Thermal model of the Munich-Genoa calorimeter for SOX

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Section 1

The calorimeter

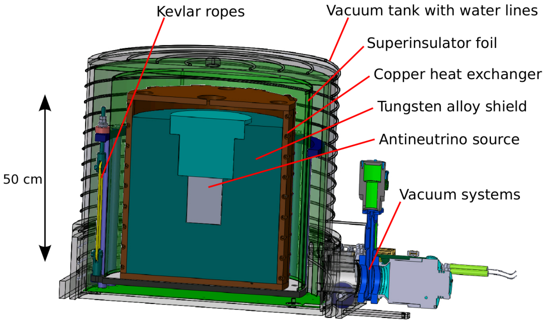
The calorimeter

A thermal calorimeter is constructed to measure the heat output of an antineutrino source with $< 1\%$ uncertainty to reconstruct the source activity.

The decay of the source will generate ~800 W thermal power at beginning of data taking (source activity 100 kCi). The source power is measured through ΔT of a precision mass flow of a cooling liquid (water) with known heat capacity.

$$P = \Phi \cdot c \cdot \Delta T$$

The activity can be reconstructed via the mean energy per decay $< E >$: $A = \dfrac{P}{< E >}$



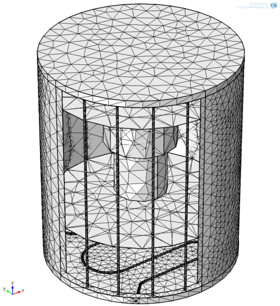
Section 2

Simulations of the calorimeter thermal response

Simulations

Impact of unknown parameters on the heat distribution was studied through simulations:

- contact pressure between solid domains
- material properties
- parameters of thermal contact between different domains (microhardness, average asperities slope and height)



Program: COMSOL Multiphysics 4.4

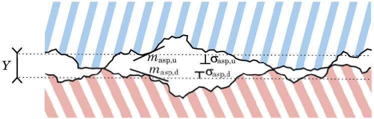
- finite elements simulation $\longrightarrow$ numerical solution of partial differential equations in a discretized geometry with boundary conditions for each element $\Longrightarrow$ Approximation!
- heat transfer: first law of thermodynamics (conservation of energy) is solved
- liquid flow: Navier Stokes equations are "solved"

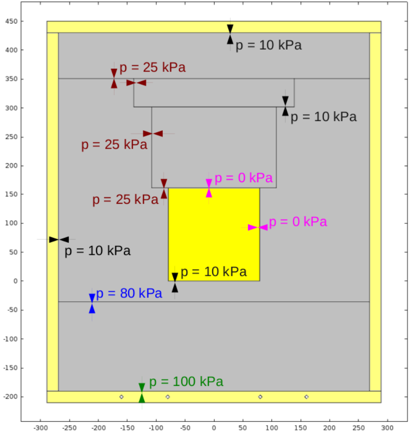
Thermal contact

Heat transport and distribution inside the calorimeter is ruled by the properties of thermal contact between adjacent domains. These are characterized by

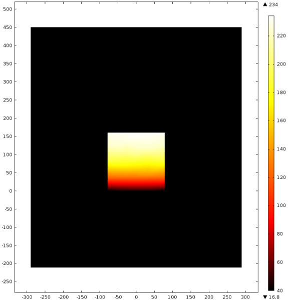
- contact pressure p
- asperities average height σ_{asp} and slope m_{asp}
- microhardness H_c

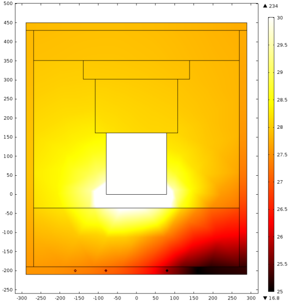
$$\Longrightarrow \text{conductance } h_c = 1.25 k_{contact} \frac{m_{asp}}{\sigma_{asp}} \left(\frac{p}{H_c} \right)^{0.95}$$

