The MUGAST campaign at GANIL

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Abstract. The paper describes the MUGAST campaign at GANIL designed for direct reaction measurement. The physics cases addressed in this campaign deal with shell model evolution, nuclear astrophysics and unbound states. The set-up consist of state-of-art stripped silicon array, MUGAST coupled with the large acceptance spectrometer, VAMOS and with the state-of-the-art gamma array AGATA. It also accommodates cryogenic targets and specific targets. The challenges of the measurements performed are described.

1. The MUGAST set-up
1.1. Detectors arrangement
MUGAST [1] is a Silicon array dedicated to direct reactions measurements with radioactive beams. It has been designed to couple with AGATA and VAMOS at GANIL. It is composed of twelve double-sided strip Silicon detectors (DSSD). In the backward direction, 5 trapezoidal nTD type DSSDs and an annular detector are assembled as shown in Fig.1 and 2 to cover about 50% of the backward angles (see Fig.2). The trapezoidal detectors are 500 µm thick detectors, reverse mounted and at about 15 cm from the target. Their custom packaging from Micron Semiconductors Ltd [2] features very thin frames and two kaptons bent at 90 degrees. Each side is divided into 128 strips with a pitch of 710 µm in the front side and 760 µm in the rear side.

Figure 1. The MUGAST set-up at GANIL.
The annular detector is a customized 500 µm thick Si annular detector (S1) from Micron Semiconductor Ltd. It is divided into 4 quadrants each comprising each 16 rings on the front side and 4 sectors in the rear side. In the forward direction, 4 MUST2 [3] detectors are arranged as shown in Fig.2 with an opening angle of 7 degrees. They consist of a DSSD of 300 µm thickness followed by 16 CsI crystals read by photodiodes. The DSSD are highly segmented with 128 strips on each side. At 90 degrees, a single square 500 µm thick DSSD with slightly different dimensions than the MUST2 but the same number of strips is mounted. The overall angular resolution is better than 1 degree and the intrinsic energy resolution reaches about 40 keV.

![Diagram of the MUGAST array](image)

**Figure 2.** (Left) The MUGAST array with the cryogenic target. (Right) Simulated efficiency of the MUGAST array with a solid target perpendicular to the beam direction.

MUGAST has been designed in order to cope with the constraints of transparency towards the AGATA array [4]. Thus the only material in between the target and the AGATA detectors is the 500 µm thick Silicon detectors and 3 mm of aluminium from the reaction chamber. The measured gamma efficiency at 18 cm at the target position with the MUGAST array is of about 6-7% at 1.3 MeV.

MUGAST is also designed to accommodate specific targets like tritium targets, plunger or cryogenic targets. During the campaign of 2019, a cryogenic target of 3He has been inserted. The target is cooled down to about 6 K through circulating LN and LHe. The target is 3 mm thick with Havar windows of 3.8 µm operated at 1 bar. This gives an equivalent target thickness of about 2 mg/cm². The target stability can be monitored through the evolution of the pressure and temperature. Its thickness is also controlled with the beam energy loss by monitoring the Bρ position in the focal plane detectors of VAMOS.

### 1.2. Electronics and acquisition

MUGAST electronics is based on the MUST2 electronics [3]. The front-end boards are called MUFEES. They lie between 20 and 40 cm from the detector under vacuum. The power consumption for one detector is about 15W/telescope and is drained via a heat exchanger sandwiched in between the two MUFEES boards. They are cooled down to about 5 degrees. Each board encloses 9 ASIC (either MATE (see [3]) or ATHED) and a pair of MUFEES boards is needed to read the 256 channels of one DSSD. Both ASICs give energy and time information from the detector that is transmitted through multiplexing to the MUVI board. MUVI is a single width unit in VXI standard and ensures the slow control and data coding for 4 telescopes. The full MUGAST set-up comprises 3 MUVI set on 3 different VXI boards in order to reduce the dead time as much as possible.
All the VXI acquisition is first merged together on an event number basis. Then the full MUGAST event is merged into the VAMOS flow using VAMOS timestamp. Finally the AGAVA board [4] distributes the AGATA timestamp and the last merge with AGATA data results in an ADF file with 41 clusters and a 42nd cluster corresponding to the MUGAST-VAMOS data.

2. Physics cases and performances
Three experiments have been performed in the 2019 campaign at GANIL with the Spiral1 radioactive beams.

First the spectroscopy of the unbound nuclei $^{15}$F and the decay modes of its negative parity states have been studied. The $5/2^-$ state predicted at about 6 MeV has been searched for by the resonant elastic scattering method. Its two-proton decay has been investigated to determine whether it is a direct two proton decay or a sequential one. In addition, a very narrow $1/2^-$ state just above the threshold with a structure of a core of $^{13}$N plus two quasi bound protons was evidenced recently [5]. The goal of the experiment was also to observe, for the first time, the gamma decay between the unbound $1/2^-$ resonance and the ground state of $^{15}$F.

Secondly, $^{46}$Ar has been investigated to probe the role of the protons for N=28 nuclei. $^{46}$Ar is an intermediate nucleus between the doubly magic $^{48}$Ca and the collective nucleus $^{44}$S that challenges theory for the description of the experimental B(E2) values. This discrepancy could be due to a problem in the description of the neutron-proton interaction in this region [6]. The key point is the occupation of the $\pi s_{1/2}$ orbital in $^{46}$Ar, which varies by 30% in the different models and which determines the magnitude and sign of theoretical predictions for spin-orbit reduction. This occupation has been measured via the transfer reaction $^{46}$Ar($^3$He,d)$^{47}$K using a cryogenic $^3$He target.

Finally, the connection between the CNO cycle and rp-process at the $^{15}$O waiting point has been addressed by measuring the alpha width of key resonant states in $^{19}$Ne through the alpha transfer reaction $^{15}$O($^7$Li,t)$^{19}$Ne. This alpha width has strong impact on the behavior of X-ray bursts. From the previous measurement, only upper limits on the width have been obtained and the present values do not agree with astronomical observations. In order to limit the theoretical uncertainties, the mirror reaction $^{15}$N($^7$Li,t) has been measured at the same time.

Several experimental challenges were addressed during this campaign in particular high beam intensities up to $10^8$ pps had to be handled. The forward detectors of MUGAST were partially masked and a wide finger (4 cm) was set to remove the direct beam into the focal plane of VAMOS. The time of flight information for particle identification was recovered by reconstructing the trajectories of the heavy residues in VAMOS with a very good accuracy.

The triple coincidence measurement between the light ejectile, the heavy residue and the emitted gammas has shown its power in terms of background suppression and selectivity of the reaction channel of interest. The relative efficiency between MUGAST and AGATA at 1 MeV is about 8% and the relative efficiency of VAMOS with respect to MUGAST is about 80% depending on the counting rate in the focal plane.

The MUGAST campaign will be continued in 2020 at GANIL with an improved particle efficiency in the backward direction up to about 85%.

References
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