Research and development of the ADRIANO dual-readout calorimeter and the ORKA detector

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The ADRIANO calorimeter has been proposed as a way to more precisely measure the energy of subatomic particles produced in particle collisions. One proposed use of ADRIANO is in the ORKA detector, which seeks to precisely measure the branching ratio $K^+ \to \pi^+ \nu\bar{\nu}$. I present a discussion of the construction of a prototype ADRIANO calorimeter. This involves molding leaded glass into the proper shapes required for use in the calorimeter, and, in order to do this effectively, I must use an Arduino microcontroller device to control an industrial press that is used to mold the glass. In addition to the modifications to the press and the construction of the prototype glass tiles, I discuss the calibration of several Photomultiplier Tubes (PMTs), which are used to read the Čerenkov radiation produced as particles pass through the glass. Finally, the completed prototype is used to collect data from cosmic rays.

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I. INTRODUCTION

A. Calorimetry

Calorimeters play a vital role in high energy physics, as they measure the energy of particles produced in an interaction. Calorimeters are typically divided into two groups: hadronic calorimeters, and electromagnetic calorimeters.[1] Hadronic calorimeters primarily study non-electromagnetic particles, including mesons and jets, which are showers of particles produced from strongly interacting particles such as quarks and gluons.[2] Electromagnetic calorimeters study electromagnetic showers, which are made up of photons, electrons, and positrons. These particles can deposit energy through several means, including radiation and ionization. All calorimeters must have two elements: an absorbing medium and an active medium, which produces the signal. Calorimeters in which those regions are the same are called homogenous, while sampling calorimeters split those roles into two media, which allows the detection of a cleaner signal.[1] In a third type of calorimeter, known as an integrally ac-tive calorimeter, the absorber and active medium are split up as in a sampling calorimeter, but information is read from the absorber as well as the active medium, allowing greater precision in energy measurements.[3]

B. Kaon decay and the ORKA experiment

Kaons are mesons consisting of a strange quark bound to a first generation quark. Specifically, K^+ is made up of an up quark bound to an anti-strange quark ($u\bar{s}$). There are two primary modes for K^+ to decay: into an antimuon and a muon neutrino ($K^+ \to \mu^+\nu_\mu$), which occurs with a branching ratio of 63.55±.11%, and into a positively charged and a neutral pion ($K^+ \to \pi^+\pi^0$), which occurs with a branching ratio[4] of 20.66±.08%. The decay of a K^+ into a positively charged pion and neutrino-antineutrino pair ($K^+ \to \pi^+\nu\bar{\nu}$) is very rare, and, in the Standard Model, is predicted to be strongly suppressed, with a theoretical branching ratio[5] of $(0.781\pm.075)\times10^{-10}$. The E949 experiment at Brookhaven National Laboratory reported the first observation of this decay, when three candidate events they observed were combined with previous events from E787 for a total of seven events.[6] They measured a branching ratio of $(1.73^{+1.15}_{-1.05})\times10^{-10}$. While this is higher than predicted by the Standard Model, the statistical uncertainty due to the low number of events observed is too high to show a statistically significant difference. The goal of the ORKA experiment is to more precisely measure the branching ratio.[5] In order to successfully do so, it requires a high performance calorimeter to both measure the energy of the π^+ and to efficiently veto photons. If the branching ratio is indeed larger than that predicted in the Standard Model, it would signal new physics; many proposed Standard Model extensions require this larger branching ratio.[6]

1. ADRIANO

The ADRIANO (A Dual-Readout Integrally Active Non-Segmented Option) calorimeter is a proposed dual-readout, integrally active calorimeter with the potential to function as both a hadronic and electromagnetic calorimeter. ADRIANO has been proposed for use in the ORKA detector, where it could provide a very efficient photon veto. ADRIANO uses a dual-readout technique and measures both scintillating light produced as particles pass through a scintillator and Čerenkov radiation produced as particles pass through an absorber.[3] ADRIANO has alternating layers of lead glass and scintillating plastic fibers. The lead glass acts as the calorimeter's absorber; it also has the added advantage that Čerenkov radiation is produced when particles pass through it, which is collected through wavelength shifting fibers. The layers of leaded glass alternate with layers of scintillating plastic fibers. As particles pass through the plastic, the plastic is excited and emits light. By combining the readings from both sources, a more accurate and precise determination of particle energy is obtained than is possible using only one source.

