TACTIC: A new detector for Nuclear Astrophysics Experiments

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Abstract. Directly measuring nuclear astrophysics reactions presents unique challenges. Low energy reaction products and small reaction cross sections are just two of the issues that the TACTIC detector addresses. TACTIC is the "TRIUMF Annular Chamber for Tracking and Identification of Charged-particles" detector being developed by TRIUMF and the University of York, UK. TACTIC is a cylindrical, active-target TPC providing high detection efficiency; a "shielding" cathode traps the ionization created by the beam and allows for higher intensities than typical TPCs. The 480 anode signals are collected through custom preamplifiers, digital electronics and acquisition systems. Acquisition and analysis software is also undergoing extensive development. Amplification of the small signals is accomplished using a Gas Electron Multiplier (GEM). The fill gas, He-CO\textsubscript{2}, provides both particle detection and a homogeneous, variable-thickness target for studying reactions on \( ^8 \)Li, such as \( ^8 \)Li\((\alpha,n)^{11}\)B. A preliminary study of this flagship reaction was carried out in June 2009 and the results are providing feedback into the development of the final detector and infrastructure.

1. Introduction

Measuring the excitation functions and hence the cross sections of nuclear astrophysics reactions is a major experimental challenge. The energies at which reactions take place in environments such as novae, supernovae and X-ray bursters are comparatively low in energy, typically requiring beams with energy of the order 1 MeV/u. This presents some unique challenges. Firstly, the reactions being studied are typically very low in cross section, therefore any detector system built for the study needs to be highly efficient. To maximise the yield of the reaction under study the maximum amount of available beam must be utilised. This requirement is particularly relevant when using radioactive ion beams (RIB). RIB production is extremely challenging in its own right, therefore its efficient utilisation is a prime design requirement of any experiment.

The initial impetus for the TACTIC project was a desire to study important nuclear astrophysics reactions, such as \(^8\)Li\((\alpha,n)^{11}\)B. This reaction is thought to play an important role in supernovae, particularly in its role in crossing the mass-8 gap in the chart of the nuclides. In this role it may be important in the production of the seed nuclei for the r-process.

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The energies at which this reaction is important ($E_{c.m.}=0.4-3 \text{ MeV}$) means that the energy of the recoiling $^{11}\text{B}$ is typically less than 10 MeV (in the laboratory). Therefore the use of a typical enclosed-gas target is not possible as the recoils would barely exit the target with sufficient energy to be detected. This immediately points to the need for an “active” target - a detector in which the target nucleus (in this case $^4\text{He}$) is a component of the detection gas. Such a detector in a cylindrical configuration has intrinsically high geometrical efficiency. The fundamental difference between TACTIC and previous active targets such as MAYA [1] and MSTPC [2] is that TACTIC does not track each incoming beam particle and therefore its limit in terms of event rate is defined by elastic scattering rather than the beam intensity.

2. The TACTIC Detector Prototype - Design and Build

![Figure 1. Schematic view of the TACTIC detector](image)

The criteria discussed above form the basic design specification of the TACTIC detector (TRIUMF Annular Chamber for Tracking and Identification of Charged-particles).

The design of the TACTIC prototype was undertaken by members of the TACTIC collaboration both at TRIUMF and the University of York, with the final design drawings being provided by STFC Daresbury Laboratory Design Group [5]. The manufacture of the prototype detector was undertaken at the University of York.

A schematic of the basic design is show in cross-section in figure 1. The detector is designed to operate by taking beam from an accelerator (labelled “1”), which enters the detector (at point “2”) through a window that encloses the target/detection gas within the detector in isolation from the accelerator vacuum. The beam particles enter the target region and when a scattering event occurs the ejectiles pass out of the central cylindrical cathode and enter the drift region of the detector. Here the ejectiles ionise the drift gas causing the ejectile to lose energy. The drift field of the detector is radial, thus the gas ionisation is drifted radially from the cathode to the segmented anode which surrounds the cylindrical gas volume. Due to the low energy of the ejectiles (and hence small number of electrons produced along the ejectiles path), a gas electron multiplier (GEM) [3] is utilised to provide proportional amplification of the small signals. The GEM is a thin (50 $\mu$m thick) kapton foil coated on both sides with copper with a fine mesh of holes through the whole structure. Application of a moderate voltage (100-500V) results in a significant field gradient through the holes. When drift electrons pass through the holes as they move in the drift field, avalanching occurs but proportionality is maintained.

