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Characterization of first germanium target system prototypes for the NUMEN Experiment

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Summary. — The purpose of the NUMEN Experiment is to measure the cross section of Double Charge Exchange (DCE) reactions and to extract data potentially useful in the search for neutrinoless double β-decay ($0\nu\beta\beta$). NUMEN targets must endure intense ion beams (several μA), while interfering as little as possible with the reaction products' energy to preserve the energy resolution of the measurements. For these reasons, few hundreds nm thick targets are deposited by PVD techniques on few μm thick Highly Oriented Pyrolytic Graphite (HOPG) substrates. In this work, results of the characterization of new germanium samples will be shown. Results of Monte Carlo simulations on the targets' energy resolution will be reported as well.

1. – Introduction

In recent years, neutrino physics attracted a widespread interest in the dedicated physicists community. One of the most debated subject is the neutrino's Majorana nature, explored by searching for neutrinoless double β-decay ($0\nu\beta\beta$), but no experimental evidence has been found yet, due to neutrino's feeble interaction with ordinary matter and a general lack of data on the topic. However, $0\nu\beta\beta$-decays share some similarities with Double Charge Exchange (DCE) processes [1], which could be used to obtain more quantitative information about the $0\nu\beta\beta$. By exploiting such similarities, the NUMEN Experiment is measuring the DCE cross section of several reactions, and the results will be used to reduce the currently large uncertainty of the $0\nu\beta\beta$ Nuclear Matrix Elements [2]. The values of the studied DCE reactions cross sections are in the nb-μb range, therefore intense beams of heavy ions (more than $10\,\mu$A of completely stripped ^{18}O and ^{20}Ne, at energies higher than $15\,$MeV/u) must be used to reach the desired statistics.

(*) On behalf of the NUMEN Collaboration.

Targets must also be thin, less than half a micrometer in general, to limit their effect on the energy of the reaction products and, consequently, on the final energy resolution. The heat generated by the interaction of the beam with the target is removed by a highly thermally conductive substrate of Highly Oriented Pyrolytic Graphite (HOPG), few μm in thickness. So far, several prototypes of Sn and Te have been produced and characterized [3]; such studies led to define the optimal thickness of the samples, which maximizes the reaction rate while keeping energy resolution within the desired values. In this work, results of Ge target prototypes characterization will be presented; such data have been used to perform Monte Carlo simulations, whose results will be shown as well.

2. – Characterization of germanium target prototypes

The first prototypes of germanium target systems for the NUMEN Experiment have been produced by using the Electron-Beam Physical Vapor Deposition technique, as the tellurium and tin target systems [3]. The target layer has been deposited on 2 μm and 5 μm thick HOPG. All the produced prototypes have been examined with the Alpha Particle Transmission (APT) technique and with the Rutherford Backscattering Spectroscopy (RBS) technique to get information about the thickness distribution and elemental composition. The topography of the deposition surface of the prototypes has been studied by using Field Emission Scanning Electron Microscopy (FESEM).

The APT measurements have been performed in the Polytechnic of Turin, with the set-up described in [4]. The alpha beam is provided by a ^{241}Am source and is detected downstream of the sample by a silicon detector. The parameters of the thickness distribution can be derived from the comparison between the APT energy spectrum acquired with only the HOPG substrate and the APT energy spectrum acquired with the entire target system (target + HOPG), by fitting both the energy distributions with Crystal Ball functions [5], shown as red lines in plots of figs. 1 and 2. This technique provides quantitative estimation of the sample average thickness and its thickness uniformity, with resolution of 5 nm. In case of a composite sample, RBS measurements are useful to simultaneously measure the average thicknesses of all the layers composing the target system, detecting also their elemental composition. RBS measurements have been performed in the Laboratori Nazionali INFN di Legnaro, at the AN2000 accelerator. A 2 MeV alpha beam has been used, measured in backscattering at 160°.

Here, prototypes evaporated on HOPG foils of different thickness are presented: B22, backed by a 5 μm thick substrate, and C11, backed by a 2 μm one. In fig. 1 the APT (left) and the RBS (right) measurements performed on the target system B22 are shown. From the analysis of the APT black spectrum, acquired before the Ge layer on the substrate, the HOPG substrate resulted to be 4.335 μm thick, with a non-uniformity of 2%. The orange APT spectrum has been acquired with the whole target system, after the target deposition. From the comparison of the two APT spectra, the average thickness of the germanium target resulted to be 405 nm, with a non-uniformity of 16%. From the RBS measurements, the germanium layer resulted to be 385 nm, being in agreement with the APT result within 5%. Figure 2 illustrates APT and RBS measurements performed on prototype C11, deposited on a 2 μm thick HOPG substrate. The analysis of the APT measurements determined an average HOPG thickness of 1.845 μm (non-uniformity of 4%) and an average target thickness of 350 nm (non-uniformity of 13%). Thanks to the RBS measurements, the average thickness of the chromium buffer, used to enhance the adhesion between target and HOPG, has been examined; its thickness has been measured as 10 nm. According to RBS analysis, the average thickness of the target layers

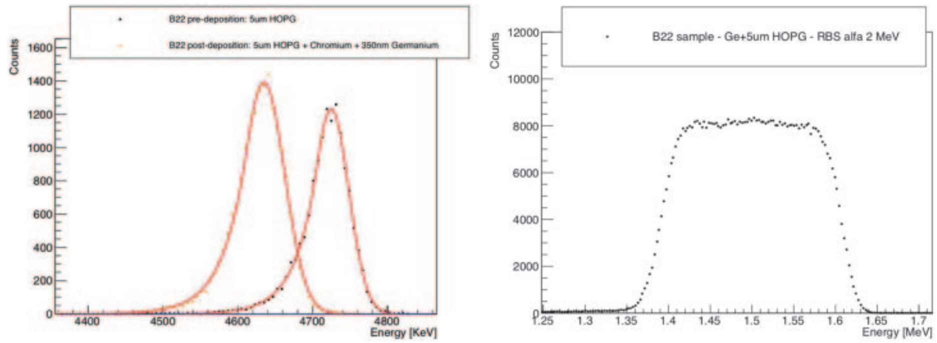

Fig. 1. – Left: APT analysis of the HOPG substrate used for the B22 sample (black dots) and the B22 target system (HOPG + target, orange dots). Right: RBS analysis of the B22 target layer performed with a 2 MeV α beam detected at 160°.

