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Experimental challenges and construction status of the NUMEN Project

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Summary. — The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project at INFN-Laboratori Nazionali del Sud aims to investigate the Nuclear Matrix Elements that govern neutrinoless double beta decay. The strategy is based on measuring double charge exchange reactions with intense heavy-ion beams on candidate isotopes. To cope with the extremely low cross sections, the LNS facility has been upgraded to provide beams up to 10^{13} pps. A new target system and high-performance detectors for the MAGNEX spectrometer are under development, capable of sustaining ion rates of 5×10^6 Hz and allowing simultaneous γ-ray detection. This work provides a status update on the construction of the NUMEN apparatus, discussing recent progress and key experimental challenges.

1. – Introduction

The observation of neutrinoless double beta ($0\nu\beta\beta$) decay would constitute direct evidence of lepton number violation and is the most promising probe to determine the neutrino nature, proving that it is a Majorana particle. The decay rate would then allow us to constrain the effective Majorana mass, provided the Nuclear Matrix Elements (NMEs) are reliably determined. Current NME calculations, however, exhibit significant model-dependent discrepancies [1], which constitute the dominant uncertainty in the interpretation of $0\nu\beta\beta$ results.

The NUMEN project is designed to provide insight into the $0\nu\beta\beta$ decay NMEs through measurements of heavy-ion Double Charge Exchange (DCE) reaction cross sections. These measurements employ oxygen, neon, and carbon beams (15–70 AMeV) from the LNS-INFN Superconducting Cyclotron (CS) on isotopes that are candidates for $0\nu\beta\beta$ decay [2]. The experimental setup combines the large-acceptance MAGNEX spectrometer [3] with Focal Plane Detectors (FPD) for ejectile identification and the new G-NUMEN γ array, placed around the target position, for coincident detection. The measurement of very low DCE cross sections (∼nb level) requires exceptional sensitivity to disentangle the signal from the overwhelming background. To this end, the ongoing upgrade of the CS will enable the delivery of beams with intensities up to 10^{13} pps, about two orders of magnitude higher than before. In parallel, a dedicated experimental setup for high-sensitivity spectroscopy is being developed, designed to operate reliably in a high-radiation environment. The technical aspects are described in the NUMEN TDR [4] and in subsequent reports [5-8].

The present work provides an update to [9], highlighting recent advances in the construction of the NUMEN apparatus with a stronger focus on the outcomes of the development and characterisation tests of the G-NUMEN detectors, and discussing key experimental challenges.

2. – FPD

The FPD provides the trajectory, atomic number, mass and charge state of reaction ejectiles with high resolution [10-12]. The new system must meet stringent requirements: rate capability: 50 kHz/cm, radiation hardness: 10^{11} ions/cm^2/year, time resolution < 2 ns, double-hit event probability $< 3\%$ across the entire FPD, and ability to operate in a low-pressure gas environment (tens of mbar). To achieve this, a *Gas Tracker* has been developed in which the multiplication of primary electrons is obtained with Multi-Thick Gas Electron Multiplier (M-THGEM), followed by the Particle Identification Wall (*PID Wall*): 720 stopping telescopes (36 towers) composed of large-area SiC detectors and CsI(Tl) scintillators that enable ΔE-E measurements. Details on the mechanical design, dimensions, and materials of the new FPD system are outlined in [5, 6, 8].

Gas Tracker: it measures the ejectile phase space parameters at the focal plane with high resolution: $x_{\rm foc}, y_{\rm foc}$ (< 0.6 mm) and $\theta_{\rm foc}, \phi_{\rm foc}$ (< 5 mrad). The drift chamber ($1200\times116\times108$ mm^3) is filled with isobutane and uses a 1 mm-thick triple-layer THGEM for electron multiplication. Position reconstruction combines segmented anode signals (x, z, θ) with electron drift time (y, ϕ). To optimise the gas tracker performance, different M-THGEM hole geometries and segmentations of the anode were tested. Initial tests at the INFN-LNS Test Bench , using α sources and ^{18}O ions at E = 270 MeV, demonstrated that high gas gains of $\sim 10^5$ can be achieved even at low pressures (~ 10 mbar) with minimal ion backflow [13]. The best performance was obtained using a full-coverage THGEM foil configuration with holes arranged in a square pattern, coupled with an anode segmented into pads in the x-z plane. Based on these findings, a prototype was developed featuring the above M-THGEM and anode design but scaled to one-fourth of the full tracker length along the dispersive x-direction (see figs. 1 and 2 in [14]).

