Update on the AlCap Experiment*

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Abstract

The AlCap experiment studies the emission products following muon capture on an aluminium nucleus. Such a measurement is important in the context of the up-coming muon-to-electron conversion experiments, COMET and Mu2e, which will both use an aluminium stopping target. Despite this, and the potential nuclear and astrophysical implications, the existing range of measurements is incomplete, with the majority of measurements on proton and neutron emissions already some 40 years old.

AlCap first ran in 2013, and will have run twice more by the end of 2015. It is a joint effort by the Mu2e and COMET collaborations.

INTRODUCTION

Both the COMET experiment at J-PARC [1, 2] and the Mu2e experiment at Fermilab [3], aim to improve the search for muon-to-electron conversion by around four orders of magnitude compared to the current limit, set by the SINDRUM-II experiment [4]. Such an increased sensitivity is achieved by the use of a pulsed muon beam and a relatively light stopping target, made of aluminium. Significant background suppression can be achieved since the lifetime of the muon in aluminium is 864 ns, compared to the typical beam flash time of 200 ns. However, this poses an issue for the next generation of μ-e conversion experiments since the stopping of negative muons in aluminium has not been well studied.

In particular, whilst the decay of a muon bound to a nucleus can be relatively well theoretically modelled [5], the nuclear capture of the muon is much harder due to the complexity of the nuclear environment. Captured muons cause emission of various particles, through both prompt and nuclear relaxation mechanisms, which in general can be written as:

$$\mu + N(A, Z) \to \nu_\mu + N^*(A, Z-1) \tag{1}$$

$$N^*(A, Z-1) \to N(A', Z') + X \tag{2}$$

where X is any combination of additional final state particles, such as protons, neutrons, photons, deuterons, alpha particles and so on.

Although producing a 105 MeV electron following muon capture is highly unlikely, the emission of these final state particles causes several additional difficulties in the design and operation of COMET and Mu2e for several reasons. Firstly, neutral particles such as neutrons and photons can cause difficulties for any electronics systems near the detectors. Emitted neutrons can also create fake vetoes in the active Cosmic Ray Veto systems which are based on scintillating bars that a neutron recoil could trigger. If the neutron flux were too high, shielding of the veto system and more radiation-hard electronics might be required. On the other hand, the charged particle emissions will increase the detector occupancy. Since low energy protons are strongly ionising they can blind large parts of the detector to any signal electron. Controlling these particles would require some additional absorbing material between the target and the detector, the downside of this being that any signal electron will also be affected essentially reducing the resolution of the detector. It is important then that the rates and energies of the emitted particles be well understood in order to optimise the designs of the upcoming μ-e conversion experiments.

As a joint collaboration between COMET and Mu2e, AlCap therefore aims to measure:

- the emitted charged particle rates and spectra down to 2.5 MeV with a 5-10 % resolution,
- X-ray and gamma spectra and the relative intensities in the various peaks,
- the neutron spectrum and rate from 1 to 10 MeV.

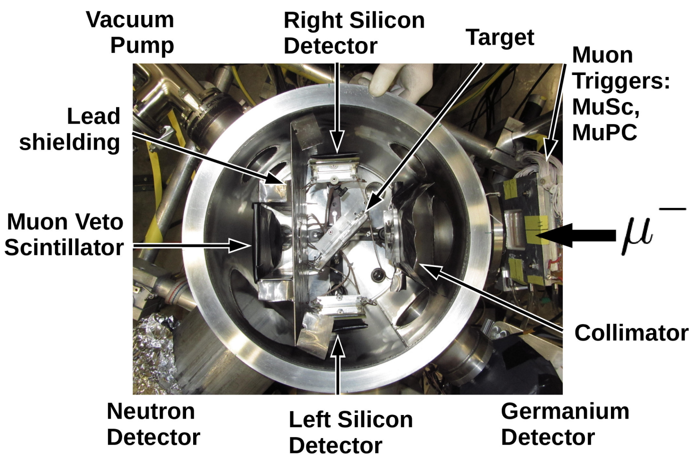
Work towards these goals has been split between three separate runs, each taking place at the Paul Scherrer Institute (PSI), near Zurich. The first run, Run 2013, took place during the winter of 2013, focussed on charged particle emission but also ran some preliminary neutron measurements. Two runs will have taken place during 2015 with the first, Run 2015a, held in June and focussed primarily on neutral particle emissions (photons and neutrons). Finally, Run 2015b will run during November 2015 and repeat and improve the charged particle measurement from Run 2013.

