AstroBox2E: a detection system for very low energy β-delayed proton decay

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Abstract. To study very low-energy β-delayed proton decay, which are of interest for astrophysics, it is essential to achieve an efficient suppression of the β-background. ASTROBOX is such a device: energetic precursor nuclei are produced, identified and then stopped in the gas volume of the detector. The resulting β or β-proton decay traces are ionizing paths in the gas. The electrons produced through ionization are drifted in an electric field and are amplified with a Micro Pattern Gas Amplifier Detector (MPGAD). High gain and high signal to noise ratio are expected to be obtained. The two predecessors of this detection system which is under construction now in our group are AstroBox and AstroBox2, which were built and commissioned at Texas A&M University. The goal of this project is to build and use AstroBox2E at European facilities.

1. Introduction
Resonant reactions are important in many explosive hydrogen-burning scenarios. The most significant parameters in understanding the astrophysical reaction rates are the energies and decay widths of the associated nuclear states along the reaction paths [1]. The relevant energies for proton capture reactions are located in the Gamow window (stars are “cold”, reactions occurring at low energies, tens or hundreds of keV), just above the associated proton separation threshold. The properties of these states can be investigated by using indirect methods, which include β-decay studies.

The use of decay spectroscopy tools is an important method to find resonances relevant in various radiative proton capture reactions of significance in nuclear astrophysics. Over the past decade, a program of measurements was started at the Cyclotron Institute, Texas A&M University, using the excellent conditions given by the primary beams from the superconducting cyclotron K500 and the MARS recoil separator [2]. One of the main methods used was the spectroscopy of states populated by β-delayed proton emission.
2. β-delayed proton emission

This method is useful for cases where the proton capture is dominated by low-energy resonances. The resonant capture of protons is a two-step process, where the proton incident on a nucleus populates first a metastable state in the compound nucleus (1st step) that then de-excites (2nd step) by gamma-ray emission. The corresponding astrophysical reaction rates are given by the properties of the narrow, isolated resonances only: spin and parity, energy and resonant strength [3]. To study these resonances at astrophysical energies through direct measurements is not always easy or even possible. An alternative is to populate the same metastable states and determine their spectroscopic properties by other means. One method is focused on the decay spectroscopy: choose an exotic nucleus that will beta-decay to these same states. Important conditions should be verified:

i. the energy of the excited state of daughter nucleus (after its parent went through beta decay) has to be larger than the proton separation energy, and

ii. the spin and parity selection rules must allow the population of the states that represent the most relevant resonances to examine.

The relation between these decay spectroscopy studies and the proton capture reactions that occur through narrow, isolated resonances in stellar environments is presented in Figure 1.

![Decay spectroscopy and Resonant Capture](image)

**Figure 1.** Schematic presentation of the relation allowing the use of beta-delayed proton decay in resonant proton capture ($S_p$ - proton separation energy from the $^{31}$S nucleus; $Q_{EC}$ – beta decay energy; $J^p$ – spin and parity of the excited state; $\Gamma$ – transition width) [4].

3. The AstroBox detection system

A number of decay studies involving nuclei that undergo β-delayed proton emission have been done in the past at Cyclotron Institute, Texas A&M University [5-8]. The experimental procedure involved the separation of short-lived proton-rich radioactive nuclei, implanting them in a detector and measuring the gamma-rays and protons emitted after beta-decay. This type of set-up consisted of very thin Silicon(Si) strip detectors, which proved to be successful in the detection of protons, with energies as low as 200-400 keV, but with a large background from positrons. To lower the β-background and improve the resolution at low-energies, a new type of detector was developed.

3.1 AstroBox1

AstroBox1 was the first gas detector developed. The gas was used as a medium to stop particles and the MICROMEGAS (MICROMEsh GAseous Structure) were used for signal collection. A schematic drawing can be seen in Fig. 2. The whole system consisted of a stainless steel chamber using the
MICROMEGAS structure, the grid, the cathode, the equipotential rings and the gas [9] (see Fig. 3). MICROMEGAS is a detector consisting of a two-stage parallel-plate avalanche chamber with a drift region and a small amplification gap, providing large gas gain and very good energy resolution [10].

3.2 AstroBox2

The detector described above proved to be an efficient tool to investigate the beta-delayed proton decay. In the fall of 2014, a new type of detector was commissioned at Texas A&M University. The main difference of this detector compared to its predecessor is the more appropriate geometry, regarding to the stopping distribution of the beam in the gas of the detector. Another difference is that it has 29 separate pads and correspondingly 29 signals, compared with only 5 for AstroBox1. The 29 rectangular anode pads are arranged into a symmetric geometry along the beam axis. This new configuration allows better control of the heavy-ion implantation and also gives more possibilities for decay studies.