The remaining beam passes out of the detector through an exit window (at “3”). This is important in the use of RIB as stopping the beam in the detector would give rise to a significant...
background of decay events. The configuration of the windows is fully adjustable allowing the
target region to be tuned to the kinematics of the reaction under study. The windows are
typically aluminised mylar or SiN of the order of 1 \( \mu \)m thick. At beam intensities of up \( 10^8 \) pps,
the cooling provided by the thermal contact of the detection gas has been found to be sufficient.

![Figure 2. Detailed view of the central cathode wire rings for the TACTIC Detector](image)

**Figure 2.** Detailed view of the central cathode wire rings for the TACTIC Detector

The central cathode (figure 2) comprises two concentric rings of wires, the inner radius
being 10 mm and the outer radius 12 mm. The two rings are electrically isolated allowing
the application of two different voltages. Figure 3 shows a GARFIELD [4] calculation of the
field lines produced by such an arrangement and voltage scheme, these being almost wholly
contained within the outer cathode ring. This means that any ionisation caused by the beam
passing through the target region will have only minimal effect on the exterior drift region. This
allows TACTIC to use high beam intensities and differentiates it from most other active target
detectors which are limited in the rate at which they can take beam. This limit in conventional
active target detectors is due to the fact the detector must track each and every impinging beam
c Particle with a resultant dead-time due to the recovery time of the detector.

The anode and GEM are mounted independently on a support structure that additionally
has a guide ring at each end of the drift region. The guide rings step the voltage down in a
\( r^{-1} \) progression to maintain the radial field lines at the edges of the detector. The anode is in
two halves with each half segmented into 60 strips longitudinally (at 4 mm pitch) and 4 sectors
azimuthally, giving 480 separate anode signals in total.

![Figure 3. GARFIELD calculation of electric field produced by two concentric differentially biased wire rings. The blue wires are held at -1800V and the red wires are at -2000V](image)

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3. TACTIC Readout and Analysis Infrastructure

The anode signals are brought to the exterior of the chamber on 64 way custom made PCB
feedthroughs (see figure 4), on the air side of which two 32 channel preamplifiers are mounted
(figure 5). The preamplifiers were designed and built at TRIUMF and provide a gain of
\( \sim 10 \text{mV/fC} \) of collected charge.

The preamplifier signals are digitally recorded using VF48 modules manufactured by the
University of Montreal [6]. The VF48 modules are 48 channel 10 bit digital ADCs that operate
Figure 4. Detailed view of the signal feedthroughs at one end of the TACTIC Detector

Figure 5. Preamplifier mounted on TACTIC detector.

at 40 MHz sampling frequency. The onboard FPGA can be programmed to provide some pulse shape analysis meaning that data can be collected as either full waveforms or more efficiently as energy-time parameters. The trigger to the DAQ is provided by the first detected anode signal (in practice this is the lowest energy, over threshold, signal arising closest to the anode), and all times are measured relative to this first signal. The voltage, gas pressure and flow-rate are also read into the datastream due to the fact that the GEM response has been found to vary with all three parameters and these parameters are all influential on the energy readout of the detector.

The acquisition software for the DAQ is based on the TRIUMF/PSI MIDAS system [7] and a complete software suite is in place for simulation, analysis and visualisation.

4. Results

Extensive testing of the prototype detector has been undertaken with \( \alpha \) sources and also in-beam. Three stable beam tests have taken place: two at the tandem facility at the University of Notre Dame and one at TRIUMF. In addition to this a brief test with \(^{6}\text{Li}\) beam was undertaken at TRIUMF in summer 2009. This latter test run also utilised part of the DRAGON BGO array [8] which allowed the DAQ to be tested with signals of highly differing speeds.