RUN 2013: CHARGED PARTICLES

The 2013 run dealt primarily with measuring the charged particles emitted following muon capture, and took place from mid-November to the end of the year using the piE1 beamline of the Swiss Muon Source (SμS) at the Paul Scherrer Institute (PSI). A brief description is provided here whilst more information is provided in [6, 7] .

The primary aim for this run was to obtain the emission rates and distributions for low energy protons, deuterons, tritons and alphas particles. To reduce the amount of scattering of the charged capture products both the aluminium target and detector systems were placed in a vacuum and the target size kept to a thickness of less than 1 mm. At such a thickness a beam momentum of around 30 MeV was expected to be roughly optimal to stop all muons in the target. At this energy the muon rate in the piE1 beam was roughly 3-6 kHz, running in a continuous mode.

Fig. 1 shows the experimental set-up for this run. The muon beam reaches the target by passing through several beam monitors (namely, a scintillator paddle, muSc, and a scintillator paddle with a hole centred on the beam axis, muScA, which together with the muSc



(a) Setup

Dataset	Target	Run Time (hrs.)
Al50	50 μm Al.	50
Al100	100 μm Al.	17
Si16	65 μm Si.	8
SiR2 (Active)	1.5 mm Si.	8

(b) R13 Datasets

FIG. 1: Experimental set-up and acquired datasets from Run 2013. See text for a full description of the experiment set-up.

defined an on-axis muon entering the chamber, and finally a proportional wire chamber which gave a measurement of the beam profile before the chamber), entering the vacuum chamber through a light-sealed mylar window and passing a lead collimator.

The stopping target was mounted at 45° to the beam to reduce the amount of target material the charged daughter products would have to pass through before reaching the two charged particle detectors, which sat to the left and right at 90° with respect to the beam direction at the target position. Behind the stopping target sat another scintillator paddle to veto muons that did not stop in the target. All the remaining surfaces that faced the beam were covered in lead so that secondaries from capture of scattered muons could be removed by a prompt-time cut, since the muon lifetime in lead is only 75 ns.

Each of the two charged particle telescopes consisted of a pair of silicon detectors and a punch-through scintillator paddle. The first of the silicon detectors was only about 65 μm in thickness and divided into 4 quadrants, whilst the second was a single silicon detector of thickness of 1.5 mm. Information on both the particle's identity and energy can be obtained using a coincidence between the thick and thin silicon detectors. Although a vacuum pressure of around 10^{-2} Pa would have been sufficient to reduce multiple scattering, to prevent arcing between the quadrants of the thin silicon detector the vacuum was maintained at below 10^{-4} Pa.

Finally, outside of the vacuum chamber were placed a germanium detector to measure the X-ray and gamma spectrum as well as liquid scintillator neutron detectors.

The 64 or so detector channels were digitised on a mix of custom-built Flash ADCs and CAEN digitizers. All of the silicon detector outputs were passed through both fast and slow analogue filters to provide better time and energy resolution of the individual pulses. Each channel was then operated in a self-trigger mode within a DAQ-active gate that was initiated by the global DAQ system. The DAQ-active gate lasted 112 ms and typically had a dead-time between gates of about 10 ms.

Datasets

Several different datasets were obtained with both silicon and aluminium targets. Fig. 1b gives a summary of the different datasets obtained in the 2013 run.

Runs dedicated to calibration, background measurements and other cross checks were also performed. These included the use of one of the silicon packages as an active target, which was used both to tune the beam and as a means to cross-check aspects of the analysis.

