MetroBeta: Beta Spectrometry with Metallic Magnetic Calorimeters in the Framework of the European Program of Ionizing Radiation Metrology

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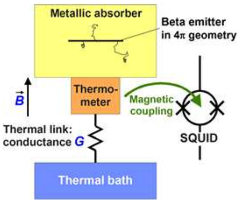
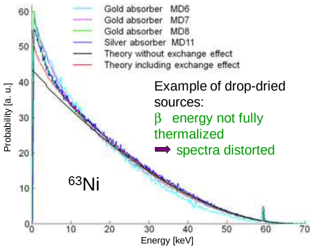
MetroBeta is a European project aiming at the improvement of the knowledge of the shapes of beta spectra, both in terms of theoretical calculation and measurement. It is part of a common European program of ionizing radiation metrology. The precise knowledge of the shapes of beta spectra is required for the activity measurement of pure beta emitters, i. e. the realization of the unit of Becquerel for these nuclides. Metallic magnetic calorimeters (MMCs) with the beta emitter embedded in the absorber have in the past proven to be among the best beta spectrometers, in particular for low energy beta transitions. Within this project, new designs of MMCs optimized for five different beta energy ranges were performed and the fabrication of the first MMC wafers is just finished. A new detector module with thermal decoupling of MMC and SQUID chips was developed. An important aspect of the research and development concerns the source/absorber preparation techniques. Four beta spectra will be measured: ^{151}Sm (Q = 76.3 keV), ^{14}C (Q = 156.5 keV), ^{99}Tc (Q = 293.8 keV), ^{151}Sm (Q = 709.5 keV). Improved theoretical calculation methods and complementary measurement techniques complete the project.

Beta spectrometry with metallic magnetic calorimeters



Source embedded inside
the detector absorber

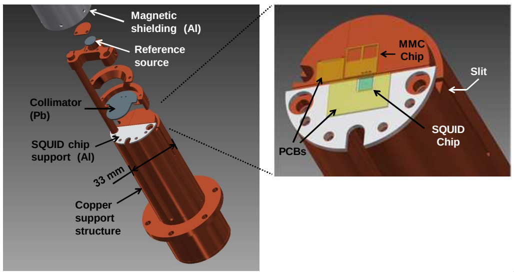
- 4π solid angle
- no back-scattering
- energy loss of beta particles in the source:
  full thermalization of β energy must be ensured



Example of drop-dried sources:
β energy not fully thermalized
⇨ spectra distorted

Detector module with thermal decoupling of MMC and SQUID chips

In single stage SQUID setup, the power dissipation in the SQUID shunts can prevent the MMC to be cooled to below ~ 20 mK.
A slit in the copper support structure provides reduced thermal coupling between MMC and SQUID chips.

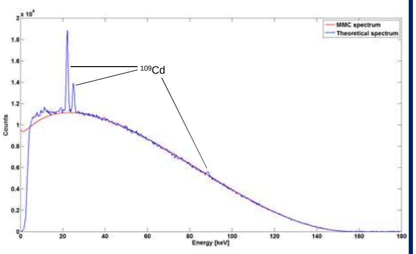


First measured spectrum

^{14}C

Beta emitter characteristics
E_{max} = 156.476 keV
Half life 5700 y
Allowed transition
Calculated with LNHB-code BetaShape

Detector characteristics
Au absorber, 1 mm^2 × (2 × 30) µm
Embedded source activity 25 Bq,
prepared from triazol solution (370 MBq/g)
Very long pulse decay time (> 100 ms)
→ strong pile-up, degraded energy resolution



Next spectra

^{151}Sm

Beta emitter characteristics
E_{max} = 76.3 keV
Half life 90 y
First forbidden unique transition

Detector characteristics
Ag absorber, (0,9 mm)^2 × (2 × 15) µm
Embedded source activity 7.6 Bq,
electroplated on silver foil
Pulse decay time 6.8ms
Measurement done, data analysis pending

^{99}Tc

Beta emitter characteristics
E_{max} = 293.8 keV
Half life 211.5 × 10^3 y
Second forbidden non-unique transition

^{36}Cl

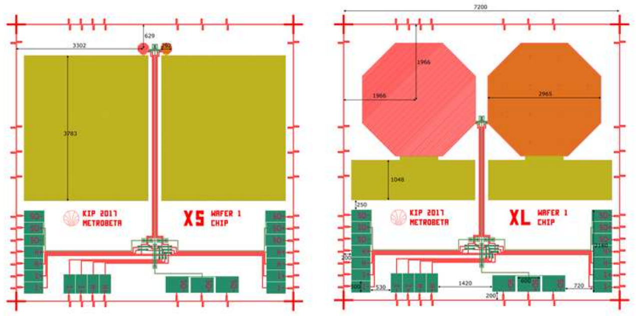
Beta emitter characteristics
E_{max} = 709.5 keV
Half life 302 × 10^3 y
Second forbidden non-unique transition