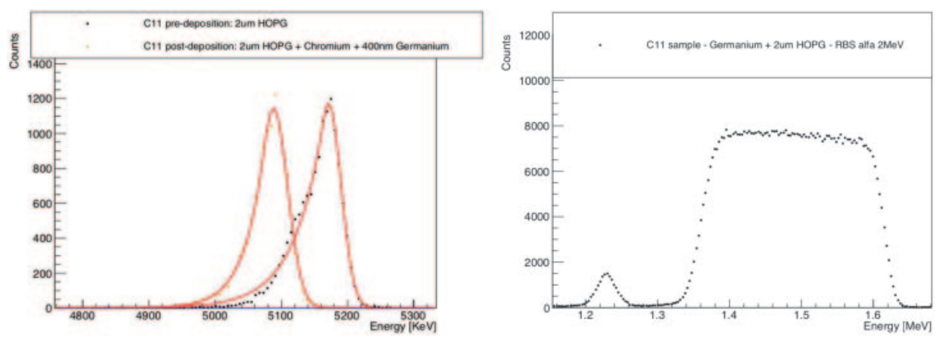

Fig. 2. – Left: APT analysis of the HOPG substrate used for C11 sample (black dots) and of the C11 target system (HOPG + buffer + target, orange dots). Right: RBS analysis of the C11 target layer performed with a 2 MeV α beam detected at 160°.

is 380 nm (agreement with APT result within 6%). FESEM images of the two prototypes (not shown for brevity) highlighted quite flat and uniform deposition surfaces, with few structures smaller than 100 nm.

3. – Evaluation of the energy resolution

The change in energy of the reaction products of DCE events is affected by several factors, namely straggling, non-uniformity of deposition and substrate, final states of daughter nuclei and reaction depth. The concurring effects of such factors are evaluated with Monte Carlo simulations, which take into account the energy distribution of the ion beam, the error introduced by the MAGNEX spectrometer and the trajectory reconstruction algorithms as well. The simulations are run using data collected from the above mentioned APT and RBS characterization, namely target and substrate thicknesses and their non uniformity; the DCE reaction probability is assumed to be constant throughout the target; finally, the first 3 excited levels of both the ejectile and the recoiling nucleus are considered (all of them are assumed to be equally probable due to a lack of experimental data in the literature). Each peak corresponds to a different

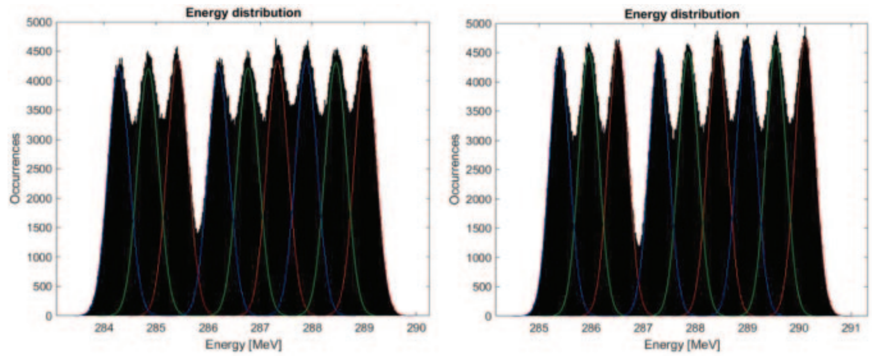

Fig. 3. – Left: energy distribution of the ^{20}O ejectiles of the DCE reaction ^{76}Ge(^{20}Ne,^{20}O)^{76}Se, using the prototype B22 as target system. Right: energy distribution of the ^{20}O ejectiles of the DCE reaction ^{76}Ge(^{20}Ne,^{20}O)^{76}Se, using the prototype C11 as target system.

combination of ejectile-target daughter energy levels; the red gaussian corresponds to a target daughter in the ground state, while green and blue Gaussian fits are the first and second excited states of the target daughter. The desired energy resolution, taken as the FWHM of the first peak on the left-hand side, must be sufficient to distinguish the Ge first excited state (2^+) from its ground state, whose energy gap is 0.562 MeV. The energy resolution of sample B22 (left panel of fig. 3) resulted to be equal to 0.567 MeV, slightly above the desired limit. This can be attributed to the relatively thick HOPG substrate. Conversely, the energy resolution of sample C11 (right panel of fig. 3) falls within the established limits, being equal to 0.543 MeV. The reduced thickness of substrate and target compensate the higher non-uniformity of the target layer.

4. – Conclusions

In the NUMEN Experiment, intense beams react with thin targets, which must satisfy strict requirements. In this work, prototypes of Ge targets deposited on HOPG substrates of different thicknesses have been presented. Each sample has been characterized by using FESEM imaging, RBS and APT techniques, to assess the fulfilment of the requirements, namely the target and substrate thickness and non-uniformity. The obtained results were used to run Monte Carlo simulations on the energy distribution of the reaction products and on the related energy resolution. Sample B22, deposited on a 5 μm thick substrate, did not comply with the energy resolution requirements, while sample C11, deposited on a 2 μm thick substrate, did meet the experimental requirements.

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