Preliminary Analysis

Stopped Muon Normalisation

When negative muons come to a stop in a material they become bound to the nucleus. An electromagnetic cascade down to the lowest energy atomic orbital takes place over very short time scales, with the emission of characteristic X-rays corresponding to the transition energy between the muonic atom energy levels. To determine the number of stopped muons during the run, the X-rays from this cascade were observed using the external germanium detector. In particular, the $2p$–$1s$ line was used, since it has the highest relative intensity and is well

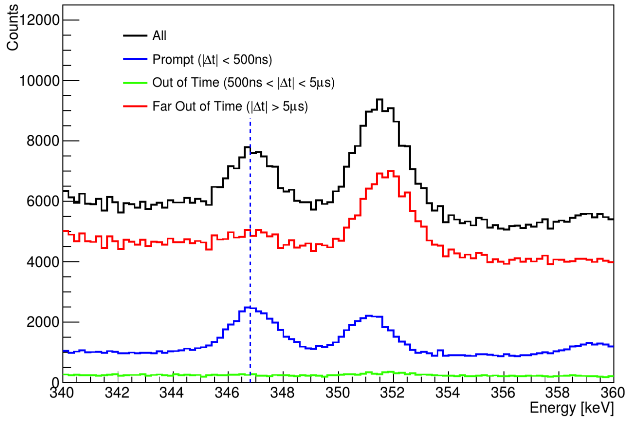


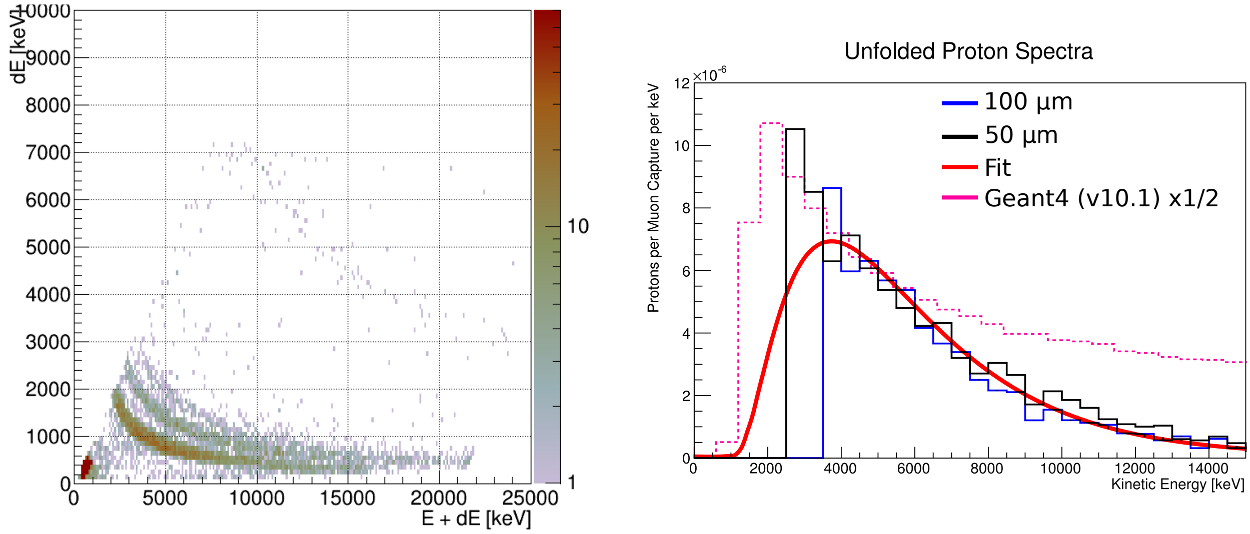
FIG. 2: A close up of the $2p$–$1s$ transition line at around 347 keV used for the normalisation of stopped muons for the Al100 dataset. The blue solid line shows x-rays coming within 500 ns of muon entering the chamber as determined by the muSc entrance scintillator that was fitted with two Gaussians and a linear background. The second peak at around 352 keV is believed to be a combination of X-rays coming from the radioactive decay chain of lead and thallium.

separated from any nearby background peaks. A prompt timing cut was made between the germanium detector and the incoming muon scintillator paddle (muSc) to remove accidental backgrounds. The same muon pile-up protection cut was also applied as described below for the charged particle analysis. Fig. 2 shows the X-ray spectrum from the Al100 dataset around the $2p$–$1s$ peak. The peak was fitted with a Gaussian plus a linear background and the area under the peak extracted. The detector's acceptance was found using an Eu-152 source and cross checked with a Monte Carlo simulation, and the efficiency at a given energy was obtained by an empirical fit to calibration data. The observed value was scaled by this to give the total number of muons stopped during a run.