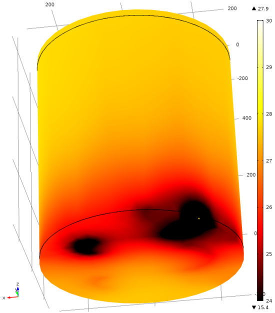




Results



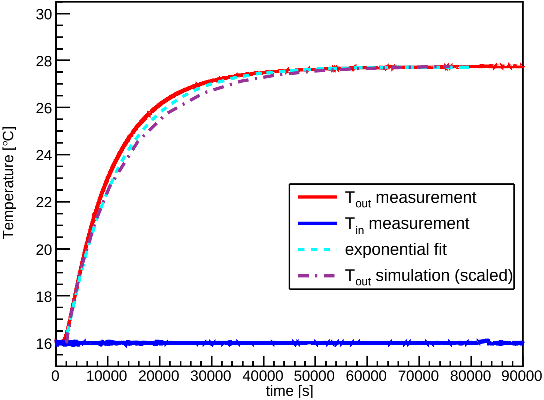




- $T_{max} = 280\ ^\circ\mathrm{C}$, T on copper surface $\sim 30 \pm 4\ ^\circ\mathrm{C}$ at 750 W source power.
- variations of the material and thermal contact properties have only small effects on the temperature distribution

Time dependent simulations

After what time is the calorimeter in thermal equilibrium, after the calibration heat source has been turned on?

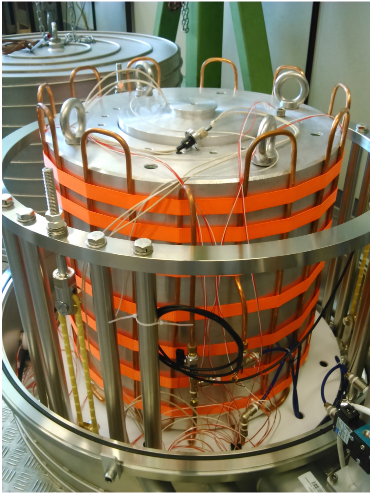


The temperature of the water at the outlet of the heat exchanger is fitted with:

$$T(t) = T_0 + \Delta T \cdot (1 - e^{-t/\tau})$$

τ is the characteristic time constant of the calorimeter. It is determined by the speed of heat propagation inside the calorimeter. Therefore measurements can validate the simulations.

The mockup



Measurements were conducted with a mockup heat-source:

- test the setup
- simulate the activity measurements
- validate the simulations
- calibrate the calorimeter

Compared to the final setup, the thermal response time of this setup is

- shorter due to the missing copper heat exchanger ($-110\,000$ J/K)
- longer due to the worse thermal contact of the copper tube to the heat source. At higher mass flows, the water does not reach the temperature of the aluminum cylinder surface.

Section 3

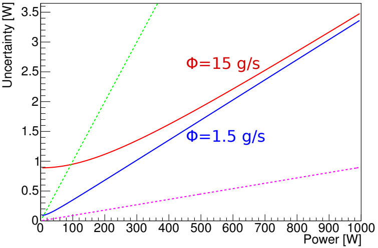
Uncertainty of the heat measurement and power reconstruction

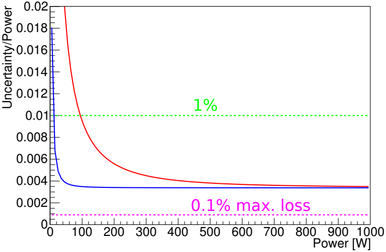
Uncertainties of the calorimetric measurement

$$s_P = \sqrt{s_{\Delta T}^2 \cdot \left[\frac{\partial P}{\partial \Delta T}\right]^2 + s_c^2 \cdot \left[\frac{\partial P}{\partial c}\right]^2 + s_\Phi^2 \cdot \left[\frac{\partial P}{\partial \Phi}\right]^2}$$

The absolute uncertainty depends on Φ and P:

$$\boxed{s_P(\Phi, P) = \sqrt{3502\ [\mathrm{J/kg}] \cdot \Phi^2 + 1.114 \cdot P^2}}$$





If the uncertainty of the calorimeter instrumentation is a systematic shift, the calibration can compensate it. Losses could be measured then.

