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Original
Thickness and uniformity characterization of thin targets for intense ion beam experiments / Capirossi, V., Delaunay, F., Iazzi, F., Pinna, F., Calvo, D., Fisichella, M., Rigato, V.. - In: ACTA PHYSICA POLONICA B. - ISSN 0587-4254. - ELETTRONICO. - 51:3(2020), pp. 661-666. [10.5506/APhysPolB.51.661]

Availability:
This version is available at: 11583/2843484 since: 2020-08-31T12:32:29Z

Publisher:
Jagellonian University

Published
DOI:10.5506/APhysPolB.51.661

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11 November 2026

THICKNESS AND UNIFORMITY CHARACTERIZATION OF THIN TARGETS FOR INTENSE ION BEAM EXPERIMENTS*

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(Received January 8, 2020)

The NUMEN Experiment aims to get information on the Nuclear Matrix Elements of the Neutrinoless Double Beta Decay, by measuring heavy-ion induced Double Charge Exchange (DCE) reactions cross sections. A good energy resolution is needed to clearly distinguish energy states of DCE products. To measure the energy of reaction products with the required resolution, the target must be thin and uniform to minimise dispersion and straggling effects on the ejectile energy. Few hundreds of nanometers of the target isotope are deposited on a Highly Oriented Pyrolytic Graphite substrate a few micrometers thick. The results of the characterisation of the first target prototypes of tin and tellurium are presented. The Scanning Electron Microscopy was used to qualitatively analyse the samples surface. A setup to study Alpha Particle Transmission has been assembled to measure thickness and uniformity of the targets; the thickness results have been verified by the Rutherford Backscattering measurements. To evaluate the effects of the thickness on the resolution of the DCE products energy, a Monte Carlo code has been implemented, using the measured thickness and uniformity as input data for the simulation.

DOI:10.5506/APhysPolB.51.661

* Presented at the XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

1. Introduction

One of the most investigated topics in the modern nuclear physics is related to the neutrino nature. In particular, many experiments are directly searching for the Neutrinoless Double Beta Decay ($0\nu\beta\beta$) to find out if neutrino is a Majorana or a Dirac particle. The $0\nu\beta\beta$ half-life is related to the Nuclear Matrix Element (NME) that up to now is calculated with a considerable uncertainty by different nuclear models. The NUMEN project fits in this context, measuring the cross sections of the heavy-ion induced Double Charge Exchange (DCE) reactions, whose NME shares many similarities with that of $0\nu\beta\beta$ [1]. NUMEN is a fixed target experiment based at INFN-LNS in Catania. Since DCE reactions are rare (cross sections range from few nb/sr to some μb/sr), very intense ion beams are required to collect a statistically significant set of data, in a reasonable time. For this reason, beam intensity will reach 50 μA with energy from 15 to 60 MeV/u. The NUMEN target isotopes are also candidates for $0\nu\beta\beta$. Some of the planned reactions that will be studied are: ^{116}Cd(^{20}Ne, ^{20}O)^{116}Sn, ^{130}Te(^{20}Ne, ^{20}O)^{130}Xe, ^{76}Ge(^{20}Ne, ^{20}O)^{76}Se, ^{116}Sn(^{18}O, ^{18}Ne)^{116}Cd, ^{76}Se(^{18}O, ^{18}Ne)^{76}Ge. The intense beams will release a large amount of energy inside the target, thus an efficient cooling system is necessary. Therefore, target isotopes will be deposited on a thin substrate of Highly Oriented Pyrolytic Graphite (HOPG), which will quickly transfer the heat outside the target thanks to its high in-plane thermal conductivity [2].

2. Target requirements

DCE are detected by measuring the energy of the ejectile and a good energy resolution is mandatory to clearly identify the reaction. There are some fixed contributions to the NUMEN energy resolution, due to the cyclotron and the spectrometer, evaluated as 1/1000 of the energy each. The target features must be also carefully evaluated in order to estimate the energy dispersion and energy straggling effects.

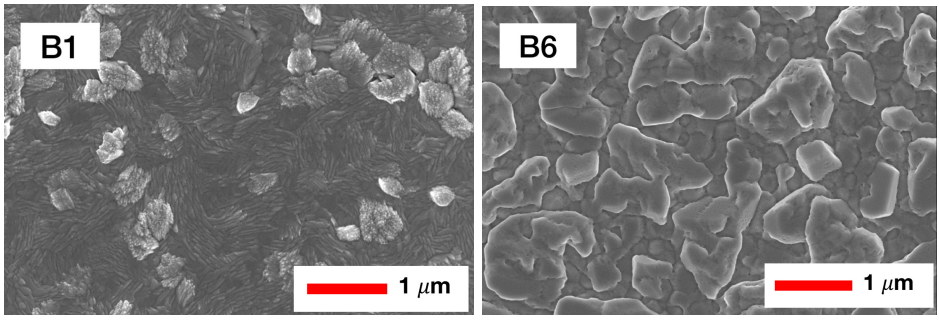
The energy straggling is due to statistical fluctuations of the number of collisions between the ion and target electrons. Straggling occurs both in the target and in the HOPG substrate and is proportional to the square root of the crossed thickness. Instead, the energy dispersion is related only to the target, since it is due to the uncertainty on the depth where the DCE reaction takes place. This effect is proportional to the target thickness.