Charged Particle Measurement status

For particles stopping in the thick silicon, a coincident hit in the thin allowed for a measurement of both the particle's dE/dx and its total energy. These two values taken together provide for particle identification as shown for simulated data in Fig. 1a. Variation in the dE/dx due to different angles of incidence was small, given the distance from the target to the detector and was estimated to be around 10%, far less than the separation of the different bands. This set-up allowed for the distinction of protons, deuterons, tritons and alpha particles, over a range of energies from about 2 to 10 MeV. So far only the proton band has been analysed although it is thought that sufficient data was taken to estimate an integrated rate for at least deuteron emission.

The selection criteria for detecting a charged particle used the following cuts: coincidental hits in both thin and thick silicon (to remove accidental backgrounds and noise pulses); coincidence with a Muon-like hit in the muSc (to ensure the particles came from a muon a hit in the muSc must have occurred with 10 μs and have an amplitude corresponding to the typical energy deposited by a muon); no other muon hit in muSc within 10 μs (removes the mis-identification of protons coming from close-arriving muons, which would complicate



(a) Data

(b) Preliminary Proton Spectrum

FIG. 3: Charged particle analysis and preliminary results. (a) Bands corresponding to the observation of different particle species at one of the silicon detectors. (b) The preliminary unfolded proton emission spectra from the two aluminium datasets of R2013. Only the range between 3.5 and 10 MeV is considered reliable, since outside of this range the unfolding of the different datasets does not seem stable. The uncertainty on each bin is still under analysis, so no error bars are shown here. Additionally the spectrum produced by standard Geant4 (v10.1) is shown, scaled by a factor 1/2.

the normalisation and timing distributions); time since muSc hit must be greater than 100 ns (removes scattered muons and protons coming from capture in the lead shielding or collimator).

Once a hit is identified as coming from a charged particle emitted after capture in the stopping target, particle identity cuts are applied based on either a geometrical cut on the dE/dx plot or using a probability that the event was from the desired particle, based on a Monte Carlo simulation. Fig. 3a shows the raw spectrum obtained after applying the above cuts for one of the silicon telescopes.

Preliminary results

Once the raw spectrum has been acquired, to obtain the 'true' spectrum following muon capture and account for scattering in the target and the detector's acceptance, a Bayesian unfolding procedure is applied using the RooUnfold tool-kit [8]. The total response matrix for the combined target-detector system was found using a Monte Carlo simulation based on Geant4 [9]. For protons below around 2.5 MeV the acceptance drops to zero since below this energy they are unable to penetrate the target and thin silicon detector. Above around 4 MeV the response becomes roughly linear.

This procedure has been successfully applied to the aluminium datasets, however, for the active target runs using the silicon detector as the target, the statistics have been too low to perform a successful unfolding and so analysis of those datasets cannot continue. This is unfortunate as it could in principal provide a good cross check of the unfolding process since more information on the distribution at the target is known. This is an area that future runs will address.

Fig. 3b shows the unfolded spectra where it can be seen that approximate agreement is found from around 3 to 10 MeV between the different 50 μm and 100 μm aluminium datasets. This region has been fitted with the same function as previously used by the COMET and Mu2e collaborations [10], which is empirically motivated and given by the equation:

$$f(x) = \left(1 - \frac{T_{\mathrm{th}}}{x}\right)^{\alpha} \exp\left(-\frac{x}{T_0}\right), \tag{3}$$

where T_{th} is a threshold energy, expected to relate to the Coulomb barrier and Fermi energy of nucleons in the intermediate nucleus, α is a shape parameter that controls the form of the spectrum around the emission threshold, and T_0 should be related to the thermal energy associated with the nucleons in the free-Fermi gas nuclear model.

