

A high precision calorimeter for hunting the sterile neutrino in the SOX experiment

L.Di Noto¹, M.Agostini², K.Altenmüller², S.Appel², A.Caminata¹,
L.Cappelli³, R.Cesereto¹, S.Farinon¹, M.Gschwender⁴, H.Hess²,
J.Martyn⁵, R.Musenich¹, B.Neumair², M.Nieslony⁵, T.Lachenmaier⁴,
L.Oberauer², M.Pallavicini¹, L.Papp², C.Rossi¹, S.Rottenanger⁴,
S.Schönert², G.Testera¹, A.Trantel⁴, S.Weinz⁵, M.Wurm⁵,
S.Zavatarelli¹

¹ Dipartimento di Fisica, Università degli studi e INFN, 16146 Genova, Italy

² Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany

³ INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy

⁴ Eberhard Karls Universität Tübingen, 72072 Tübingen, Germany

⁵ Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

E-mail: lea.dinoto@ge.infn.it

Abstract. A thermal calorimetric apparatus was designed, built and calibrated for measuring the activity of the artificial $^{144}\text{Ce} - ^{144}\text{Pr}$ antineutrino source. This measurement will be performed at the Laboratori Nazionali del Gran Sasso in Italy, just before the source insertion in the tunnel under the Borexino detector and a precision better than 1% is required for a disappearance technique measurement in the SOX (Short distance neutrino Oscillation with BoreXino) project. In this work the apparatus is described and the most important results from the calibration measurements are shown, where the final precision of few per thousand is demonstrated.

1. Introduction

Since the neutrino anomalies can be explained by the existence of a sterile neutrino and they hint to the short distance neutrino oscillations ($\delta m^2 = 1 \text{ eV}^2$)[1], the SOX experiment [2] was proposed with the goal of using a $^{144}\text{Ce} - ^{144}\text{Pr}$ antineutrino artificial source for a possible direct observation of the short distance oscillations and at the same time, for a precise disappearance experiment, if the source activity is measured better than 1% precision. The $^{144}\text{Ce} - ^{144}\text{Pr}$ artificial antineutrino source of $\sim 150 \text{ kCi}$ activity (1200 W) is being produced at the Mayak Production Association in Russia after a chemical extraction from spent nuclear fuel. After the transportation to the Laboratori Nazionali del Gran Sasso, before the insertion in the tunnel under Borexino detector, the calorimetric measurement will occur thanks to two different calorimeters (the INFN-TUM calorimeter and the CEA calorimeter). In this work the INFN-TUM apparatus is presented.



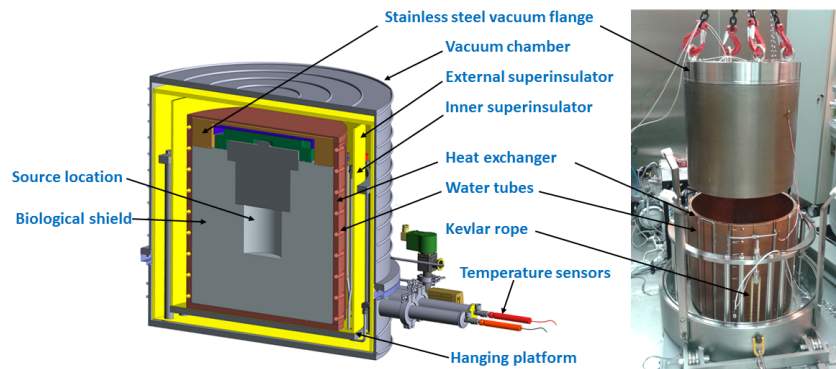


Figure 1. At left: the section view of the calorimetric apparatus; the main components are shown. At right: picture of the apparatus before the tungsten alloy shield is lowered inside the copper heat exchanger. In the copper heat exchanger the water pipe is clearly visible.