C. The Arduino device

The glass tiles used in the ADRIANO calorimeter are molded using an industrial press, which we control with an Arduino device. The Arduino device is a platform which allows a computer to interact with the outside world.[7] Arduino devices consist of a board with several pins. These pins can be set to function as inputs or outputs, using a programming environment on the computer. Once a program is written, in a language similar to C++, it can be compiled and loaded onto the device. In our lab, we have a press which normally is controlled by setting a pressure and time and depressing two buttons; the press then runs until the desired pressure has been exerted for the specified time. We desire to automate this process, and use an Arduino to control the press. The press is used to mold tiles for the prototype ADRIANO calorimeter which we construct. The glass these tiles are made of must be molded at precise pressures for a specific length of time. We are unable to control the press precisely enough by hand to avoid either shattering the glass or allowing the glass to cool before it is molded.

D. Photomultiplier tubes

The prototype ADRIANO calorimeter, which I participate in the construction of, contains several photomultiplier tubes (PMTs) to gather light produced in the glass and scintillating plastic. After light is produced, it is captured by wavelength shifting fibers, which bring the light to the PMTs and shift it to the wavelength at which the PMTs have the best response. PMTs are used throughout high-energy physics to detect photons. PMTs consist of a photocathode, which emits photoelectrons when impacted by an incident photon, followed by several dynodes. The high voltage difference between the dynodes increases the number of electrons; eventually, by now large number of electrons reaches the end of the PMT, where they appear as a sudden negative voltage spike. We have several Hamamatsu R-647 PMTs[8] which we will use to detect the light produced in the ADRIANO calorimeter. Before they can be used, they must be calibrated and a relationship between the output voltage and the number of incident photons (the PMT's gain) derived.

II. PROCEDURE

A. Interfacing the Arduino device

In order to control the press automatically, we interface it with the Arduino device. Several steps are necessary for this: the Arduino must read position measurements from a digital micrometer, and, depending on these measurements, tell the press to elevate or decline. The Arduino must also override the press' starting buttons.

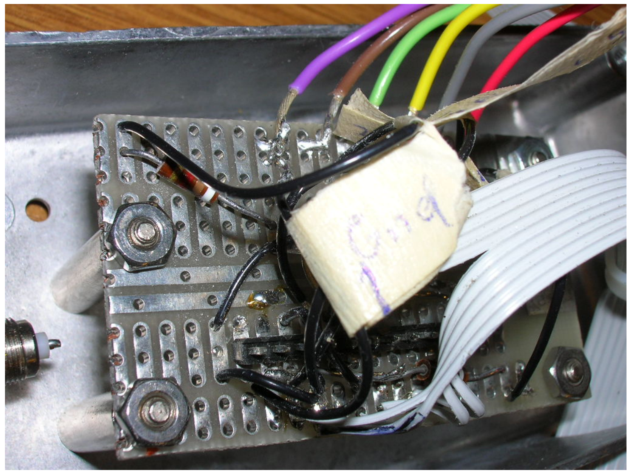

FIG. 1. The connector between the Arduino and micrometer, showing the 10-pin cable from the micrometer and the output to the Arduino.

1. Reading micrometer

In order to measure the press's position, we attach a Mitutoyo Digital Micrometer to it. The micrometer's output is as a 10-pin connector; the first 5 pins are used to transmit the data and timing signals.[9] The micrometer receives a clock signal from the computer, and sends several bits of data when requested. I built a chip that I use to connect the micrometer to the Arduino device. My code, derived from that presented in[10], instructs the Arduino to request the micrometer to transmit the data when desired, and reads in the data, converting it to a human-readable form, which it prints to the screen. When the micrometer is attached to the press and calibrated appropriately, this indicates the distance between the plates.

