we spent about ten days on the planned measurements, shown in Fig. 9. The program started by using SiR as an active target, followed by a measurement on a 65 μm thin silicon detector segmented into 16 strips (Si16). These measurements with an active target served several purposes. First, it allowed the selection of clean muon stops in the target to calibrate the X-ray detector and identify background components. Second, it will allow a comparison with the only low energy proton spectrum available in the literature [4], obtained in silicon with the same active target technique. Finally, it will help to calibrate the response matrix for energy losses in the target.



Measurement	Target	Geometry
SiR target	SiR	
Si16 target	Si16	
Standard	Al, Ti 100,50,25 μm	
Standard with absorber	Al 50	
Standard with mu+	Al 50	

Figure 9: Sketch of planned measurements. Detector packages left/right indicated by thin/thick silicon detector combination. Standard targets red. Special targets for calibration and systematic studies. μ^+ and absorber are background studies.

After the runs with the Si targets, we started the Al target program. At each target thickness we tuned the beam to determine the optimal muon momentum that maximized the number of stopping muons inside the target by counting the number of characteristic Al muonic X-rays seen in the germanium detector.

A summary of all the data collected is presented in Table 1. A representative ΔE versus total energy plot is displayed in Fig. 10, which is used for particle identification and to suppress background.

Key items of the program outlined in Fig. 9 were achieved. However Ti targets and 25μm Al could not be measured because of the limited run time. Also the Si16 target detector was only partially read out.

Target	**Momentum scaling factor**	**Run time (h)**	**Number of muons**
Si 1500 μm	1.32	3.07	2.78×10^7
	1.30	12.04	2.89×10^8
	1.10	9.36	1.37×10^8
Si 65 μm	1.06	10.29	1.72×10^8
Al 50 μm	1.09	14.37	2.94×10^8
	1.07	2.56	4.99×10^7
Al 50 μm	1.07	51.94	8.81×10^8

Table 1: Run statistics. Momentum scaling normalized to 28 MeV/c.

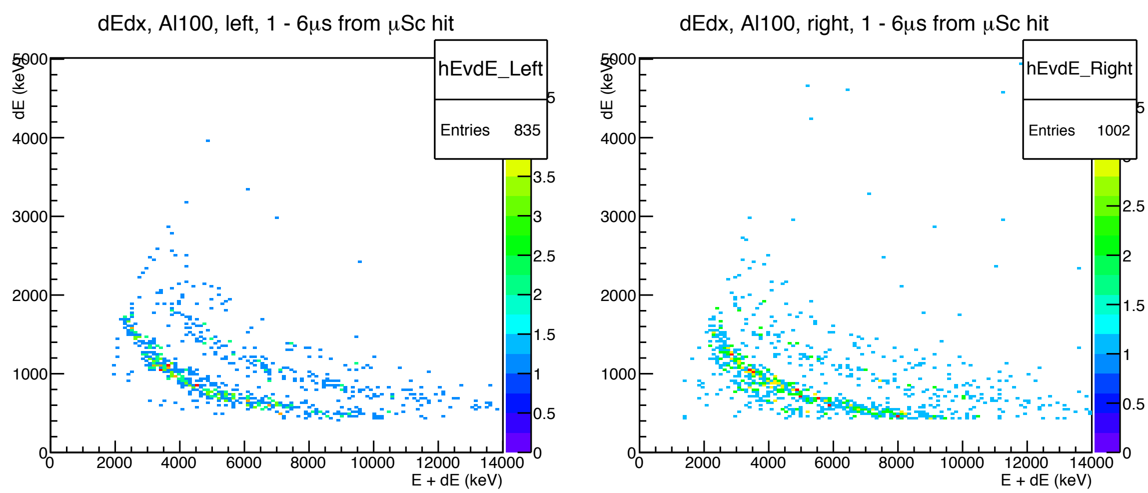


Figure 10: ΔE vs. ΔE + E scatter plots for SiL and SiR detector packages. Here ΔE is the energy deposition in the thin Si detector and ΔE + E refers to the total energy deposited in both Si detectors. The bands, starting from the bottom, correspond to protons, deuterons and tritons emitted in muon capture.

3 Plans and Outlook

As the first AlCap run has just ended we decided to postpone our next Beam Request until 2015. This year we will focus on

- **Analysis R2013**. The framework has to be developed towards full physics analysis capabilities. Distinct analysis topics are the thick silicon measurements, where protons are stopped inside the detector, the thin silicon measurements, where the protons escape and are detected outside and finally the aluminum targets. Background and consistency between the active and passive target analyses and the symmetric detector packages have to be carefully checked. Depending on the outcome of these analyses we might perform additional Al measurements and will collect the missing Ti data.

- **Preparation of neutron detectors**. Initial neutron data has been taken in R2013. We plan to carefully calibrate the neutron detectors at TUNL or LANL to measure their response matrix. This is a prerequisite for the required unfolding of the measured spectra. The stability of different unfolding codes will be investigated. After that we are ready for a dedicated neutron measurement, which would consist of a low mass set-up to minimize scattering corrections.

After this analysis is finalized and the neutron detectors are calibrated, we anticipate to ask for beam time early 2015.

4 Acknowledgements

We want to express our gratitude to the terrific PSI staff. Without their help, we would not reached production quality in our first run. This includes, in particular, Stefan Ritt, who supported us as the PSI contact person, Konrad Deiters and his group, for providing his studio and infrastructure for the preparation of the experiment, Claude Petitjean for beam tuning, the vacuum group, who taught and helped us in many respects, the IT department for assisting in refurbishing and upgrading our frontend computer, the electronics group, the survey group and last, not least, the Hallendienst.

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