DESIGN AND TEST OF AN INNOVATIVE STATIC THIN TARGET FOR INTENSE ION BEAMS

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(For NUMEN Collaboration)

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The purpose of the NUMEN project is to measure the cross-section of Double Charge Exchange (DCE) reactions, a strong process at the end of which $Z_{\text{target}}$ increases by 2 units while $Z_{\text{projectile}}$ decreases by 2 units (and vice versa).
Data collected in NUMEN will help in establishing the Nuclear Matrix Element value of the neutrino-less double β-decay (ββ0ν), providing that the measurement errors are small.

NUMEN is hosted at the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (Catania, Italy), taking advantage of the intense ion beams facility.

For further information please look at: https://web.infn.it/NUMEN/index.php/it/
Although $\beta\beta_0\nu$ and DCE are driven by different interactions, they share several similarities, like the same initial and final states of the target and projectile (see plenary talk by F. Cappuzzello).

In addition to the elements listed in the table aside, also Gd, Mo, Xe, etc.

The studied targets are used in experiments searching for $\beta\beta_0\nu$, like Cuore, Gerda,...

### DCE Reactions in NUMEN

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Mass</th>
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<tbody>
<tr>
<td>$^{116}\text{Sn}(^{18}\text{O},^{18}\text{Ne})^{116}\text{Cd}$</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Se}(^{18}\text{O},^{18}\text{Ne})^{76}\text{Ge}$</td>
<td></td>
</tr>
<tr>
<td>$^{130}\text{Te}(^{20}\text{Ne},^{20}\text{O})^{130}\text{Xe}$</td>
<td></td>
</tr>
<tr>
<td>$^{116}\text{Cd}(^{20}\text{Ne},^{20}\text{O})^{116}\text{Sn}$</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Ge}(^{20}\text{Ne},^{20}\text{O})^{76}\text{Se}$</td>
<td></td>
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[...]
To have a good statistics, it is necessary to collect a suitable amount of data. This can be done either thickening the target or increasing the beam intensity.

Unfortunately, increasing the target thickness would also increase the error due to the straggling and the dispersion, worsening the quality of the data.

This error would be added to unavoidable error sources; the cyclotron beam and spectrometer both introduce an error of the 0.1% of the beam and ejectyles energy.
The main error associated with the target is the energy dispersion, which depends on where the reaction occurs. It increases both with the target thickness and non-uniformity.

Considering a Sn target, dispersion error becomes comparable to other sources for a 600nm flat target, but things get worse for a non uniform target.
Hence, a thickness of 400 nm has been chosen as a compromise.

The targets must be thin, so it is necessary to increase the beam intensity.

What is the maximum current that can be withstood?
NUMEN Targets

- The NUMEN target used for low intensity beams can be approximated as a disk. The red spot is the beam spot, the blue region is the cold frame, the light blue region is the portion of target clamped by the frame. The orange disk is the target region where the heat flows to reach the cold frame.

- The latter region has been considered to calculate the maximum beam current achievable in this configuration.
NUMEN Targets

- Supposing stationary conditions, the heat equation has been solved in the orange region.

- Since the target is thin, $T$ has been supposed $z$ independent. The heat equation is therefore:

\[
k_r \left( \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right) = \rho c_p \frac{\partial T}{\partial t}
\]
Solving the heat equation and using the Fourier equation to relate incoming heat and temperature, one finds that a simple cooling frame is not sufficient to cool down the target.
Graphite Substrate

- To overcome the issues in the heat dissipation, a highly conductive substrate has been used.
- The target (in green) is deposited on a large graphite disk (grey and blue).
- The idea is to clamp the graphite with a cold frame, exposing to the beam just the target and the underlying graphite.
Graphite Substrate

In this way, the heat generated in the target (and in the substrate) will be quickly transferred to the cold frame, thanks to the graphite excellent thermal conductivity. The commercially available graphite comes in sheets 10 µm thick and several cm large.
The sample holder would be composed by two halves made in copper, which would encase tightly the graphite substrate. The exploded-view shows the target, the graphite and the sample holder.
Graphite Substrate and Cryocooler

- The beam would impinge at the centre of the target (red spot), without touching the copper frame.
- The system would be mounted on a cryocooler, able to dissipate up to 40 W of power while keeping the sample holder at 40K.
Graphite Substrate and Cryocooler

- The beam would impinge at the centre of the target (red spot), without touching the copper frame.
- The system would be mounted on a cryocooler, able to dissipate up to 40 W of power while keeping the sample holder at 40K.
To evaluate and quantify the benefits deriving from the usage of a graphite substrate, the heat equation must be solved for both the target and the substrate.