For these reasons, the target has to be thin (300–500 nm, depending on the isotope) and as uniform as possible, and the substrate thickness must be limited (around a few micrometers).

3. Target production

First prototypes of tellurium and tin targets were produced by the Electron-Beam Physical Vapour Deposition. Deposition parameters (substrate temperature, chromium buffer to facilitate the adherence) have been adjusted in order to increase the uniformity of the target films [4]. First explorative prototypes were produced using a 10 μm thick backing. Once the best deposition parameters have been established, new samples were deposited on a 5 μm thick HOPG substrate. To minimise straggling and dispersion effects, the tellurium and tin targets must be around 250 μg/cm^2 thick.

The Field Emission Scanning Electron Microscopy (FESEM) was used to quickly and qualitatively examine the target surface. Figure 1 shows top view images of tellurium (B1) and tin (B6) depositions on 5 μm HOPG. In the case of tellurium, the substrate was kept at room temperature and no chromium buffer was used. The deposition is quite uniform and flat, with some small structures. For the tin deposition, the HOPG was heated to around 400 K, using a chromium buffer to obtain a uniform cover of the tin layer. A homogeneous deposition covers all the area, with some flat and irregular structures over an underlying layer made of smaller grains. The same study has been performed also on targets deposited on 10 μm HOPG: in general, there are no significant differences between the depositions on substrates of different thickness.



(a) (b)

Fig. 1. FESEM images of tellurium (a) and tin (b) depositions on 5 μm HOPG.

4. Target thickness and uniformity evaluation

Low-energy ion beams can be used to evaluate the thickness of a sample measuring the beam energy loss. In order to evaluate both thickness and uniformity of targets and substrates, a set-up to perform Alpha-Particles Transmission (APT) measurements has been assembled at Politecnico di Torino. The α particles are provided by a ^{241}Am source and collimated by a cylindrical collimator with diameter $\simeq$ 3 mm (close to the size of the

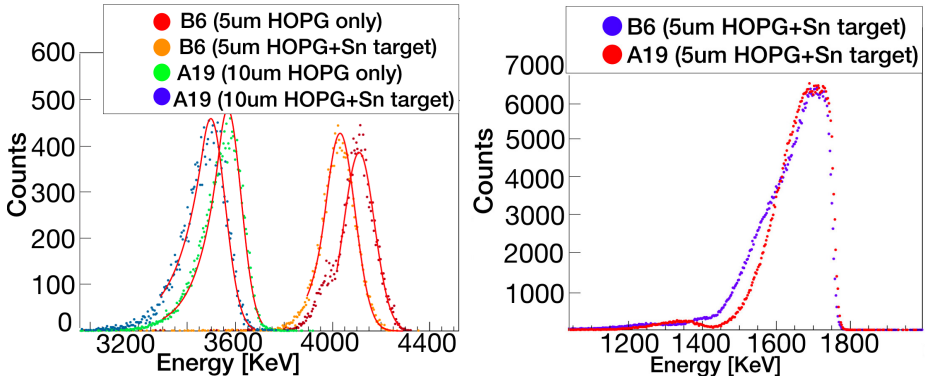
NUMEN beam). The energy of α particles after passage through the sample under study was measured by an ion-implanted silicon detector, placed downstream from the target. A chain of electronics (pre-amplifier, amplifier, ADC) and MAESTRO software [3] were used for data readout. The energy calibration of the set-up was performed before every data taking, by using an additional source of ^{148}Gd, to correct the electronics drift due to temperature variations.

The obtained energy spectra were analysed in the ROOT framework, performing a fit of the peaks with Crystal Ball functions. The Crystal Ball peak shape was preferred over a Gaussian shape because of the low-energy tail of the APT energy spectra. Figure 2 (a) shows an example of APT spectra of the analysed tin targets, acquired before the deposition (only HOPG) and after the deposition (target + HOPG). The HOPG thickness for samples A19 and B6 was equal to 10 μm and 5 μm, respectively. The peak of the energy spectrum represents the most probable thickness crossed by the beam, while the standard deviation σ is related to the thickness uniformity and to the energy straggling. The thickness of the target is given by the shift between the two peaks before and after the deposition. The target non-uniformity can be estimated from its contribution $\sigma_{\text{target non}-\text{uniformity}}$ to the total standard deviation σ_{tot} as

$$\sigma_{\text{target non}-\text{uniformity}} = \sqrt{\sigma^2_{\text{tot}} - \sigma^2_{\text{HOPG}} - \sigma^2_{\text{target straggling}} - \sigma^2_{\text{detector+noise}}},$$

where σ_{tot} is the standard deviation of the distribution after the deposition, approximately given by the Crystal Ball fit, σ_{HOPG} is the same before the deposition (it contains HOPG non-uniformity and straggling), $\sigma_{\text{target straggling}}$ is the standard deviation due to straggling inside the target, and $\sigma_{\text{detector+noise}}$ takes into account the detector resolution and the electronics noise.