2. Apparatus description

The radioactive source is made of few kilograms of CeO_2 powder pressed into a two double wall stainless steel container, closed inside a tungsten alloy biological shield, with a minimum thickness of 19 cm (see Fig. 1). Since the shield debars a precise and direct β or γ spectroscopic activity measurement, a calorimetric apparatus was designed in order to estimate the heat released from the source that is directly linked to the total activity. In the INFN-TUM calorimeter the thermal heat is absorbed by the water flowing inside a pipe, embedded in a copper heat exchanger, directly in contact with the tungsten shield and by measuring the mass flow \dot{m} and by knowing the temperature of the entering T_{in} and the outgoing T_{out} water respect with the copper exchanger, the power P emitted by the source can be obtained by the relation:

$$P = \dot{m} [h(T_{out}, p) - h(T_{in}, p)] \quad (1)$$

where $h(T, p)$ is the water enthalpy function, which depends on the temperature and on water the pressure p in the pipe line, and tabulated with about 0.1% accuracy by the International Association for the Properties of Water and Steam in [5].

The apparatus was designed in order to minimize all the heat losses and in particular the convection was reduced thanks to a big vacuum chamber, where a residual pressure of the order of $p \sim 10^{-5}$ mbar can be achieved by a scroll and a turbo molecular pump. In addition, the source and the copper heat exchanger were placed on a platform kept suspended by three Kevlar ropes (whose heat capacitance is low) in order to reduce any conduction between the copper exchanger and the external vacuum chamber. Finally in order to minimize the radiation, two stages of super insulators (10 layers each) were built and located between the copper exchanger and the vacuum chamber and a water pipe was soldered on the chamber surface for allowing the chamber thermalization to a temperature closer to the average copper exchanger temperature. The apparatus here described is shown in Fig.1, where all the main components are visible in the section view.

The water circulating inside the copper exchanger is pumped and cooled by a chiller, the massflow is measured by two Coriolis flowmeters (0.05% precision) and the flow is regulated and actively controlled by a pneumatic valve in a feedback loop with the flowmeter. Just before the inlet and the outlet of the copper exchanger the water temperature is measured by two Semi-Standard Platinum Resistance Thermometers immersed in the water line and read out by a high precision thermometer, ensuring a final precision of 3 mK on the water temperature. Thanks to an active Proportional, Integrative and Derivative control based on a 150 W heater in a

feedback loop with the thermometer, the temperature of the entering water can be stabilized up to 0.04°C of maximum oscillation around the average value, compensating any environmental fluctuation or chiller instability during the measurements, and preventing any instability also on the T_{out} temperature.

In addition a water loop was installed in order to heat the vacuum chamber to the desired temperature; in this case a centrifugal pump and a 1000 W heater allows the hot water to circulate with an high value of massflow (around 30 g/s for reducing to few degrees the temperature gradient on the chamber) inside the stainless steel pipe soldered on the external surface of the chamber. Thanks to a dedicated feedback loop based on the temperature sensor on the chamber, a temperature of the order of $20 - 35^\circ\text{C}$ can be set, with a maximum fluctuation around the average value of about 0.4C .

During the calibration phase, the INFN-TUM calorimeter was tested with a mock-up source made by six electrical heaters inserted in a copper cylinder, closed inside the tungsten alloy shield. A power ranging from 700 W up to 1200 W was set with 0.04% uncertainty and the set value was obtained by measuring the current flowing in the circuit and the voltage as applied just close to the stainless steel flange on the top of the tungsten shield. The electrical power was continuously controlled by regulating the applied voltage in order to compensate any heating effect on the heaters resistance during the measurement or to reproduce the source decay during the time.

3. Calibration measurements results

The calibration measurements were divided in two groups: in the first phase the optimization of the system parameters was performed in order to evaluate the losses in different conditions, whilst in the second phase the behavior to an exponential decaying power simulating the source was investigated. For each measurements the temperatures in many points inside the apparatus were acquired continuously and the losses were investigated as a function of the temperature distribution. The parameters that can be set are:

- the massflow value \dot{m} , that ranges between 5 and 13 g/s: in fact values lower than 5 g/s generate too high T_{out} value, inducing the formation of bubble in the water, whilst values higher than 13 g/s produce a positive (bigger than 0.4 W) spurious power due to the friction;
- the temperature of the vacuum chamber T_{ch} that can be increased of about 10°C above the environmental temperature;
- the temperature T_{in} , ranging between 10 and 20°C and it was chosen around 16°C , just few degrees lower than the environmental temperature for allowing the temperature control.

