

Measurement of Direct Muon Atomic Radiative Capture in Lead

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1 Introduction

Parity violating processes are expected in muon interactions with nuclei, with possible new physics contributions dominating, but are as of yet unobserved. The use of muons captured directly into the 2S state of a high Z (>30) material and measurement of the $2S_{1/2} \rightarrow 1S_{1/2}$ transition photon angular asymmetry would provide a measurement of any parity violation.

2 Overview

As a prerequisite for such a parity violation search, measurement of the photon stemming from the muon atomic radiative capture (ARC) process into the 2S or 1S state, which has never before been measured, would be required as a first step [1]. This has been conducted at the Paul Scherrer Institut using a 36 MeV/c μ^- beam on a thin lead target.

A small fraction of incoming muons can be captured directly in to the 1S state through ARC [2]. This process generates a photon with energy equal to the sum of the binding energy of the level with principal quantum number n (corrected for finite size) and the kinetic energy of the muon [2].

$$E_{\gamma}^{1S} = 16.717 \text{ MeV} \quad E_{\gamma}^{2S} = 9.731 \text{ MeV}$$

Calculation of the $\gamma_{\text{ARC}1S}$ cross section, including finite size correction, has been done in [3] giving the following

$$\sigma_{\text{ARC}}(1S) = \frac{2^9 \pi \alpha^2 E_1^4}{3 p^2 \omega^2} \frac{\exp(-\frac{4}{pa} \cot^{-1}(\frac{1}{pa}))}{1 - \exp(-\frac{2\pi}{pa})}$$

where p is the momentum of the muon, a is the Bohr radius, E_1 is the 1S binding energy of the muon, and ω is the energy of the photon emitted in the ARC process.

3 Experimental Setup

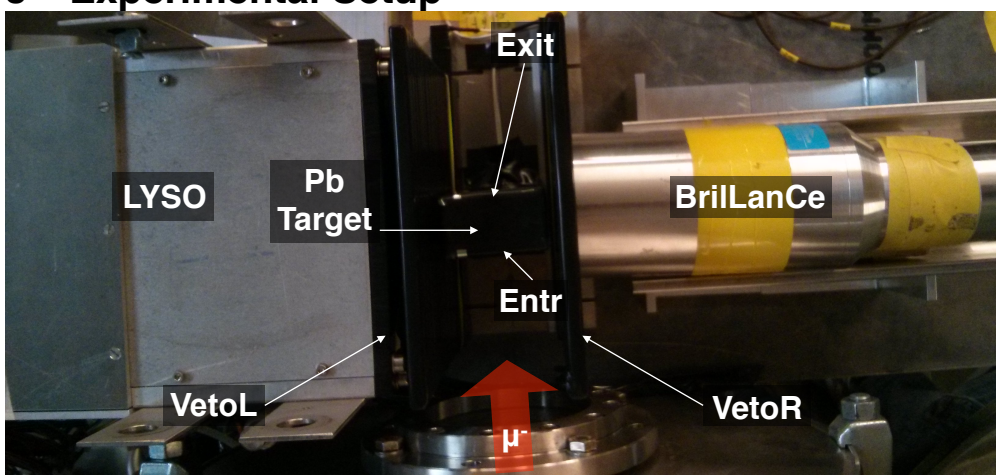


Fig. 1. The muon beam enters from the bottom of the picture shown. The lead target is surrounded by several detector systems, including an entrance and exit detector. To the left and right of the target are veto detectors, as well as a LYSO crystal array and a single BrillLanCe detector system.

A 25 μm lead target is placed just downstream of the beam window. Upstream and downstream of the target are thin plastic scintillator entrance and exit detectors. Left and Right of the target are two thick plastic scintillator veto detectors. A large LYSO 5x5 crystal array coupled to SiPMs is located to the left of the target. To the right of the target is the BrillLanCe detector with integrated PMT.

The trigger logic was an anti-coincidence of entrance detector and exit detector, indicating a stopped muon.

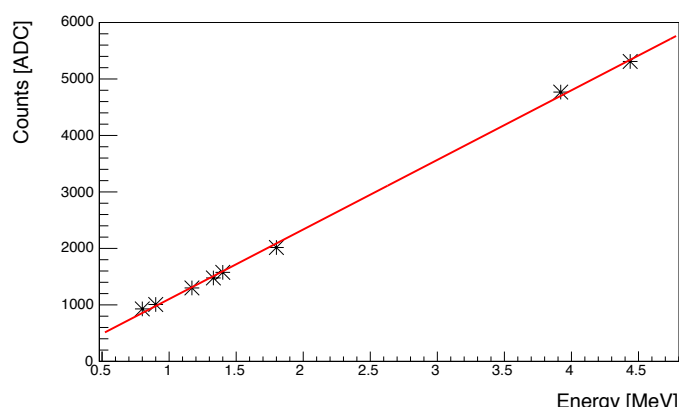


Fig. 2. Calibration of the BrillLanCe was done during the measurement period with several gamma ray and neutron sources from 0.8 to 4.438 MeV.

