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Characterization of first prototypes of thin targets for the NUMEN Experiment

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Summary. — The NUMEN Experiment, at INFN-LNS, aims to get information on the nuclear matrix elements of the neutrinoless double beta decay, by measuring double charge exchange reactions cross-sections. To get a good energy resolution, target thickness must be minimized. To allow heat dissipation (intense beams will be used), around 400 nm of target isotope will be deposited on a $2\,\mu$m thick highly oriented pyrolytic graphite substrate, that has high in-plane thermal conductivity. First NUMEN target prototypes of tin and tellurium have been produced. Thickness and uniformity analysis performed by alpha-particle transmission and Rutherford backscattering spectroscopy will be reported, together with the evaluation of the energy resolution with a Monte Carlo code.

1. – Introduction

One of the most interesting topics of the modern Particles Physics is neutrino's nature: if a neutrino is a Majorana particle (being at the same time particle and its own anti-particle), the conservation law of the leptonic number has to be redefined. The study of the Neutrinoless Double Beta Decay (NDBD) could play a crucial role in this research. Since the NDBD research is challenging, the study of other processes is useful to provide complementary information. Double Charge Exchange (DCE) reactions have many similarities with NDBD [1], so experimental measurements of DCE cross-sections could help in the determination of the nuclear matrix elements involved in the NDBD model. Since DCE reactions cross-sections span from some nb/sr to a few μb/sr, very intense ion beams are required to perform these measurements with fixed-target experiments. The NUMEN project [2], based in the INFN-LNS laboratories in Catania (Italy), will use ion beams of tens of μA impinging on very special targets to detect and study several DCE reactions. These targets must be very thin, to fulfil the energy resolution requirements of the experiment, and also heat resistant, to avoid damaging due to the energy released by the intense beams.

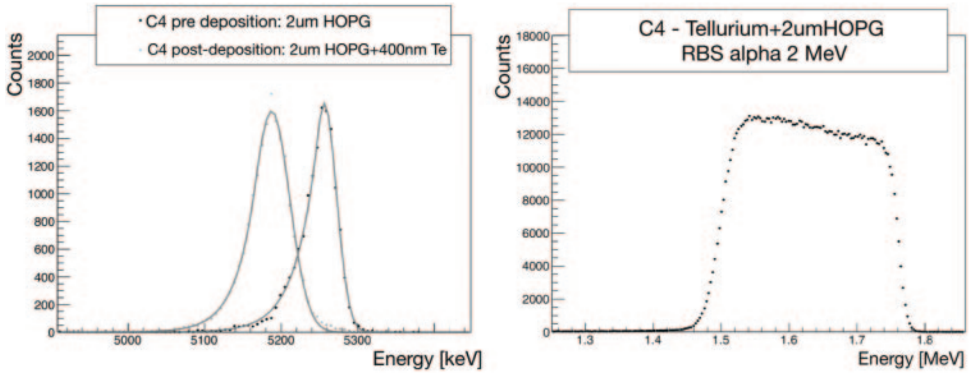

Fig. 1. – On the left: APT analysis of the HOPG substrate used for C4 sample (black dots) and of the C4 target system (HOPG+target, grey dots). On the right: RBS analysis of the C4 target layer performed wth a 2 MeV α beam detected at 160° degrees.

These two main features make the NUMEN targets very innovative: a few hundreds of nanometers of isotopic material, required to get a DCE reaction, are deposited on a few micrometers thick Highly Oriented Pyrolytic Graphite (HOPG) substrate. Thanks to the HOPG high in-plane thermal conductivity, the heat produced by the beam in the target can be quickly transferred through the substrate to a cooling system. The substrate and the target have to be accurately characterized in thickness and uniformity, since their knowledge is crucial in the evaluation of the NUMEN overall energy resolution [3]. This paper will report the characterization of the best prototypes of tin and tellurium targets with different analysis techniques, together with the evaluation of the energy resolution performances when using these target systems.