A first characterisation of the tracking performance of the prototype coupled with a single SiC detector was performed at INFN-LNS using 55 kBq and 11 MBq ^{241}Am radioactive sources [14]. In this work, by studying the acquired tracks produced by

α-particles emitted from the two ^{241}Am sources and applying constraints on the SiC detector signals, it was possible to reproduce the previously defined geometry. Future tests will be performed to better understand the device performance under very high rates. A second characterisation of the prototype has been recently done at the University of São Paulo, using ^{7}Li, ^{12}C and ^{16}O tandem beams at different energies and at different rates of incident particles.

PID Wall: Each SiC element has an active area of 1.5×1.5 cm^2, with a peripheral edge structure of 0.4 mm width, a thickness of 100 μm and a 10 μm-thick dead layer on the back side. The CsI(Tl) inorganic scintillator is 5 mm thick and is coupled to a Hamamatsu S3590 photodiode with an active area of 1×1 cm^2. Initial prototypes used epitaxial SiC growth with two doping concentrations (3×10^{13} and 9×10^{13} atm/cm^3), corresponding to different full depletion voltages. For NUMEN's SiC detectors, a low doping concentration (below the standard 10^{14} atm/cm^3) is critical to ensure low depletion voltage and prevent discharges in low-pressure environments.

These first detectors were characterised in terms of full depletion voltage, depletion depth and energy resolution [15]. Additionally, energy loss tables for SiC were experimentally checked using these detectors [16]. They exhibited a good energy resolution ($\sim 0.5\%$ FWHM), well within the NUMEN requirement of $\leq 2\%$, however, differences in depletion depth and doping profile were observed between samples from the two different-doping concentration wafers. The low-doping concentration wafer exhibited a depletion depth lower than the nominal value and a poorer uniformity in terms of the doping profile. Since a lower doping concentration is essential for NUMEN, new wafers were recently produced using a different doping process with doping profiles that appear to meet the required uniformity standards. Further tests will be conducted once detector fabrication is completed. To investigate the charge collection efficiency across the active volume and near the edges of a SiC detector, Ion Beam Induced Charge measurements were performed with a proton microprobe at the Ruđer Bošković Institute. The results show excellent charge collection uniformity, except at two of the four edges [17].

A test campaign was performed at the TANDEM+ALPI facility of INFN-LNL to evaluate the PID Wall's performance, using a ^{16}O beam at 15 AMeV and two towers placed at forward angles inside the PISOLO scattering chamber. First results show that we are able to identify ions of interest (C, O, F, Ne) with a resolution $\Delta Z/Z = 3.3\%$ in the Ne region [18]. Excellent time resolution (hundreds of ps) for the SiC detectors and double-hit probability below 2.5% were found, demonstrating the effectiveness of the chosen segmentation. Data analysis is ongoing, and the final results will be presented in a forthcoming publication.

Radiation tests confirmed robustness of the PID Wall components: the SiC detectors have operated reliably under fluences of up to 10^{13} ions/cm^2 [5,19,20], while the CsI(Tl) scintillators have sustained fluences above 7.5×10^{11} ions/cm^2 [5], thereby fully meeting the requirements of NUMEN.

3. – The G-NUMEN γ array

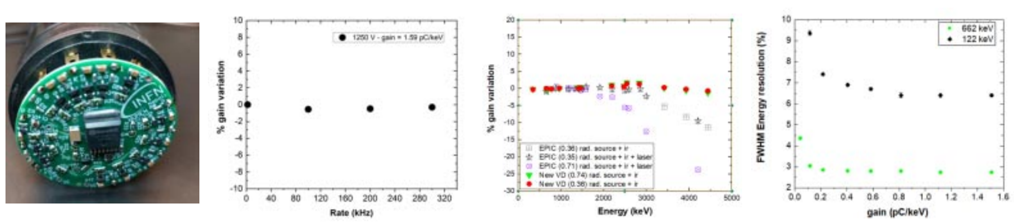
The G-NUMEN array is dedicated to the detection of γ-rays in coincidence (or anti-coincidence) with the DCE reaction ejectiles in the FPD, whenever the MAGNEX energy resolution and high selectivity [21, 22] is not adequate to separate closely-spaced energy states [4, 23]. The array consists of 110 EPIC Crystal $LaBr_3$(Ce) scintillators (38 mm diameter $\times$ 50 mm length), each coupled to a Hamamatsu R6231-type photomultiplier tube (PMT). The system covers a solid angle of 20% and exhibits an expected total photopeak efficiency of 4% at 1.3 MeV. The G-NUMEN detectors must meet [4]: (i) 10-20% energy resolution at 200 keV; (ii) 1-2 ns time resolution; (iii) low observational limit; (iv) stable PMT charge conversion gain up to a count rate of ∼300 kHz; (v) linear energy response; and (vi) radiation hardness to fast neutrons up to 10^{11}-10^{12} n/cm^2.