2. Controlling press

Once we are capable of taking measurements of the position of the press, we directly interface the press with the Arduino. To do so, there are two circuits in the press we must interrupt: one that determines whether or not the press's start buttons are pushed on, and one that determines whether or not the press is elevating. For each of these circuits, I inserted a solid-state relay in the circuit. When I connect the relays' power supplies to the Arduino, I can use it to turn the relays—and thus the circuits—on and off. A simple modification to the existing code that reads the micrometer output can turn on the start buttons, determine

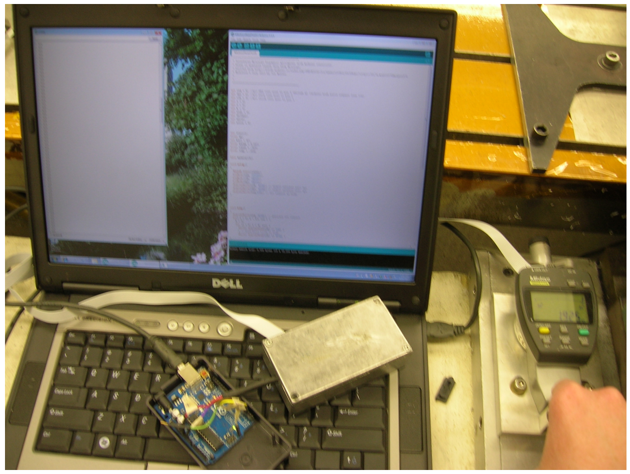

FIG. 2. The Mitutoyo micrometer in operation before being attached to the press, showing the sensor, connector box, Arduino, and output on the computer screen.

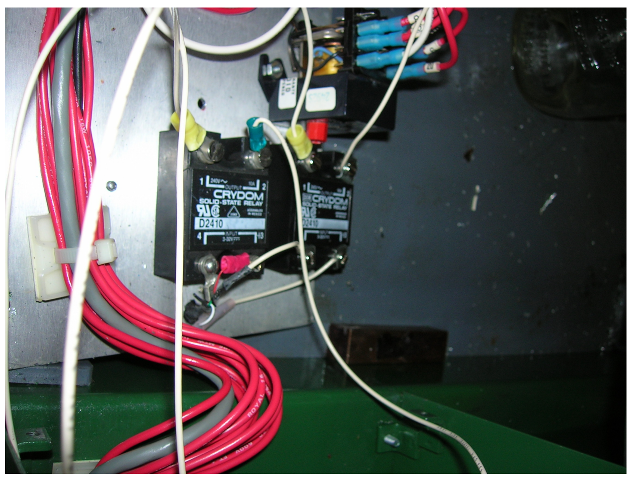

FIG. 3. The interior of the press, showing the two added solid state relays.

whether the press is at the level it should be, and instruct the press to elevate if it is not. A future extension of this work would be to add a load cell to more precisely measure the pressure exerted by the press. The press has a built-in pressure sensor that we use for this work, but the addition of a load cell would allow for more precise measurements and better interfacing with the Arduino.

B. PMT calibration

In order to read the signals from the glass in the prototype calorimeter, we use several PMTs. Before using them, we must calibrate them. To accomplish this, we put each PMT

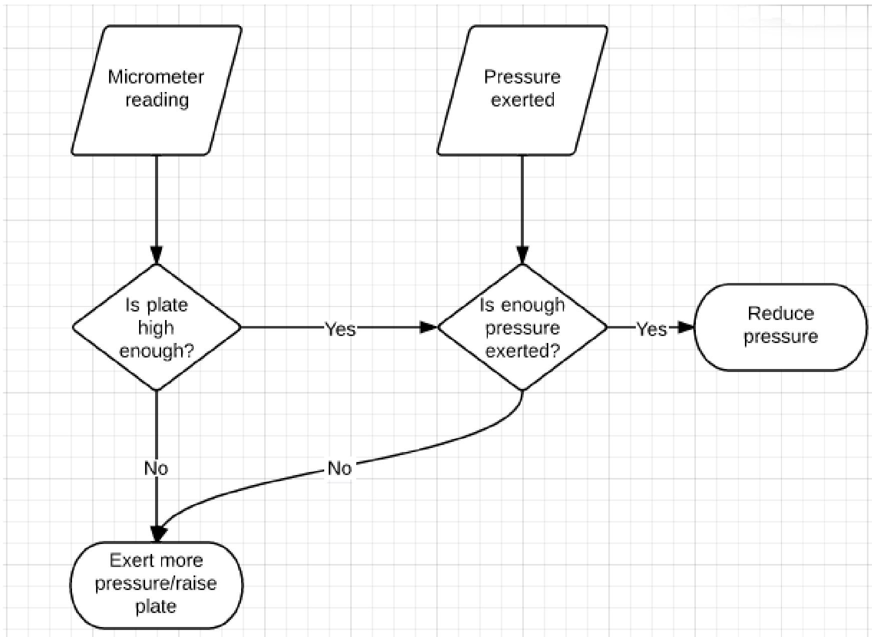

FIG. 4. A flow chart of the Arduino's code, with the future installation of the load cell.