4. Description of the AstroBox2 detection system

The general operating principle of the detector and associated components is similar to the description given in Ref. [9]. The detector, shown in Fig. 4, is a rectangular-shaped gas detector, and is operated in a mode that allows the relevant ions to be stopped inside the gas volume and the decay be observed. The electrons created by the decay radiation that ionizes the gas drift towards a gas amplifier based on MICROMEGAS technology [10].

The MICROMEGAS detector element has an active area of 100 mm x 145 mm, and is divided into 29 rectangular anode pads of various sizes arranged symmetrically along the beam axis. At the moment of commissioning, only a detector with a 128 µm amplification gap had been tested. The pad layout is shown in Fig. 5 and Fig. 6. The PCB (Printed Circuit Board) doubles as a sub-flange that allows the signals to be transmitted directly to the readout electronics, reducing the electronic noise that is induced by the cables connecting the detector to the pre-amplifiers.

The field cage equipotential rings with spacing of 16.5 mm are mounted on the detector PCB. The gating grid is the equipotential ring closest to the MICROMEGAS and contains two small PCBs with a set of 50 µm thick wires between them. This is used to limit the transmission of the drifting electrons during implantation to protect the detector.

Since the fall of 2015, the detection system has been tested, in-beam and off-beam, and was also used in various experiments at Texas A&M University, involving nuclear astrophysics. The next section presents a short summary about the tests and one of the experiments that involved the beta-delayed proton decay of $^{31}$Cl.
Figure 4. Photograph of the AstroBox2 detector during off-line testing showing the anode flange with the PCB attached and the copper equipotential rings.

Figure 5. Schematic of the MICROMEGAS anode. BI-beam-in pads; C-center pads; CL-center left pads; CR-center right pads; OL-outer left pads; OR-outer right pads; BE-beam exit pads. Beam enters from the left.

Figure 6. Photograph of the MICROMEGAS anode attached as a sub-flange to the feed-through flange of the detector chamber.

5. Tests and beta-delayed proton decay of $^{31}$Cl

All tests were carried out using a P5 gas mixture (5% CH$_4$ + 95% Ar) at 800 torr pressure. The detector response for $\alpha$ sources was tested with a mixed $\alpha$ source containing $^{148}$Gd, $^{239}$Pu, $^{241}$Am and $^{244}$Cm. A typical resolution of 3% was achieved for the 5.486 MeV $^{241}$Am $\alpha$ decay. Also, a set of tests was carried out with a $^{55}$Fe X-ray source. The resolution achieved for the 5.9 keV X-ray was 14-16% across the whole detector.

The astrophysical experiment focused on the beta-delayed proton decay of $^{31}$Cl was done at Cyclotron Institute. The MARS recoil spectrometer [2] was used to produce a high purity and high intensity $^{31}$Cl secondary beam which was implanted into the AstroBox2 detector. Data was taken by pulsing the beam, alternating implantation and decay measurement cycles. Using the versatility of the anode pad geometry it was possible to reduce the $\beta$-background in the software to 100 keV. As a consequence of this level of beta-suppression, it was possible to observe clearly the known proton states around 800-1000 keV, and also detect a potentially new proton group in the energy region 200-600 keV.
6. Conclusions and future perspectives
In the last decade many experiments that involved unstable nuclei which undergo beta-delayed proton decay were performed at Texas A&M University. After the extensive study with various Si detectors reached its limits in what concerns lowering of the $\beta$-background, a new type of detection system was developed. AstroBox1, and a few years later, AstroBox2, proved to be an improved tool to perform decay studies. In particular, AstroBox2 has very good characteristics in what concerns the resolution, the particle identification, the geometry between the radioactive beam and the whole detection system. An additional advance of this detector is its limited cost, due to decades of developed MICROMEGAS technology, making the effort building this detector financially feasible.

At the time of submitting this paper, the Nuclear Astrophysics Group (NAG) at IFIN-HH has in development and construction an European version of AstroBox2E, to be used at European facilities which can provide radioactive ion beams. Broadly, the geometry of the detection system will not be changed. We will continue to use MICROMEGAS detectors and already have acquired two of them, one with an amplification gap of 128 $\mu$m, and the other with an amplification gap of 64 $\mu$m. Also, the gas handling system is under construction, as well as the stainless steel housing for the MICROMEGAS detectors.

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