NEURAL - a tracking detector for neutron-induced reactions of astrophysical importance

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Abstract. Observations from gamma ray telescopes indicate that most of the galactic $^{26}\text{Al}$ originates in massive stars. Several sites have been discussed for its production, including proton burning in the winds of very massive stars, and the later, explosive burning stages of these stars. Observations from the RHESSI and INTEGRAL missions currently seem to point to the latter scenario. In the advanced burning stages of massive stars the presence of neutrons becomes an important factor in nuclear reaction networks, so in addition to the $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ reaction the neutron capture reactions $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ can lead to the destruction of $^{26}\text{Al}$, and thus alter the observed $^{26}\text{Al}$ abundance. NEURAL is a detector design to measure the excitation functions of these reactions over a wide range of energies. $^{26}\text{Al}$ targets implanted at TRIUMF will be exposed to a pulsed neutron beam at the neutron time-of-flight facility at LANSCE (Los Alamos Neutron Science CEnter). NEURAL is designed to detect all charged reaction products, combining a time projection chamber for the heavy ions, and Si detectors for the light particles mounted around the target. A first prototype has been built and partially tested at TRIUMF and LANSCE in December 2009.

1. Astrophysical motivation

Timmes et al. [1] find that the later burning stages of massive stars are sufficient to explain the abundance of $^{26}\text{Al}$ inferred from gamma astronomy. They predict a $^{26}\text{Al}/^{60}\text{Fe}$ gamma flux ratio of 0.16 agreeing with recent observations by RHESSI [2] and INTEGRAL [3] (0.16 and 0.11(3) respectively). At these sites the neutron-driven reactions $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ have to be taken into account for the destruction of $^{26}\text{Al}$. While both reactions have been measured at thermal and other energies [4, 5], a full excitation function and thus stellar reaction rates are missing for neutron energies below 500 keV [6].

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2. Setup

NEURAL is a two detector setup consisting of a tracking time projection chamber (TPC) for heavy ions and a surrounding segmented Si array for light ejectiles (fig. 1). The design of the Si array is based on the SHARC array [8]. The whole setup is symmetric to a central plate that acts as target holder and TPC cathode. Wires across the side faces of the TPC frame are kept at appropriate voltages to get a uniform electric field inside the chamber. The Si detectors are shielded from the high voltage in the TPC by a grounded mesh a few mm from this wire plane. Unfortunately this arrangement distorts the field inside the drift region significantly (see fig. 2), as the equipotential planes are basically bent by 90 degrees at the position of the shaping wires, but this problem can be somewhat mitigated by adding a second plane of wires in between the original wire plane and the ground mesh, keeping the wires of this secondary plane at the same voltages as their neighbouring inner wires (fig. 3). The TPC anodes will be segmented to about 90 hexagonal pads (diameter ≈8 mm, exact layout to be determined) each, which means the signals will be too small to be usable with normal preamplifiers, so a gas amplification element in front of the anode is needed. GEMs (gas electron multiplier [9]) or a PGAC (parallel grid avalanche counter) region are being considered.

The Si strip detectors have 16 strips per side, leading to 256 channels for all 8 detectors, making the total number of channels 436. They will be mounted on a slightly modified version of the SHARC frame and the TPC will slide inside on rails. The entire setup will be mounted on one flange of a standard TRIUMF vacuum box. The neutron beam will enter through a Teflon window to reduce scattering. The digital part of the data acquisition system (DAQ) will be entirely handled by TIG64 sampling-ADCs manufactured at the University of Montreal, these are 64 channel ADCs with a sampling frequency of 50 MHz. They are already being used by SHARC but will require firmware modifications to handle the signals from the TPC.

![Figure 1](image-url)  
**Figure 1.** Design of the NEURAL detector setup: a TPC and four segmented Si detectors are arranged upstream and downstream of the target. Since this is a neutron experiment, TPC pads can be placed in the beam path, they will be mounted on Teflon instead of G10 to eliminate n-p-scattering.
3. Tests at TRIUMF and LANSCE
A first prototype using GEMs for amplification was built at TRIUMF in the second half of 2009 and signals were observed during alpha source tests with a 90/10 Ar/CO$_2$ mixture as drift gas. The prototype had a simpler and larger geometry (see fig. 4) and was tested with double sided silicon strip detectors borrowed from DRAGON instead of the SHARC type detectors. The DAQ consisted of the VF48 based TACTIC DAQ with additional ADCs and TDCs for the Si detectors.

The setup was taken to Los Alamos in December 2009 and tested in flight path 5 at the Lujan Center at LANSCE. This flight path provides pulsed neutron beams at energies from thermal to several hundred keV. The neutron energy can be determined by time of flight, although we should also be able to calculate it from reaction kinematics. The tests provided important insight into the environment at the lab and revealed several problems that will have to be addressed in the next run, such as insufficient beam collimation and large electronic noise that disappeared and reappeared but could not be traced to a specific source.