Based on this fit, the total proton emission rate per muon capture is estimated to be around $3.3 \pm 0.4\%$ although it must be stressed that this is a preliminary value with the final analysis and error assessment still ongoing. At this stage, the leading systematic errors are due to the unfolding process, misalignment in the geometry, uncertainties in the muon stopping distribution and beam profile at the target, and energy calibration of the silicon detectors. Each of these issues will be addressed directly by improvements in the upcoming Run 2015b.

The impacts of this measurement are already being felt for both COMET and Mu2e. Mu2e is re-optimising their proton absorber whilst for COMET Phase-I it has been removed. Furthermore, it is clear that the built-in modelling of muon capture in Geant4 needs improving, since it produces a much harder spectrum with a rate about 7 times to large, as shown by the overlay of the preliminary fitted AlCap spectrum to that from Geant4 in Fig. 3b.

RUN 2015A: NEUTRAL PARTICLES

Although the 2013 run did include neutron and X-ray detectors, the need for a vacuum chamber and thin target complicated the neutral particle measurement and reduced the final statistics. To improve the situation a two week run dedicated to measuring the neutral particle products without the vacuum chamber and with a thicker stopping target took place in June 2015. This used the piE5 beamline also at PSI, and future home to the Mu3e experiment [11]. With the thicker stopping target, a higher muon beam momentum of about 36 MeV/c could be used which increased the muon rate to about 10 kHz.

Setup

Unlike the charged particle run, no vacuum chamber was needed for the neutral particle measurement. As such, detectors were placed facing a central stopping target directly which improved acceptance and reduced backgrounds from scattered muons. Neutrons from the muon stopping target were observed by two liquid scintillator neutron detectors, whilst a germanium detector measured the muonic X-rays and gammas. A LYSO array was also included in the set-up to monitor very hard gamma rays from the capture process.

As well as the removal of the vacuum chamber and the thicker target, several other improvements from the 2013 run were included. In particular, better ADCs increased the DAQ stability and a continuous input test pulse has improved the time calibration of signals. Furthermore, the neutron detectors had been calibrated before the run at the Triangle Universities Nuclear Laboratory (TUNL), in North Carolina, USA.

The data taken from Run 2015a is summarised in Table I. As well as measuring neutrons and photons from muon capture on aluminium, some time was dedicated to other targets. In particular, titanium, which is an alternative stopping target material for COMET and Mu2e, was studied as well as lead and water to understand potential backgrounds for this measurement.

Activation Study

The current baseline for COMET and Mu2e uses the prompt X-ray spectrum from the electromagnetic cascade of the stopped muon to estimate the number of stopped muons. However, one alternative idea is to look at X-rays coming from decays of the radioactive magnesium isotope Mg-27, left from muon capture. This might suffer fewer backgrounds than the prompt X-ray spectrum and so might be more reliable. To confirm this method a target was activated and monitored with a second germanium detector away from the beam area.