MMC design for MetroBeta

MMCs have been designed to match five different absorber heat capacities corresponding to beta spectra of maximum energies ranging from ~ 20 keV to 700 keV. The designs are based on optimization calculations with the constraints of erbium concentration and sensor thickness being equal for all five designs, in order to be able to fabricate all sensors on one wafer. The table below summarizes the results of the optimization. The calculations were optimized for an operation temperature of 20 mK and performed assuming the following parameters fixed for all designs:
SQUID white noise level 0.35 µΦ_0/√Hz; SQUID 1/*f* noise level @ 1 Hz 2.6 µΦ_0/√Hz; signal decay time 1 ms; erbium concentration 310 ppm; sensor thickness 3 µm

detector		XS	S	M	L	XL
absorber heat capacity		8 pJ/K	28 pJ/K	110 pJ/K	400 pJ/K	1.70 nJ/K
designated SQUID	type	X1	X1	X1	XS	S
	input inductance	2 nH	2 nH	2 nH	27 nH	65 nH
linewidth of pickup coil		2.5 µm	5 µm	5 µm	5 µm	5 µm
pitch of pickup coil		5 µm	10 µm	10 µm	10 µm	10 µm
meander /sensor area (square shape)		(249 µm)^2	(335 mm)^2	(538 µm)^2	(1427 µm)^2	(2663 µm)^2
meander inductance (single meander)		3.4 nH	3.1 nH	8.0 nH	56 nH	196 nH
expected flux coupling		3.8%	4.0 %	2.6%	0.8 %	0.5 %
optimum field current		38.2 mA	67.8 mA	75.7 mA	63.3 mA	67.1 mA
expected energy resolution		5.17 eV	9.46 eV	19.1 eV	37.5 eV	74.4 eV
expected signal size		23.2 mΦ_0/keV	12.9 mΦ_0/keV	6.41 mΦ_0/keV	2.97 mΦ_0/keV	1.61 mΦ_0/keV
sensor heat capacity		7.57 pJ/K	17.9 pJ/K	50.6 pJ/K	308 pJ/K	1.17 nJ/K

As examples, the smallest and the largest sensor designs, corresponding to absorber heat capacities of 8 pJ/K @ 20 mK and 1,7 nJ/K @ 20 mK, respectively. The red octogons are the meandering pickup coils (meander lines invisible in this scale), the orange octogons the Au:Er sensor layers. Dimensions are in micrometers.



Absorber design for higher energy (≳500 keV) spectra

At E_{max} ≳500 keV, the measured beta spectra may be distorted by escape of Bremsstrahlung from the absorber. The absorber material may have a major influence on this phenomenon.

- Probability of Bremsstrahlung production as a function of the atomic number *Z* of the material:

$$\left(\frac{dE}{dx}\right)_r = \frac{NEZ\,(Z+1)e^4\alpha}{m_0^2c^4}\left(4\ln\frac{2\,E}{m_0c^2} - \frac{4}{3}\right)$$

⇨ low *Z* advantageous

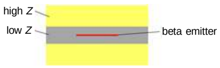
- A higher *Z* material offers a higher absorption probability for the photons

⇨ high *Z* advantageous

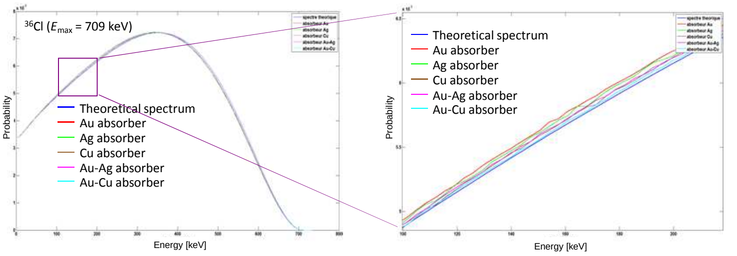
- Absorber heat capacity as a function of electron stopping power

⇨ high *Z* advantageous

- Composite absorber with an inner layer of low *Z* material and an outer layer of high *Z* material may be advantageous



Monte Carlo simulations of monolithic Au, Ag, Cu and Au-Ag, Au-Cu bilayer absorbers:



⇨ strongest spectrum distortion: monolithic Au absorber
⇨ weakest spectrum distortion: Au-Cu bilayer absorber

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