4 Results

Signal and Background Simulation

Monte Carlo simulations of the experimental setup generating signal and background processes were done with the GEANT4 toolkit G4Beamline. Specifically, $3D_{5/2} \rightarrow 2P_{3/2} \rightarrow 1S_{1/2}$ and $3D_{3/2} \rightarrow 2P_{1/2} \rightarrow 1S_{1/2}$ muonic cascades [3], neutron generation from nuclear capture [4], and the signal $\gamma_{\text{ARC}1S}$ using the calculated cross section for 36 MeV/c muons [1].

Analysis

The analysis thus far has focused on the BrillLanCe detector as it provides better energy resolution over the LYSO. Estimation of the detector and cut efficiencies were done together with simulation and data using the 5.78 MeV and 5.96 MeV combined lead x-ray lines.

- **Cut efficiency:** estimated to be 50% based on the reduction of the 2P-1S lead transition peak integral.
- **Detector efficiency:** estimated to be 15% based on solid angle and energy resolution.
- **Total muon stops:** estimated based on the integral of the 2P-1S lead transition peak.
 - Nearly every muon stopped is captured by the nucleus and generates neutrons, with multiplicity > 1. This is the dominating contribution to background in the signal region.

The calculated probability of detecting the $\gamma_{\text{ARC}1S}$ per incident muon in the BrillLanCe detector is

$$\text{Prob}_{\gamma_{\text{ARC}1S}} = 3.7202 \times 10^{-7} / \mu^-$$

This all together provides a normalization for the simulation to the expected number $\gamma_{\text{ARC}1S}$ visible in the BrillLanCe detector for the entire run.

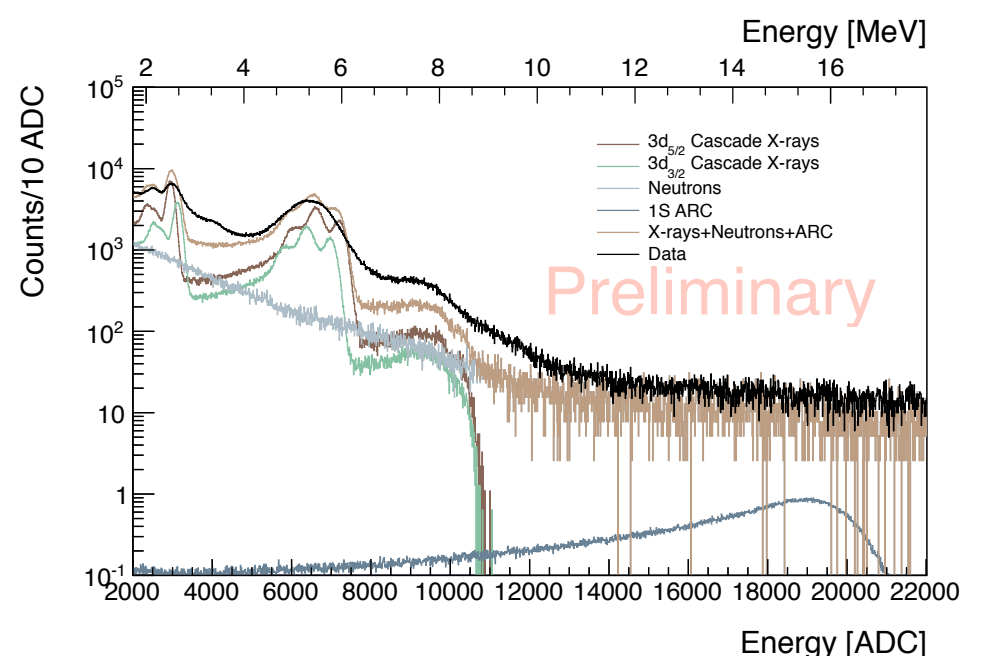


Fig. 3. The figure shows the integrated energy spectrum in the BrillLanCe detector over the full data run in black, compared with the individual components of the background and signal generated by GEANT4. The expected neutron background is a factor 10 higher at the $\gamma_{\text{ARC}1S}$ peak location. The corresponding energy in MeV is shown on the top axis.

5 Conclusion

- At this time, no $\gamma_{\text{ARC}1S}$ peak is observed in the data
 - The expected background from neutrons (before timing cuts) is more than an order of magnitude higher than the $\gamma_{\text{ARC}1S}$ spectrum
- The BrillLanCe linearity is unknown beyond 6 MeV, which could shift the ARC line
 - A linearity measurement will be done soon
- Since the full waveforms were saved for each event, further improvements to the analysis could come from neutron/gamma Pulse Shape Discrimination

6 References

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- 2) Chatterjee L. et al. Europhys. Lett., 18 (2), pp. 1450-150 (1992)
- 3) Kessler, D. et al. Phys. Rev. C 11, 1719
- 4) Measday, D. F. Physics Reports 354 (2001) 243–409