2. – Characterization of tin and tellurium best target system prototypes

Here the characterization results of two prototypes of natural tin and tellurium target systems will be presented. The deposition processes of the two elements, performed by the electron-beam physical vapor deposition technique, have been deeply studied in order to optimize the thickness uniformity of the deposited layer. The tellurium deposition is performed at room temperature, without any buffer layer. The characterization studies related to the tellurium target system prototype named C4 will be shown. The tin deposition is performed by heating the HOPG substrate(1), using also a chromium buffer, ≈ 10 nm thick, to facilitate the deposition adhesion. The characterization of the tin target system C7 will be presented. The nominal thickness of both targets is 400 nm, while the HOPG substrates have a nominal thickness of 2 μm.

Figure 1 shows the thickness measurements on the tin target system C4, performed with Alpha-Particle Transmission (APT) (left spectrum) and with Rutherford Backscattering Spectroscopy (RBS) (right spectrum) techniques.

The APT measurements have been performed with the set-up assembled in Politecnico of Torino, described in [4]. The 5.486 MeV alpha-particles beam, provided by a ^{241}Am source, is detected downstream the target by a silicon detector. From the comparison between the energy spectrum acquired before the target deposition (with only the HOPG

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(1) The temperature read by the thermocouple of the used evaporator is 130° degrees.

substrate, black dots peak in the figure) and the one acquired after the deposition (being the target system made of substrate and target layer, grey dots peak in the figure), the thickness distribution of the target deposition can be evaluated. The target average thickness and the thickness non-uniformity can be estimated by fitting the spectrum with Crystal Ball functions, that have a Gaussian core portion and a power-law low-end tail(2) (lines in the figure). From the analysis of the C4 black peak, the HOPG substrate results 1.285 μm thick. The non-uniformity R_{n-u} is estimated as the ratio between the spread of the peak in the thickness distribution and the average thickness; here R_{n-u} of the substrate is around 10%. The C4 target thickness features have been evaluated by the comparison between black and grey spectra; the average thickness is 435 nm, with $R_{n-u} \approx 1\%$.

The right image of fig. 1 is the RBS energy spectrum of the sample C4 acquired in INFN-LNL laboratories in Legnaro, Italia. A 2 MeV α beam has been detected by a silicon detector when backscattered at 160° degrees from the beam line; only the target layer can be studied since the beam energy is too low to interact with the substrate and then be backscattered to the detector. From the analysis of the left edge of the RBS spectrum, the average thickness of the target layer results to be 420 nm. RBS is here useful to verify the APT result: here the thickness results are in agreement within 4%.

C4 has been studied also by Field Emission Scanning Electron Microscopy (FESEM) analysis, whose images are not here reported for brevity. The target deposition seems quite flat, with small grains around a hundred of nm big.

The APT and RBS spectra of the measurements performed on the target system C7 are not shown here for brevity. From the APT spectra, the HOPG substrate thickness has been evaluated as 2.63 μm, with $R_{n-u} \approx 4\%$. The target thickness has been determined as 170 nm, with $R_{n-u} \approx 62\%$. The thickness buffer layer, evaluated by RBS as 40 nm, has been considered in the target thickness determination. The RBS thickness evaluation of the target is 160 nm, in agreement with the APT evaluation within 6%. In the RBS spectrum, other than the chromium buffer peak, another bump appeared: it was due to impurities in the evaporator chamber that have been trapped in the target. Their nature has been established by energy dispersive X-ray spectroscopy. FESEM analysis performed on C7 revealed a quite uniform tin superficial deposition with channels through which a underlying layer of deposited tin is visible.

3. – Energy resolution evaluation

Figure 2 reports the kinetic energy distributions of DCE ejectiles when using as reaction target C4 or C7. These spectra have been simulated by a Monte Carlo code that evaluates the effects occurring in the target that affect the experiment overall energy resolution (*i.e.*, energy dispersion and straggling), together with the contributions related to the beam energy spread and to the NUMEN spectrometer. With this evaluation, the energy resolution can be investigated: the reaction products can exit in different energy states, resulting in nine possible combinations of ejectile-target daughter energy states.