Initial tests using radioactive sources and subsequent work combining radioactive sources with a laser signal were conducted for a systematic characterisation of the detectors [24]. In the latter approach, to emulate signals corresponding to various γ-ray energies and count rates, light from a laser diode, driven by a CAEN DT5810B Dual Fast Digital Detector Emulator, was fed directly to the PMT window via an optical fiber. The driving pulses for the laser diode were carefully tuned to reproduce signal shapes closely resembling those produced by γ-ray detection. The integrated charge of the signal was scaled to the γ-ray energy at very low bias voltages, using calibration data from radioactive sources together with the scintillator's internal radioactivity. The results revealed two PMT gain issues when using the original EPIC active voltage divider: (i) a count-rate dependence, which ultimately limits the detector's performance at high rates, and (ii) an energy non-linearity that worsens with increasing the bias voltage.

To address these performance issues, a new active voltage divider was developed at INFN-Napoli. Its design employs PMOS transistors to stabilize inter-dynode voltages — effectively suppressing gain variations and count-rate effects— integrated with a tapered voltage distribution circuit. Initial tests with the first prototype showed a highly stable gain with varying count rate and significantly improved energy linearity, while preserving the excellent energy resolution previously achieved and sub-ns timing performance. The results, summarized in fig. 1 and partly reported in [9], confirm that the detector fully satisfies all NUMEN requirements.

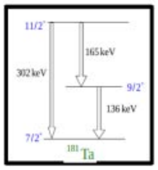
Ongoing studies focus on pulse-shape discrimination for neutron/γ separation, which is crucial for background suppression. $LaBr_3$(Ce) scintillators, produced by EPIC Crystal with different formulations, are under investigation to optimise the achieved particle-discrimination capability.

In parallel with these R&D activities, a benchmark experiment was performed at the ALTO facility (IJCLab, Orsay) to evaluate the G-NUMEN array's capability to discriminate γ-rays from DCE events in the presence of an intense background. An

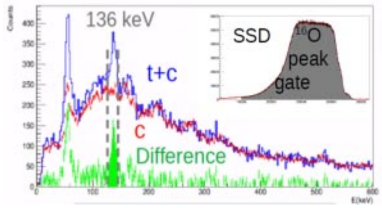


(a) (b) (c) (d)

Fig. 1. – Results with the new active voltage divider: (a) Photograph of the prototype. (b) Gain variation *vs.* count rate, normalized to the low-rate gain. The rate was modulated with a 650-keV laser signal. (c) Gain variation *vs.* energy, normalized to the low-energy gain. Measurements were performed at low rate with radioactive sources and the scintillator's internal radioactivity (ir) at two different gains (values in parentheses, in pC/keV). For comparison, results with the EPIC active voltage divider at the same gains are also shown, including measurements with a laser signal to emulate different γ-ray energies. (d) Energy resolution *vs.* gain.