A typical “event” in TACTIC consists of a number of anode signals, which arrive at differing times depending on the angle of the track. The signal closest to the anode is the first to be measured and, if over a defined threshold, triggers the acquisition readout. The distance of a signal from the anode is calculated from the radial drift time and the time of arrival relative to the final signal. Due to the suppression of the cathode interior (to enable the use of high beam intensities), the part of the track inside the cathode is lost, this impacts on both the energy and the reconstruction of the origin of the track (designated \( z_0 \)). The angle of the trajectory and \( z_0 \) can be calculated by “tracking back” linearly. The track vertex is typically measured with an accuracy of \( \pm 2.5 \)mm (i.e. to within one pad width) and currently the energy resolution (as measured with 3.5 MeV \( \alpha \) particles) is of the order of 7-8%.

However, the suppression successfully confines the space charge generated by the beam passage through the target region. In the first in-beam tests an intensity of \( 10^8 \) pps was put into the chamber. Unfortunately, the DAQ could not convert data at this rate, but by observing the raw signals on a digital oscilloscope, pile-up of signals was only observed at \( \sim 5 \times 10^7 \) pps, meaning the detector is in theory capable of much higher rates than typical active target detectors. The success of the suppression can also be seen in the shape of the tracks when the cathode is biased conventionally (i.e. the suppression is switched off), figure 6. The shape of the
start of the track (with steeper gradient) is due to the radius of origin calculation misplacing the signal due to the different drift field within the cathode. When the suppression is turned on these signals are not present. Also of note regarding figure 6 is the non-linear nature of the track in the drift region of TACTIC. This data is from an early version of the tracking algorithm and the non-linearity is due to to the radius calculation from the respective time differences not fully correcting for the radial nature of the field. This effect has been compensated for in later versions of the algorithm.

Figure 6. Screenshot of reconstructed recoil tracks when cathode suppression is switched off.

Figure 7. Origin reconstruction for $\alpha$ source data showing a good locus of origin consistent with the $\alpha$ source position. The centre of the detector is at 0mm.

The track reconstruction is accurate to within a pad as illustrated in figure 7 which shows the $z_0$ calculation for an $\alpha$ source data run. The peak of the distribution of counts coincides well with the actual position of the source within the detector.

By differentially plotting subsets of the energy signals against the total energy collected (i.e. $\Delta E-E$), particle identification is possible. This work is preliminary but the early results show reasonable separation of ion species.

The calibration of TACTIC is undergoing several improvements but the current methodology is: the pad signals at the same azimuthal angle are normalised to each other and then the total
sum energy of a track is calibrated to the calculated Bragg curve. The method being developed will utilise improved minimisation techniques and modifications to the detector are underway to allow for the installation of \( \alpha \) sources directly within the drift region, thus removing the need to estimate dead region losses in the calibration.

5. Challenges for the Future

The suppression of the cathode interior is vital to enable the use of high beam intensities; however this has a detrimental effect on both the energy measured and the track reconstruction due to the “missing track”. The calculation of these missing parameters from the charge collected from the ionising track as well as knowledge of the drift field need further development. Many aspects of the detector need to be improved and better understood in order for this to happen; including, but not confined to, more accurate gain matching of all anode-preamp-VF48 channels, improved drift time calculations and better calibration and reproducibility of the GEM response.

The prototype detector as described here has given great insight into how these techniques might be utilised in a future detector for low energy nuclear astrophysics measurements. Improvements in the detector itself (multiple GEMs, improved feedthroughs, isolated target region, larger geometry etc.) and the infrastructure (improved preamplifiers, better high voltage scheme, improved digital algorithms etc.) are at various stages of implementation. However, even the limited successes shown in this paper have led to the proposal of many future experiments of interest to nuclear astrophysicists using the TACTIC detector. These include \(^{7}\text{Be}(p,p)\) elastic scattering [9] and \(^{12}\text{C}+^{12}\text{C}\) scattering [10] in a low-background (i.e. underground) accelerator facility.

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