A numerical solution has been found with a MatLab code. The thickness of the target has been set to 400 nm, the one of the graphite to 10 µm. The heat equation in cylindrical coordinates reads:

\[ k_r \left( \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right) + k_z \frac{\partial^2 T}{\partial z^2} + \rho c_p \frac{dQ}{dt dV} = \rho c_p \frac{\partial T}{\partial t} \]
MatLab code

- The target and the underlying graphite are divided into an annular mesh;
- The heat is supplied at the center, in correspondence with the beam spot, and it is dissipated at the cold boundary, where the temperature $T_c$ is fixed.
MatLab code

- The temperature profile is mapped in every point of the mesh. The heat equation is solved every $dt$ up to the stationary state.
- The beam profile is gaussian, with a $\sigma=1\text{mm}$.
For a Sn target, the temperature becomes stable in roughly 0.07 seconds. Also for other targets, the steady state is reached in few tens of ms.
Thanks to the graphite substrate, most of the targets can tolerate beam currents of 50 $\mu$A at 15 MeV/u. The plot aside shows the temperature evolution in time, up to the maximum value.

The maximum temperature is always reached within 100 ms.
This cooling system does not guarantee the usage of such current for the Se target. For the latter, the maximum current is limited to 35 µA.

For higher energies, the maximum reached temperatures decrease.
Prototype production

- Electron Beam Deposition has been chosen as deposition technique for its versatility and good uniformity. Nevertheless, graphite is bad substrate for depositing materials, being smooth and inert.

- So far, the deposition parameters have been optimized for Sn and Te targets.

- The characterization of the deposited films is currently performed with a Field Emission Scanning Electron Microscope (FESEM), but will be soon integrated with Alpha Spectroscopy (@ PoliTo) and Rutherford Backscattering measurements (@ INFN - LNL).
For Sn targets, the best results were achieved depositing a Cr buffer on the graphite to improve adhesion.

The substrate is kept at 130° during the deposition, to improve the uniformity of the coverage.

The substrate is exposed only in few spots.
The side view of the sample shows that there are no high structures/clusters on top of the film surface.

The film detachment from the substrate was caused by the ripping of the substrate, which cannot be clearly cut.
FESEM - Te

- The Te films generally appear more uniform and compact than Sn ones.
- The showed sample had been deposited at RT, using again a Cr buffer.
Similarly to other samples, the graphite substrate prevents to have a clear cut, so side images are not optimal.

However, few structures are present above the surface, the film appears uniform and compact.
An alpha spectroscopy apparatus has been set up in the last few months. It will provide extremely useful information about the average thickness and uniformity of the samples.

A first application was the following:

Since the 10 µm graphite sheets come with a 6 µm thick layer of acrylic adhesive, which must be eliminated using plasma etching, some preliminary measurements have been performed on few graphite samples to evaluate the effects of high temperature on such adhesive.
A graphite sample was heated at 300° for several hours.

Before treatment, the peak is at 2,54 MeV and has a FWHM of about 381,5 keV.
After the heat treatment, the peak shifted at 3.4 MeV, which corresponds to an adhesive thickness reduction of 4.7 µm.

The FWHM reduced to about 236.8 keV.
Conclusions

- NUMEN experiment will use very intense ion beams; this poses a challenge on a variety of aspects in the target design;
- To reduce the errors, target must be thin (400 nm), but must withstand strong heating. Hence, they have been improved by adding a highly conductive graphite substrate. Considering numerical calculation, this solution seems promising;
- Albeit being a bad substrate, good results were obtained for Tin and Tellurium deposition, using a Chromium buffer and Electron Beam Deposition;
- Alpha spectroscopy has been used to obtain preliminary information about the substrate effective thickness.
Future work

- The analytical solution of the temperature equation for the target-graphite system is going to be calculated soon. It will be a further proof of the graphite substrate contribute;
- The deposition parameters will be studied more deeply, in order to improve the control on the film quality;
- Some samples have been irradiated by ion beams in collaboration with the University of Mexico City, at lower energy and intensity: the evaluation of the collected data is still ongoing;
- The produced samples will undergo alpha spectroscopy and Rutherford Backscattering characterization to check the effective thickness;
- Plasma etching will be used to fully remove the adhesive layer;
- Stress tests will be performed on the full cooling system, by using LASER and ion beams.
THANKS FOR YOUR ATTENTION
Further Slides
Ion Beam Test @ UNAM and ININ, Mexico

- Sn and Te targets have been irradiated with a C beam, at different energies and intensity.
- The cooling system (shown mounted inside the scattering chamber) was composed by a copper sample holder, in which LN can flow.
- The collected data will be compared to numerical calculations, to evaluate the validity of the numerical model.
Error with graphite

116Sn(18O,18Ne)116Cd 15 AMeV
Non-uniformity = 0

FWHM [MeV]

Target thickness [nm]

T Dispersion
T Straggling
C Straggling
MAGNEX
Cyclotron
TOTAL
Error with graphite

116Sn(18O,18Ne)116Cd 15 AMeV
Non-uniformity = +/- 20 %
Maximum Beam Current Tolerable by Targets

- 116Sn
- 116Cd
- 76Se
- 76Ge
- 130Te

**Beam Current [µA]**

**Beam Energy [MeV/u]**
Sample holder with aligner