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Tests of a cooling system for thin targets submitted to intense ion beams for the numen experiment / Pinna, F., Capirossi, V., Delaunay, F., Iazzi, F., Brunasso, O., Calvo, D., Fisichella, M.. - In: ACTA PHYSICA POLONICA B. - ISSN 0587-4254. - ELETTRONICO. - 51:3(2020), pp. 655-660. [10.5506/APhysPolB.51.655]

Availability:
This version is available at: 11583/2843496 since: 2020-08-31T12:43:52Z

Publisher:
Jagellonian University

Published
DOI:10.5506/APhysPolB.51.655

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06 November 2026

TESTS OF A COOLING SYSTEM FOR THIN TARGETS SUBMITTED TO INTENSE ION BEAMS FOR THE NUMEN EXPERIMENT*

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(Received January 7, 2020)

The NUMEN experiment, hosted at LNS (Catania, Italy), aims to determine the Nuclear Matrix Elements (NMEs) involved in $0\nu\beta\beta$ decay via heavy-ion induced Double Charge Exchange (DCE) reactions. High intensity beams of about 50 μA and of energies ranging from 15 to 60 MeV/u are necessary, due to the low DCE cross sections and the use of very thin targets (several hundreds of nm) needed to reach the required energy resolution. These intense beams produce a considerable amount of heat inside the target, which can be dissipated by depositing the targets on a highly thermally conductive substrate, HOPG (Highly Oriented Pyrolytic Graphite), and coupling it with a suitable designed target-cooler system. The heat transfer from the beam spot to the cold region has been studied by solving numerically the heat equation to determine the evolution in space and time of the temperature inside the target. According to calculations, the temperatures of most of the target isotopes remain under the melting points. Experimental tests with a laser were initiated to validate the whole cooling system and the calculations.

DOI:10.5506/APhysPolB.51.655

1. Introduction to the NUMEN Project

The goal of the NUMEN experiment, hosted at Laboratori Nazionali del Sud (LNS-INFN) in Catania, is to measure cross sections of Double

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

Charge Exchange (DCE) reactions in order to evaluate the related Nuclear Matrix Elements (NME). Those will be used to better constrain the NME of Neutrinoless Double β Decay ($0\nu\beta\beta$); many experiments are currently searching for $0\nu\beta\beta$, to establish whether neutrinos are Dirac or Majorana particles. However, the lack of direct experimental information on NME increases considerably the uncertainty of the decay half-life.

NUMEN is already running using a few nA beam currents on targets, which are typically thinner than 1 μm for energy resolution reasons. Some of the investigated isotopes, like ^{116}Cd, ^{130}Te and ^{76}Ge, are candidates for spontaneous $0\nu\beta\beta$ decay and are used for a direct $0\nu\beta\beta$ search. They are used to study $\beta^-\beta^-$-like transitions via the (^{20}Ne,^{20}O) reaction channel. Other isotopes, such as ^{116}Sn and ^{76}Se, are used to study $\beta^+\beta^+$-like transitions in reactions with ^{18}O beams. The amount of data collected in the preliminary runs is far from being sufficient to ensure a proper statistics; cross section values for the studied DCE reactions are of the order of a few nb, thus only a few tens of events have been detected so far [1]. The desired statistics can only be obtained following an upgrade of the whole apparatus, which is planned to start in 2020. The expected beam intensity is about 50 μA, with the energy ranging from 15 MeV/u to 60 MeV/u. A detailed description of the NUMEN experiment and its upgrade can be found in Ref. [2]. Such a high beam intensity poses a threat to the target integrity. It has been demonstrated [3] that stand-alone targets are not suited for such intense beams. The deposited power density will be about 10^5 W/cm^3, too much to be dissipated by mid-to-low thermally conductive materials.

2. Cooling system

A highly thermally conductive substrate, made of Highly Oriented Pyrolytic Graphite (HOPG), is used to drain the heat generated by the beam from the target to the sample holder. Moreover, it will mechanically sustain the target and serve as a post-stripper for reaction products [4]. The sample holder is mounted on a cooling device, which keeps it at a fixed temperature of 40 K. A scheme of the working principle is shown in Fig. 1 (a). The substrate is a few μm thick and several cm wide, so that it can be firmly pinched to the sample holder. Perfect contact is assumed at the target/HOPG interface, since the target is deposited on HOPG by Electron Beam Deposition. Displacements with respect to the substrate due to different thermal expansion coefficients do not exceed a few tens of μm along the plane. The thermal resistance between the HOPG and the sample holder is also expected to be negligible, as the latter is carefully machined to be as flat as possible, ensuring homogeneous clamping on the graphite. Moreover, HOPG is easily compressible in the direction perpendicular to the plane:

under pressure, it will conform to the harder copper surface. Therefore, the HOPG clamped within the sample holder can be assumed to be at the same temperature as the sample holder. This assumption is used as a boundary condition in a numerical code, written to evaluate the thermal behaviour of the target/graphite system.