To verify the accuracy of the APT thickness results, the samples were also systematically studied with the Rutherford Backscattering (RBS) at the AN2000 accelerator at INFN-LNL. The RBS measurements were performed with an α beam of 2 MeV (1 mm in diameter), the scattered beam detected at 150°. The average energy of the low-energy edge of the spectrum is used to evaluate the average sample thickness. Figure 2 (b) shows, as an example, the RBS spectra of the tin targets: the two deposition thicknesses are equal (the same average energy), even though the respective substrates have different thicknesses. These RBS spectra correspond to the target only, without a HOPG substrate contribution, because of the low energy of the α beam. RBS is not suited to obtain quantitative information on the thickness uniformity, even though the slope of the left edge of a RBS spectrum is somehow related to it.



(a) (b)

Fig. 2. (a) APT energy spectra of B6 and A19 tin samples before and after the target deposition. (b) RBS energy spectra of B6 and A19 tin targets.

Table I shows the APT and RBS results of thickness and the APT results of uniformity for tellurium and tin targets. The agreement on the thickness results between the two analysis techniques is generally good, below 3% for all but B6, whose measurement was affected by a mistake in the energy calibration due to a drift of electronics. These results confirm that the APT set-up is a reliable tool to obtain not only the sample thickness but also a quantitative measure of the thickness uniformity.

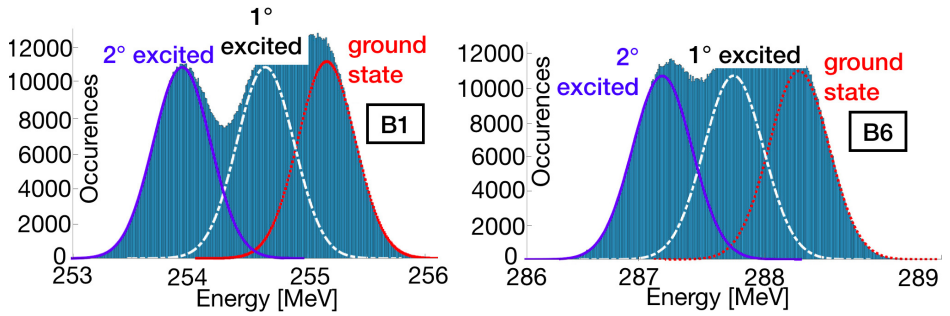
TABLE I

Thickness (APT and RBS) and uniformity (APT) results obtained for A7 and B1 targets (tellurium on 10 and 5 μm thick HOPG, respectively) and for A19 and B6 targets (tin on 10 and 5 μm thick HOPG, respectively). Δ is evaluated as $\frac{|\mathrm{RBS}-\mathrm{APT}|}{(\mathrm{APT}+\mathrm{RBS})/2}$ and the non-uniformity as $\frac{\sigma_{\text{target non}-\text{uniformity (APT)}}}{\text{thickness (APT)}}$.

Target	Thickness (APT)	Thickness (RBS)	Δ	Non-uniformity (APT)
A7	435 μg/cm^2	440 μg/cm^2	1.1%	17%
B1	470 μg/cm^2	480 μg/cm^2	2.1%	17%
A19	175 μg/cm^2	180 μg/cm^2	2.8%	29%
B6	235 μg/cm^2	195 μg/cm^2	19%	28%

A Monte Carlo code has been written to simulate the energy distribution of DCE ejectiles in order to evaluate the target effects on the energy resolution. Experimental values of target thickness and uniformity, measured by ATP, are used as input parameters. Contributions from the cyclotron and spectrometer are taken into account as well. The same cross sections

for the ground state, first and second excited levels of the residual nucleus were assumed. Figure 3 shows the energy distribution of the DCE ejectile in the case of a simulated reaction ^{130}Te(^{20}Ne,^{20} O)^{130}Xe at 15 MeV/u with the target system B1 (Fig. 3 (a)) and the reaction ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd at 15 MeV/u with the target system B6 (Fig. 3 (b)). With the current tin and tellurium target non-uniformity, it is possible to clearly distinguish the second excited state. The separation between the ground state and the first excited level is much less evident and requires further analysis.



(a) (b)

Fig. 3. Energy distribution of DCE ejectiles with the target systems B1 and B6.

5. Conclusions

Prototypes of tellurium and tin target for the NUMEN Experiment were produced and studied. Their characterization was performed with FESEM, APT and RBS. The APT technique is a useful tool to study both thickness and uniformity of thin samples, as verified by the results on thickness obtained in the RBS measurements. Thickness and uniformity of the presented tellurium and tin target prototypes are good enough to allow the identification of a DCE reaction, clearly distinguishing between the ground state of the target nucleus and excited levels higher than the first one.

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