3.1. Calibration with a constant set power

Many measurements were performed in order to estimate the losses and in order to optimize the massflow value and the chamber temperature. For each measurement a constant power was set in the range 700-1200 W and all the temperature sensors were acquired during the time. Since the big mass of the shield, the heat capacity of the tungsten and the thermal contacts between all the components, from the inner copper mockup source through the tungsten alloy shield and to the external copper heat exchanger, a *transient period* of about 3 days was found, during which all temperature sensors increase their values up to reach a stable value in the *equilibrium condition*. The stability was evaluated by calculating the incremental ratio of T_{out} during a time period of 3 hours and only the phase in which the ratio was lower than 20 mK/h was selected for the analysis. For each measurement the power was calculated by the equation 1, where T_{in}, T_{out} and \dot{m} are the average values as extracted during the equilibrium condition, of more than 4 hours duration. Since the T_{in} and \dot{m} are controlled by the feedback loop, they fluctuate around the average value and the accuracy of the instruments (3 mK for T_{in} and 0.05% for \dot{m})

was taken as error, while for T_{out} the real fluctuation during the equilibrium condition (around 10 mK and different for each point) was considered. In addition the accuracy on the enthalpy $h(T, p)$ knowledge ($\sim 0.1\%$) as tabulated in [5], was considered and it contributes significantly to the final error that is of the order of 0.2%.

The losses were studied by varying the parameters of the system as the mass flow or the temperature of the vacuum chamber T_{ch} with respect to the copper heat exchanger T_{exc} , for different set powers. As it results from the plot shown in Fig.2a) the losses are influenced mainly by the difference $T_{exc} - T_{ch}$ and they are always lower than 0.4% even in the case when $T_{exc} - T_{ch} \sim 16^\circ$ C, but it can be close to zero if $T_{exc} - T_{ch} < 8^\circ$ C. It is worth noting that the massflow value directly influences the T_{out} and T_{exc} temperature and thus it has to be chosen accordingly to the set power in order to obtain a T_{out} value around 40° C, in such a way that T_{ch} can be set around 30° C. Since the losses are induced by the temperature distribution, the massflow can be increased for higher power without increasing the total losses and by comparing measurement at different powers and different massflows it can be concluded that a massflow value close to 12 g/s has to be chosen if the power released by the source is expected to be 1200 W.

The losses were estimated also with a pressure of the order of 10^{-3} mbar (instead of 10^{-5} mbar) achieved by switching off the turbo molecular pump. In that case they resulted of the order of 0.6% but they were lowered to 0.4% when the difference $T_{exc} - T_{ch}$ was reduced as well.

From these measurements the massflow and the chamber temperature were optimized in such a way that if the residual pressure is of the order of 10^{-5} mbar, the losses are always lower than 0.2% and, since the applied value was always found inside the statistical error of 0.2%, no additional systematic uncertainty has to be introduced.

3.2. Calibration with an exponential decaying power

In order to simulate the radioactive $^{144}\text{Ce} - ^{144}\text{Pr}$ source a power function

$$P(t) = P_0 e^{-\frac{t}{\tau_{Ce}}} \quad (2)$$

where $\tau_{Ce} = 411$ days is ^{144}Ce lifetime was applied. In this case the equilibrium condition is never reached since the generated heat is measured with a delay dependent on the global thermal diffusivity of system and on the decay time τ_{Ce} . In practice, due to the massive biological shield and to the several interfaces, the delay cannot be a priori neglected and it was estimated to be about 0.2 days, by means of many finite elements simulations performed during the design phase [4]. The goal of these tests was to evaluate its influence on the final power estimation.