into a box with an LED. We power the LED with a pulsed voltage, and trigger a data acquisition system (DAQ) on the voltage pulse. The DAQ is a custom-built program at Fermilab called TB4 that can read in data on two motherboards, each of which has up to four daughterboards. When the DAQ receives a pulse, it records the PMT output voltage in the form of ADC counts, where the number of ADC counts is related to the PMT's output voltage spike. We attempt runs with several different LEDs before deciding on a blue LED, which is attached to wavelength shifting fibers that ensure the PMT receives signal at its preferred wavelength, about 420 nm.[8] This helps us to control the number of photons that reach the PMT in each pulse, as only photons which enter the wavelength shifting fibers will activate the PMT.

Once we take data for each PMT, we need to fit the data for each to an analytic function. This is typically done through a convolution of several Gaussian functions, which model the pedestal, the peak created from events where zero photoelectrons are produced, and the broader peak from events with one or more photoelectrons.[11] However, we choose a different method. In this method, the number of photoelectrons produced at the photocathode is modeled as a Poisson distribution with some mean μ, with μ equal to the mean number of photons incident to the PMT multiplied by the quantum efficiency of the PMT. The Poisson distribution is then convoluted with a Gaussian that models the dynode amplification chain

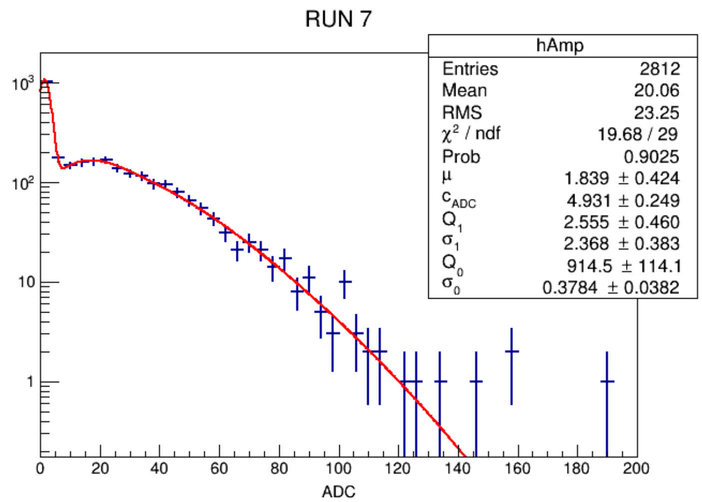

FIG. 5. PMT Calibration histogram overlaid with fit from eq. 1.

of the PMT.[12] Thus, we fit the function:

$$S_{\text{ideal}} = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n} \frac{1}{\sigma_1\sqrt{2\pi n}} e^{-\frac{(x-nQ_1)^2}{2n\sigma_1^2}} \tag{1}$$

where μ is the mean number of photoelectrons produced, n is the the number of photoelectrons, and Q_1 is the mean PMT output charge when one photoelectron is produced. We perform a chi-squared fit to the data histogram, using ROOT's built-in MINUIT fitter.[13] It is possible to further improve this by adding a second Gaussian convolution to model electronics noise and determine S_{real} rather than S_{ideal}, but our fit (example shown in Figure 5) is very good and this is not necessary.

III. RESULTS

Once we successfully control the press with the Arduino, we begin fabricating the glass tiles that will be used in the prototype calorimeter. We successfully mold eight tiles. Once complete, I clean each tile and attach a wavelength shifting fiber to each of several grooves in it. The wavelength shifting fibers gather Čerenkov light produced in the cell and bring it to the outside. We construct an optical box to hold our apparatus. On one end of the cell, we bundle all the fibers, and place a PMT to gather the light. On the other end of the cell, we split the fibers into two bundles. Each bundle is attached to a FBK 4 mm x 4 mm Silicon photomultiplier (SiPM)[14] through a Winston Cone, which gathers the light and