Section 4

^{144}Ce-^{144}Pr spectral measurements and impact on SOX

β-spectra

$$A = P / < E >$$

In order to reconstruct the source activity from the calorimetric measurement as well as for rate analysis of the signal, precise knowledge of the source's spectral shape is required. The shape of a β spectrum can be derived from Fermi's Golden Rule:

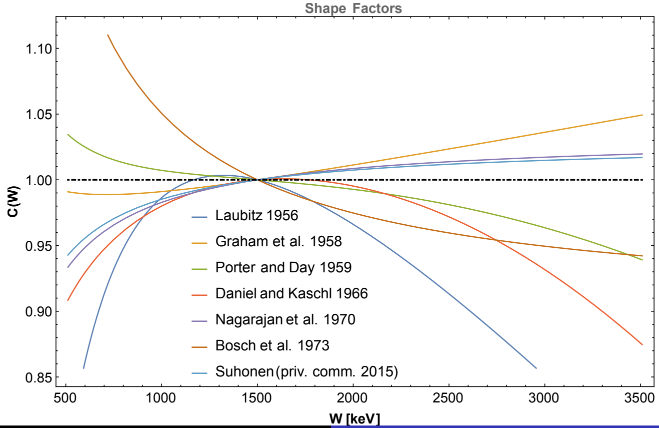
$$\boxed{N(W) = p \cdot W \cdot (Q - W + m_e \cdot c^2)^2 \cdot F(Z, W) \cdot C(W)}$$

- the Fermi function $F(Z, W)$ accounts for the Coulomb interaction of the relativistic β-particle with the electron cloud of the daughter nucleus into account
- shape factor $C(W)$, necessary for first-forbidden decays

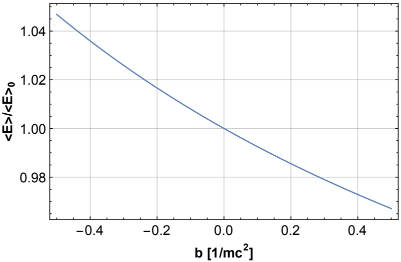
Shape factors

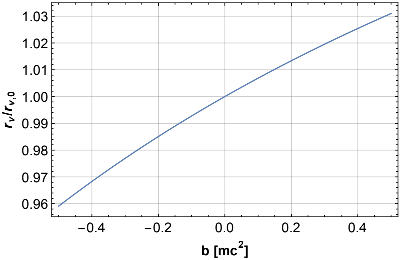
- The shape factor $C(W)$ corrects biases due to the so-called allowed approximation (the electron- and neutrino-wave functions are assumed to be equal to 1)
- $C(W)$ depends on the forbiddeness of the transition
- $\boldsymbol{C(W) = 1} + a \cdot W + \boldsymbol{b/W} + c \cdot W^2$
- $0 \rightarrow 0$ transitions (just as the main ^{144}Ce-^{144}Pr transitions) require only the parameter b [Bühring, 1963]!

The shapes have been measured by different groups and calculated by Jouni Suhonen:



Mean energy and detection rate as function of b





The mean energy per decay changes about $\sim 5\%$ according to the shape factor chosen and the detection rate about $\sim 9\%$.

> A wrong shape factor assumption distorts the rate analysis by altering the positron spectrum and by changing the reconstructed activity of the source from the calorimetric measurements.

$\Longrightarrow$ Measurements and theoretical calculation of shape factor in preparation.

Conclusions

- The SOX experiment aims to detect or refute the existence of sterile neutrinos with the help of a powerful $\bar{\nu}_e$-generator and Borexino.
- A thermal calorimeter was constructed and commissioned to measure the source power with $< 1\%$ uncertainty.
- Calculations and simulations confirmed the functionality of the calorimeter.
- Precise knowledge of the $\bar{\nu}_e$-source's spectrum is crucial for the activity reconstruction.

$\Longrightarrow$ The calorimeter is now ready and will perform heat measurements with $< 1\%$ uncertainty.
$\Longrightarrow$ A precision β-measurement is planned as well as theoretical studies.
$\Longrightarrow$ Beginning of data-taking scheduled for end of 2016.