In Fig.2b) the measured power is shown as a function of the time and the transient phase of 3 days is however visible, after which the system reaches the final phase where the measured power behavior follows the negative exponential function as well. In principle, assuming that the losses are really close to zero, the measured power is expected higher respect with the applied power, due to the delay that shifts the measured power in the time scale, but in the real case either this effect or the vertical shift due to losses, that decreases the measured power value, can happen and both can contribute to the final measured power value as described in the equation 3.

$$P_m(t) = P_0 e^{-\frac{t-\delta t}{\tau_{Ce}}} - P_{loss} \quad (3)$$

For these measurements the optimized parameters for massflow and T_{ch} , as resulted from the last section, were set and the measured power was calculated during the time, following the equation 1, where in this case T_{in} and \dot{m} are the average values, and $T_{out}(t)$ is the value as acquired at each time.

A plot of $P_m(t)$ is shown in Fig.2 and the difference between the set power and the measured power during the time is shown in the inset. The exponential function of eq. 2 was fitted both

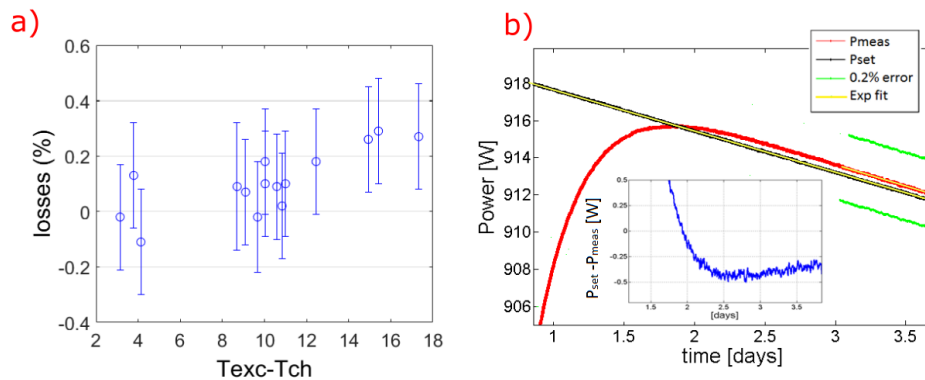


Figure 2. a): the percentage losses as a function of the temperature difference between T_{exc} and T_{ch} . b): The measured power (in red) and the power applied to the electrical heater (in black) are shown as a function of the time. The yellow line corresponds to the fit function done by using the eq.2, performed both on the set and on the measured power. The green line corresponds to the error band of 0.2% on the measured power. In the inset the difference between the applied and the measured power during the time is shown.

on the applied power and the measured power and the P_0 value as resulted from the fit on the last part of the measured power was taken as average value for the final power estimation. As a confirmation that the losses are really small, it is worth noting that the measured power value is higher than the set value due to the delay effect that dominates over the losses contribute. Assuming that the losses are close to zero, the delay time can be estimated of the order of 0.1-0.2 days in agreement with the simulations results and since the difference between the set and the measured power is of the order of 0.3-0.4 W (0.03% of the measured power), the effect is well below the statistical uncertainty and it can be neglected.

Many measurements were performed in the optimized conditions and with different power values and in all the cases the set value was found well inside the error band of 0.2% precision, evidencing that no additional systematic error has to be added.

4. Conclusions

A calorimetric apparatus here described was designed and built for measuring the $^{144}\text{Ce} - ^{144}\text{Pr}$ activity with 1% accuracy. The calibrations performed with an electrical source, replacing the radioactive source, demonstrated that the heat losses in the optimized condition are close to zero and can be neglected. In particular, when the residual pressure is of the order of 10^{-5} mbar and when the massflow value and the chamber temperature are properly set, the exponential decaying behavior can be recognized in the measured power and the final precision of the measurement was found to be 0.2%.

References

- [1] C. Giunti et al, *Phys. Rev. D* **88**, (2013) 073008
- [2] G. Bellini et al (Borexino collaboration), *JHEP* **08** (2013) 038
- [3] J. Gaffiot et al, *Phys. Rev. D* **91** (2015) 072005
- [4] Farinon et al., *Thermal analysis of the antineutrino ^{144}Ce source calorimeter for the SOX experiment*, INFN-16-08/GE (2016)
- [5] The International Association for the Properties of Water and Steam, *Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam*, R7-97 (2012), (<http://www.iapws.org>),