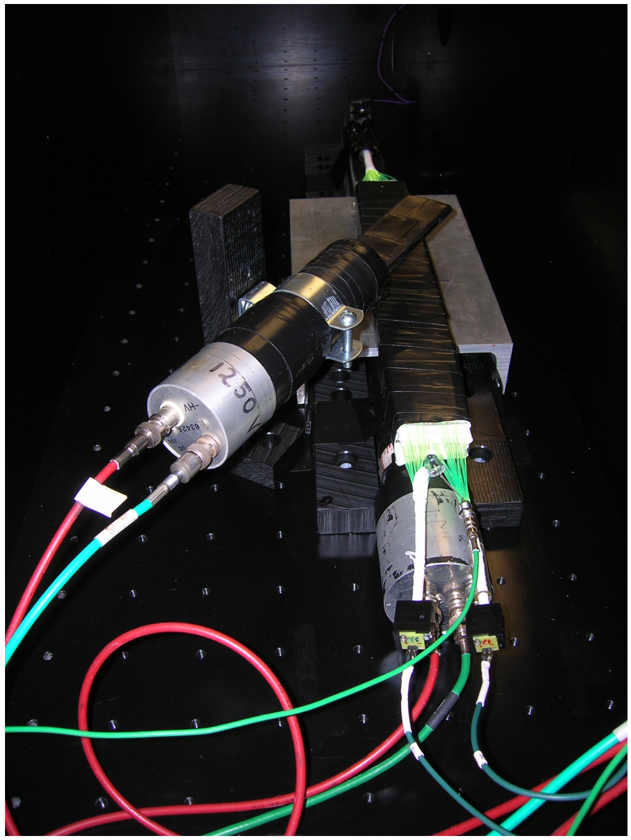

FIG. 6. The optical box, including the prototype cell and triggers.

draws it towards the SiPM.

Once the calorimeter cell is set up, we install a triggering system. The trigger consists of two PMTs that are attached to scintillators. When a cosmic ray passes through the scintillator, the PMTs output a signal. We place one PMT above the cell the the other below, and trigger the DAQ when both PMTs activate at the same time. By requiring a coincidence, where both PMTs are activated at the same time, we trigger only on cosmic rays that pass completely through the cell.

Once the setup is complete, we successfully acquire cosmic ray data. We use a piece of lead to shield the apparatus from low-energy cosmic rays. Many of cosmic rays are fairly low energy and do not deposit enough energy into the cell to activate the PMT and SiPMs that gather the light produced in the cell; by screening these out, we acquire more pure data. The remaining cosmic rays deposit large amounts of energy. These generate more light, producing a large signal in the PMT and SiPMs. An overlay of several events, demonstrating the successful operation of the prototype calorimeter, is seen in Figure 7.

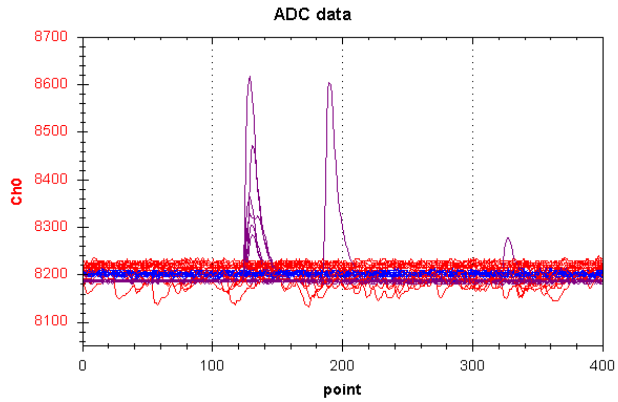

FIG. 7: Event display of several cosmic ray events. The PMT output is in purple, the two SiPMs are in red and blue.

IV. CONCLUSION

I present a discussion of the building of a prototype ADRIANO calorimeter. In order to do so, I modify an industrial press to control it with an Arduino microcontroller. This press is then used to manufacture the leaded glass tiles used in the prototype calorimeter. I also discuss the calibration of several PMTs which will be used to detect the signals produced in the calorimeter. Instead of the traditional method of using a simple convolution of two or three Gaussians to model the PMT output, we use a method that involves determining the average number of photoelectrons produced at the photocathode, modeling that as a Poisson distribution, and then convolving that with a Gaussian to model the PMT's amplification chain. The prototype calorimeter is tested with cosmic rays to show its effectiveness. It will serve as a model for a larger prototype, which will be tested more extensively in a Fermilab test beam later in 2013.

ACKNOWLEDGMENTS

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