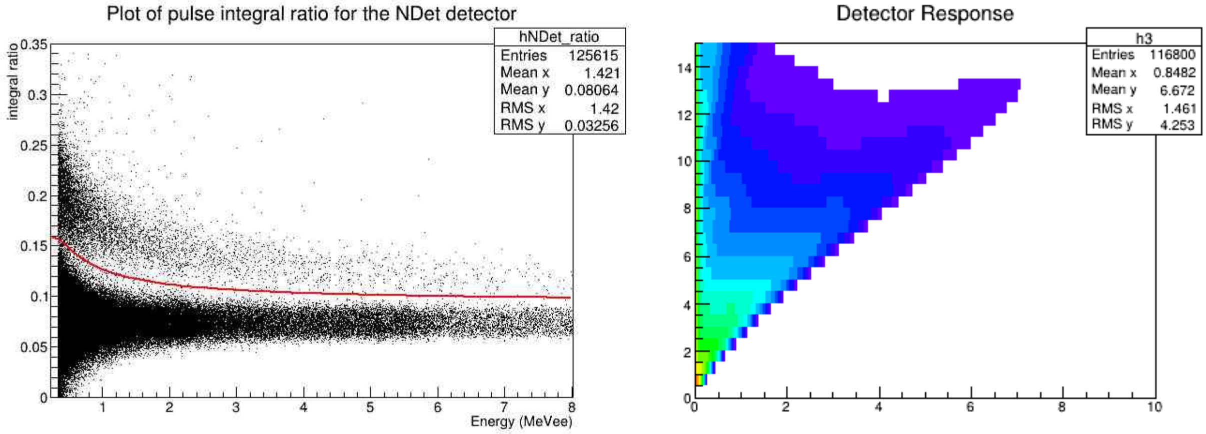
Analysis

Analysis of this run is in its very first stages, primarily focussed on data quality checks at this time. Nonetheless, the reconstruction of the neutron energy spectrum is moving along.

Firstly, since the liquid scintillator neutron detectors respond to both photons and neutrons, a separation routine must be developed to distinguish the two incoming particles. Pulse Shape Discrimination was used, where the ratio of the integral over an initial portion of the pulse to the integral over the full length indicates the cause of the pulse as a neutron or photon. Since photons in general deposit more energy in the tail of the pulse, the two particles can be separated which can be seen from Fig. 4a for the aluminium dataset of Run2015a.

TABLE I: Datasets acquired during R2015a

Target	Target Thickness (mm)	Approximate Exposure (hours)
Aluminium	2	42
Titanium	1.1	24
Lead	1.5	9
Water	~ 6 (not uniform)	4.5
Empty	-	3



(a) Pulse Shape Discrimination (b) Neutron Detector Response Function

FIG. 4: Progress on analysis of the Neutron detectors. (a) Pulse shape discrimination showing separation between gammas (below red line) and neutrons (above red line) in the neutron detector. (b) The response function for the neutron detector obtained from the TUNL neutron beam.

Uncovering the neutron spectrum is further complicated by the fact that the observed energy is actually that of a nuclear recoil from a neutron reaching the detector. Unfolding must therefore be performed to recover the real neutron spectrum from the observed energy spectrum, using the response and acceptance of the detectors, based on simulation and calibration runs. The response matrix as a function of input energy can be seen in Fig. 4b.

Analysis of the other detectors is also under way, with the germanium detector being studied using the techniques developed for the 2013 run. The LYSO array is being studied externally to the AlCap collaboration.

RUN 2015B: CHARGED PARTICLES

In November of this year, the charged particle measurement will be repeated and refined. In particular, an extra silicon detector with 1.5 mm thickness will be added to the two silicon telescopes which should increase the range for the total energy measurements up to about 25 MeV. To reduce our systematic uncertainties on the muon stopping distribution a scanning beam-monitor device will measure the beam profile at the target position during dedicated runs. Furthermore, a thinner active silicon target will improve the certainty of the stopping depth and distribution as well provide for a more rigorous cross-check of the unfolding procedures.

SUMMARY

In summary, future μ-e conversion searches need much improved knowledge of the muon capture process in order to predict and protect against the various daughter particles that can be produced. In particular for aluminium, the stopping target of choice for both Mu2e and COMET, the momentum spectrum and rates of both charged and neutral particle emissions must be measured.

The AlCap experiment is a joint effort by COMET and Mu2e to make such a measurement. The first run in 2013 successfully observed the proton spectrum from about 4 to 10 MeV finding the total emission rate to be about 3 % per capture, with a relative uncertainty of about 10 % although analysis is on-going. A second run took place in June 2015 focussed on neutral particles and used a simpler set-up than the 2013 run which had required a vacuum to reduce scattering of the charged particles in air. Thicker stopping targets were used, allowing for higher beam energy and therefore a higher muon rate. Analysis of this data is only in its earliest stages at this time. Nevertheless for the analysis of the neutron spectrum, separation of neutrons from photons has been demonstrated and the detector response function and calibration has been obtained.

Finally, a third run in November 2015 will take place to improve the 2013 results by increasing the statistical sizes, extending the observed energy range and reducing systematic uncertainties.

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