(a)



(b)

$$A_t = I_{beam}\, n_{targ}\, \sigma_t\, \varepsilon_\gamma\, T_{exp}$$

	ε_γ	I_{beam}	n_{target}	σ_t	T_{exp}	A_t
Demonstrator	0.04%	2×10^{10}/s	8×10^{18}/cm^2	4×10^{-3} b	0.7 h	645
G-NUMEN	4%	1×10^{12}/s	7×10^{18}/cm^2	1×10^{-9} b	720 h	726

(c)

Fig. 2. – (a) Low-lying level scheme of the Ta target (b) Preliminary γ-ray spectrum (single detector), gated by the ^{16}O quasi-elastic peak and by the time-of-flight between the γ-ray and the particle. The blue curve ("t+c") shows the total-coincidence spectrum gated on the main bunch, the red ("c") the chance background (gated on a subsequent bunch), and the green the true-coincidence spectrum obtained from their difference. (c) The table lists the main parameters for the ALTO run (first row) and for a NUMEN experiment with the complete G-NUMEN array (second row), for the 136-keV transition: photopeak efficiency (ϵ_γ), beam intensity ($I_{\rm beam}$), areal target density ($n_{\rm target}$), cross section (σ_t), measurement duration ($T_{\rm exp}$), and the number of counts in the 136-keV photopeak (A_t).

83.5-MeV ^{16}O beam was directed onto Ti and subsequently Ta targets, successfully reproducing the signal-to-background ratio expected for a NUMEN experiment at an intensity of 10^{12} pps. The setup employed the 15-detector G-NUMEN demonstrator positioned at 90° and a silicon strip detector (SSD) at 120° with respect to the beam direction, to study γ-ejectile coincidences. The signal of interest was the γ-transitions from the Coulomb excitation of the Ta target, corresponding to true coincidences. High trigger selectivity was achieved by shielding the SSD from ejectiles produced by the beam interacting with the upstream Ti target. The time-of-flight between the γ-ray and the particle was measured. Preliminary results (fig. 2) are in agreement with prior Geant simulations [4,25]. They confirm that coincidence techniques can isolate signals in intense random coincidence backgrounds when combined with high trigger selectivity, such as that ensured by MAGNEX in NUMEN experiments. The full analysis will be published separately.

A critical issue for G-NUMEN is the LaBr$_3$(Ce) scintillator resistance to fast neutrons. Tests at ALTO using the LICORNE source, exposed detectors to fluences up to 10^{10} n/cm^2 [26]. Evaluation of internal radioactivity spectrum, gain, time and energy resolution before, during and after irradiation show that the LaBr$_3$(Ce) maintains performance within NUMEN specifications, though light yield variations require continuous energy calibration. Future tests will probe higher fluences (10^{11}-10^{12} n/cm^2).

4. – Target system

A major challenge in the NUMEN R&D is the production of targets made of selected isotopes that can withstand intense ion beams, while still ensuring high energy resolution and statistics required for DCE cross-section measurements. The adopted strategy is to deposit thin isotopic layers, a few hundred nanometers thick, onto few micrometers-thick backings with high thermal conductivity, such as Highly Oriented Pyrolytic Graphite (HOPG) or multilayer graphene (MLG). These substrates ensure efficient heat transfer to an actively cooled support frame. A full description of the target system, including its automated handling in high-radiation conditions, is given in [8].

For the first prototype production, isotopic layers of Ge, Te, Se, Mo, Sn, and Cd were deposited by electron-beam evaporation onto HOPG foils. Deposition parameters (evaporation rate, substrate thickness and temperature) were carefully optimised and, in some cases, buffer layers were added to improve the adhesion of the deposited material on the backings, ensuring efficient heat dissipation. The resulting targets were then characterised with various techniques [27, 28].

Measurements revealed significant thickness non-uniformities in HOPG samples, whereas simulations indicated that values below 10% are required to ensure good energy resolution. Therefore, HOPG proved unsuitable as a backing for NUMEN targets. Furthermore, radiation damage was found to be a serious issue for HOPG [29].

Current R&D at INFN-Genova focuses on the use of MLG foils as alternative substrates, evaluating commercial samples and exploring novel synthesis techniques (*e.g.*, low-pressure filtration, polyimide pyrolysis). The long-term goal is to engineer substrates with optimised structural, thermal, and surface properties, designed to meet the demanding conditions of NUMEN targets.

5. – Conclusions

The NUMEN project investigates DCE reactions to gain insights into the NMEs relevant for $0\nu\beta\beta$ decay. Measuring extremely low DCE cross sections required major upgrades to the CS at INFN-LNS and the MAGNEX spectrometer, including the new G-NUMEN array, radiation-hard targets, and advanced detectors with dedicated electronics. The experimental setup is now in its final stages, with several characterization campaigns completed and additional tests underway for commissioning and data taking.

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