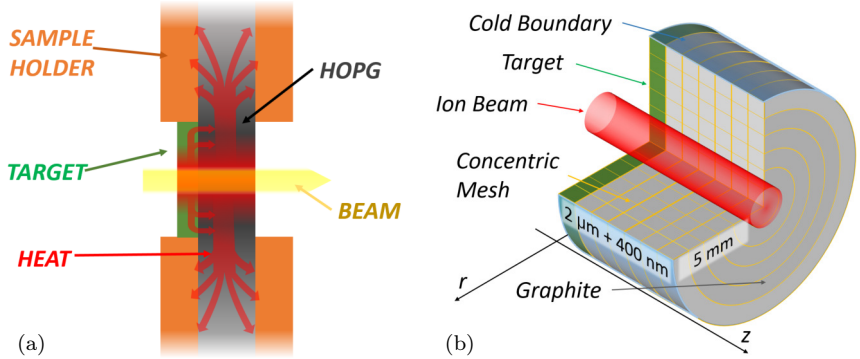

Fig. 1. (Color online) (a) Scheme of the target (in green) and HOPG (in grey) system, enclosed in a copper sample holder (in orange). Highlighted in red is the path followed by the heat inside the target/substrate. (b) Scheme of the cylindrical mesh used in the numerical code. The beam, in red and directed along positive z, has a Gaussian distribution and passes through the center; the boundary, in pale blue, remains at fixed $T_{cold} = 40$ K; target and HOPG are shown in green and gray, respectively.

The code solves the heat equation in cylindrical coordinates in the target and the underlying HOPG volume. Heat deposited by the beam is calculated using the Bethe–Bloch formula for a Gaussially-distributed ion beam, with standard deviation $\sigma \approx 1$ mm composed of fully stripped ions. The steady state temperatures, reported in Fig. 2, are obtained in the worst-case scenario: a 50 μA beam at 15 MeV/u. With this beam characteristics and supposing a 2 μm thick HOPG backing, the dissipated power is lower than 10 W. For more energetic beams, the steady state temperatures would decrease due to the lower projectile energy loss. The target thicknesses were set to a reference value of 400 nm. The actual final thickness of each target is still under investigation, but no major changes are expected in the steady state temperatures. Calculations showed that most of the targets can endure a 50 μA ion beam with an exception of selenium whose exceptionally low thermal conductivity noticeably hampers the heat flow. A maximum beam current of 30 μA should be used to keep the Se target in a safe temperature range.

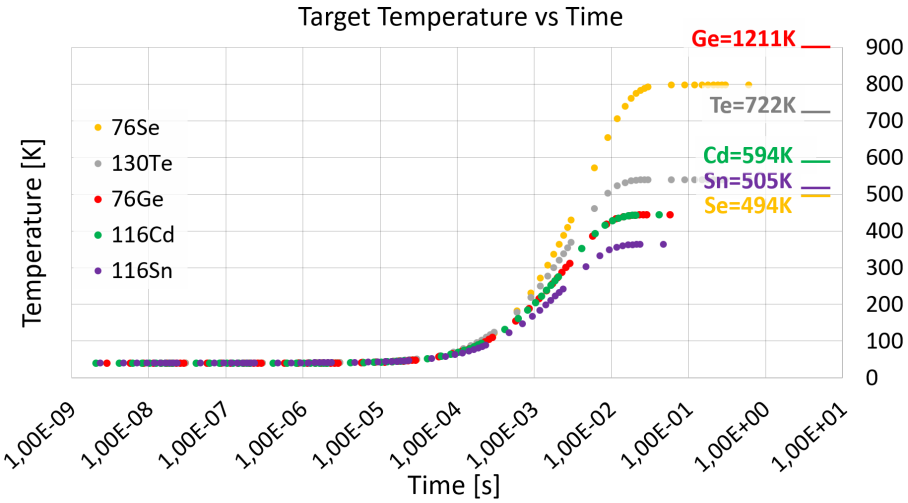

Fig. 2. Time evolution of the target center temperature for each isotope; on the right-hand side of the plot, the melting point is displayed. The used beam current is 50 μA, the energy is 15 MeV/u.