**Figure 2.** Distortion of the electric field due to the grounded mesh close to the field defining wires on the left. In this plot the cathode is at the top and the geometry is that of the prototype.

**Figure 3.** A second wire plane reduces the distortion considerably.
Figure 4. First prototype of the TPC part of NEURAL, larger than the current design and with simpler field-shaping electrodes. For this first test preamplifiers were used that had been previously utilised by the TWIST (TRIUMF Weak Interaction Symmetry Test [13]) experiment.

4. Simulation

A simplified version of the detector geometry was modelled in Geant4 [10], ignoring the frame, wire planes and thickness of the target holder (see fig. 5). No neutron physics except the actual nuclear reaction were included, ion scattering and nuclear reaction use Geant processes originally developed for TACTIC [11]. Reactions are assumed to be isotropic.

Figure 5. Simulation event in the simplified geometry: The dark grey square in the middle is the target holder / cathode, the anodes being the faces of the box parallel to it, and the green squares are the Si strip detectors. The green line represents a neutron entering the detector from the right and reacting in the target. The two blue lines are the charged reaction products: a heavy ion that gets stopped in the gas on the left and a light particle (p or α) hitting a Si detector on the right.

The most suitable gas seems to be 90/10 Ar/CO₂ at 60 mbar. This gas allows us to stop the high energy ground state ²³Na (fig. 6) while still allowing detection of the low energy third excited state (3.6 MeV) of ²⁶Mg (fig. 7). Unlike more common detection gases like P-10 or isobutane this mixture does not contain Hydrogen, so background protons from n-p-scattering are avoided.

At this pressure the degradation effect of the gas on the energies of the light reaction products is still very manageable: the protons corresponding to the ground state and the three excited states of ²⁶Mg that are below the reaction threshold (3.59, 2.94 and 1.81 MeV) are well resolved in the Si detectors (fig. 8), as are the two highest energy alphas from the ²⁶Al(n,α)²³Na reaction (ground state and 440 keV first excited state of ²³Na, fig. 9) whereas the two lowest energy alphas are stopped by the 650 nm thick dead layer of the Si detector. These alphas should be visible in the TPC, though, albeit not energetically resolved.

Fig. 10 shows how many electrons a particle traversing the detection volume of a particular hexagonal TPC anode pad will produce. Large angle tracks spread their ionization over a larger number of pads, so off-centre pads that only get reached by large angle tracks (blue, green) will on average get less electrons per track than more central ones that also see small angle tracks.
Figure 6. Distribution of end points of tracks of $^{23}$Na (ground state) in 90/10 Ar/CO$_2$ at 60 mbar (longest heavy ion tracks expected in this experiment). Beam comes from the left, target is at (0,0).

Figure 7. Distribution of end points of tracks of $^{26}$Mg in the third excited state (3.6 MeV) in 90/10 Ar/CO$_2$ at 60 mbar (shortest heavy ion tracks expected in this experiment).

Figure 8. Energy deposited in one Si pixel by protons after passing through 90/10 Ar/CO$_2$ at 60 mbar, lines correspond to the 3.59, 2.94, 1.81 and 0 MeV states of the $^{26}$Mg recoil.

Figure 9. Energy deposited in one Si pixel by alphas after passing through 90/10 Ar/CO$_2$ at 60 mbar, lines correspond to the 440 and 0 keV states of the $^{23}$Na recoil, the two higher states 2.08 and 2.39 MeV lead to alphas with not enough energy to penetrate the Si dead layer and be detected.

The number of electrons was calculated from the energy loss of a particle in the particular gas volume and the effective ion pair production energy of 26 eV/pair for Argon and 33 eV/pair for CO$_2$ [12].

5. Summary and outlook
Simulations and tests show that the combined setup of Si detectors and a tracking TPC is feasible. However the small collection area of the anode pads makes the utilization of a gas amplification stage unavoidable as the typical number of about 1000 electrons per pad is too low for efficient electronic amplification (about 0.1 fC per pad, the preamplifiers available to us provide a few mV/fC). GEMs provide a high amplification but seem to have non-linearity issues when used with high ionization densities, PGACs (Parallel Grid Avalanche Counters)
do not have this problem but provide lower gains. and the environment at Los Alamos makes special precautions necessary. The prototype is being modified to test the feasibility of a PGAC replacing the GEM as gas amplification element.

Construction of the detector is underway with a working test setup hopefully available by the end of 2010. The geometry was adapted for the use of a SHARC-like Si array and additional field shaping wire planes were added. The DAQ will be switched from the mixed system of our first tests to a simpler TIG64-only system, which will require an adaption of the TIG64 firmware; work on this will commence in September 2010.

Tests of parts of the detector and DAQ will start as they come out of production and we are planning to be ready for another test at LANSCE in 2011.

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