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(2) The Crystal Ball functions is given by $f(x;\alpha,n,\bar{x},\sigma) = Ne^{-\frac{(x-\bar{x})^2}{2\sigma^2}}$, for $\frac{x-\bar{x}}{\sigma} > -\alpha$, $f(x;\alpha,n,\bar{x},\sigma) = NA(B - \frac{x-\bar{x}}{\sigma})^{-n}$, for $\frac{x-\bar{x}}{\sigma} \leq -\alpha$, where $A = \left(\frac{n}{|\alpha|}\right)^n e^{-\frac{|\alpha|^2}{2}}$, $B = \frac{n}{|\alpha|} - |\alpha|$, $N = \frac{1}{\sigma(C+D)}$, $C = \frac{n}{|\alpha|}\frac{1}{n-1}e^{-\frac{|\alpha|^2}{2}}$ and $D = \sqrt{\frac{\pi}{2}}\left(1 + \mathrm{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right)$.

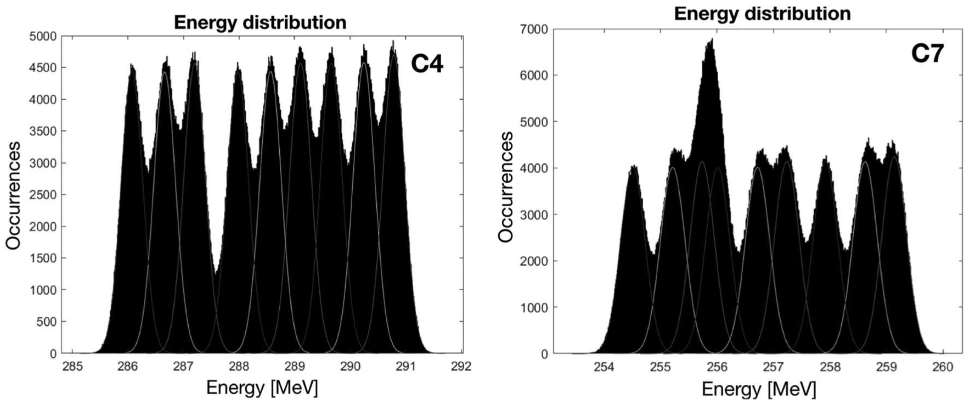

Fig. 2. – Kinetic energy distributions of DCE ejectiles for the reaction ^{130}Te(^{20}Ne,^{20}O)^{130}Xe with the C4 prototype (left) and ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd with the C7 prototype (right).

To determine the DCE cross-sections, each peak must be clearly distinguished from the near ones. This peak discrimination can be easily reached in the distribution on the left, related to the tellurium target system C4. Indeed, the target thickness uniformity is good enough to minimize dispersion and straggling effects. Instead, the tin target system C7 cannot guarantee a good discrimination of the peaks pair related to the case of ejectile in the first excited state and target daughter in the second excited state (peak around 256 MeV) and to the case of ejectile in the second excited state and target daughter in the ground state (peak on the left of the 256 MeV peak). This bad discrimination capability must be related to the not optimal thickness uniformity of the tin target layer.

4. – Conclusions

The characterization results of the best prototypes of tin and tellurium target systems have been described. The APT technique can determine both the average thickness and the thickness uniformity of HOPG and target. RBS can verify the APT average thickness estimation and provides the thickness determination of each layer composing the whole target system, with an appropriate choice of beam type and energy. A Monte Carlo code has been implemented to evaluate the NUMEN energy resolution in the reaction ejectile detection. The thickness uniformity results, reached with the tellurium deposition process, are good enough to guarantee a good energy resolution in the ejectile energy detection, while there is still much to do to optimize the energy resolution reachable when using a tin target.

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