3. Laser test apparatus and results

The performed numerical calculations indicate that the designed cooling system works. However, those calculations were made assuming that once the heat reaches the sample holder, it would be immediately dissipated into the cooling device, thanks to the assumptions made in Sec. 2. A test, using a laser as the heating source, was arranged in order to confirm these assumptions. The downside of using a laser as the heating source is the extremely high power density deposited on the target surface (several times higher than those of NUMEN beams), which could be withstood only by a graphite target. Hence, a plain HOPG targed was used for the test. The cooling device is a Leybold cryocooler 5/100, whose sample stage can be cooled down to 10 K thanks to a liquid helium circuit (Fig. 3 (a)). The sample holder, a prototype of which is shown in Fig. 3 (b), is designed to fit on the sample stage of the cryocooler (the copper cylinder on top of the cryocooler). It is composed of two halves, which are screwed together to clamp the graphite substrate, leaving the target exposed.

A large layer of HOPG (about 25 cm^2) was needed for the test, in order to fill the whole space between the sample holder halves. For availability reasons, a 10 μm thick HOPG has been used: it is much easier to obtain, while having the same physical properties as a thinner HOPG. The beam was provided by an 888 nm IR laser with a maximum output power of 40 W.

(a) (b) (c)

Fig. 3. (a) The cryocooler. The sample stage is the topmost copper object and can be cooled down to 10 K. (b) HOPG target enclosed in the copper sample holder, to be mounted on the cryocooler sample stage. The two upper holes will be used in beam calibration procedures. (c) The HOPG target and sample holder mounted on the cryocooler sample stage. The laser optical fiber is about 1 cm far from the target.

The light beam is transported into the vicinity of the HOPG target using an optical fiber (Fig. 3 (c)) in order to have a beam spot of about 5 mm, roughly the same size as the beam spot expected for the upgraded NUMEN ion beam. The net power absorbed by the target is obtained by subtracting the reflected power (about 40% [5]).

The target temperature was measured with a thermal camera. The temperature of the sample stage, which is equal to that of the sample holder, is nearly proportional to the power absorbed by the sample holder itself, and was measured with a thermocouple. These two temperatures are reported in Fig. 4 as a function of the net power absorbed by the HOPG target. The values obtained with the thermocouple are used as a boundary cold temperature in the numerical code. The calculated steady state temperatures are reported in Fig. 4. The agreement between the experimental data and the numerical results is quite good: the error bars of the two datasets overlap in each point.

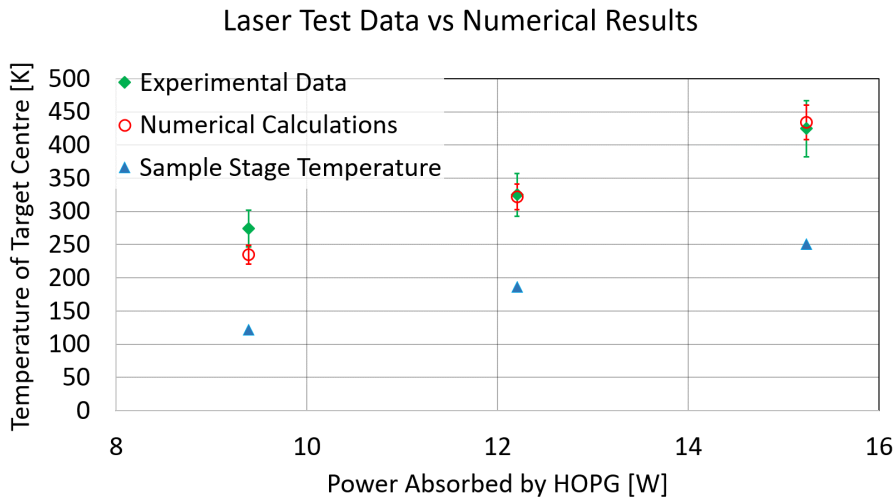

Fig. 4. (Color online) Comparison between target temperatures measured during the laser irradiation test (green diamonds) and results of numerical calculations (red open circles). The error bars on the numerical calculations are related to uncertainties of the density and thermal conductivity; those on the experimental data are due to the thermal camera resolution. Error bars on the cold head temperature (blue triangles) are smaller than the symbol size.

4. Conclusions

A cooling system for the NUMEN experiment target has been designed. To withstand tens of μA of ion beam current, targets are deposited on a HOPG substrate; numerical calculations confirmed the feasibility of the design. The whole cooling system, composed of a HOPG target, copper sample holder and cryocooler, was tested using an IR laser as the heating source. Experimental data and numerical results show satisfactory agreement in the explored temperature range. A more realistic test with a heavy-ion beam is under study to be performed in 2020.

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