IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

MMC-based phonon-scintillation detection for rare-event search experiments

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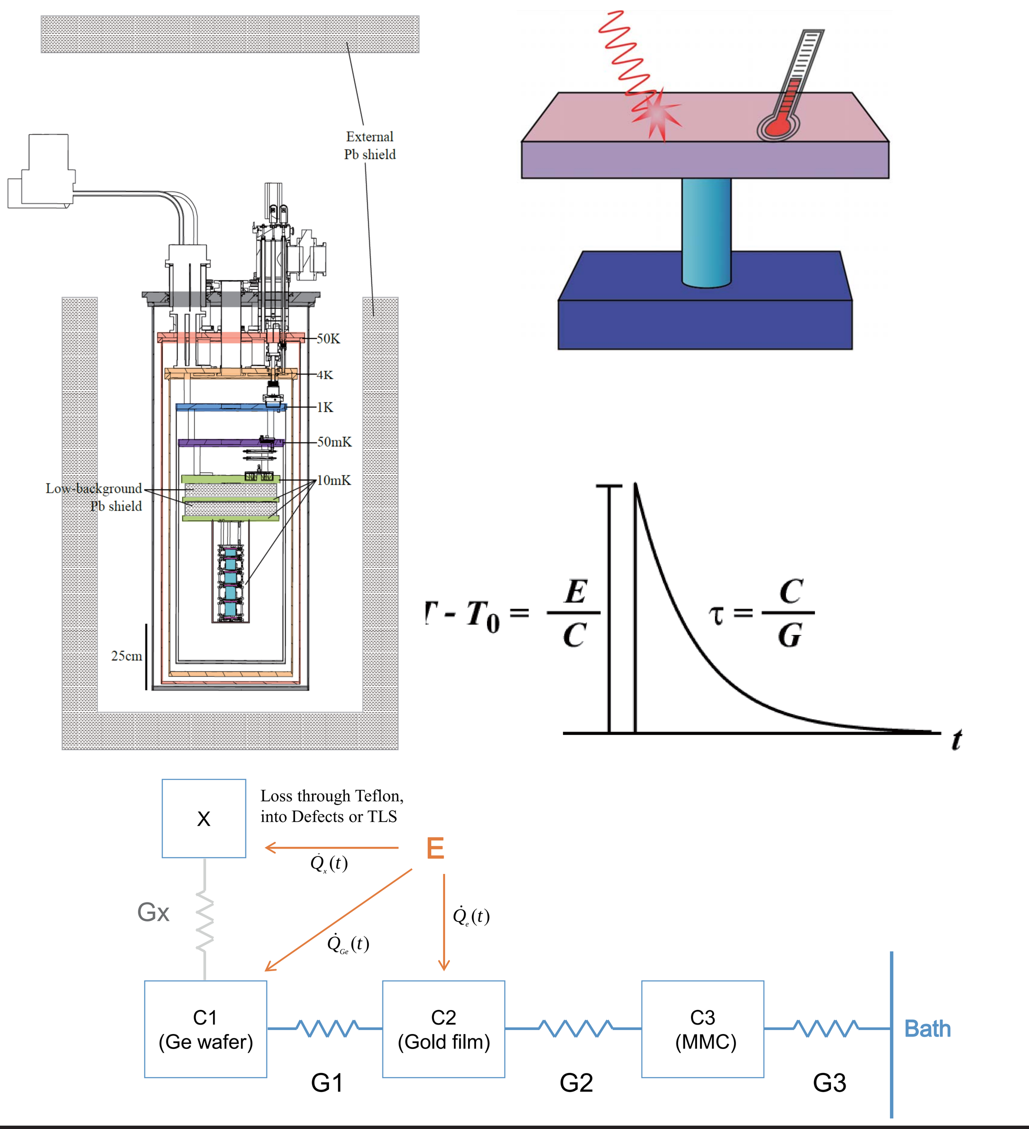
Introduction

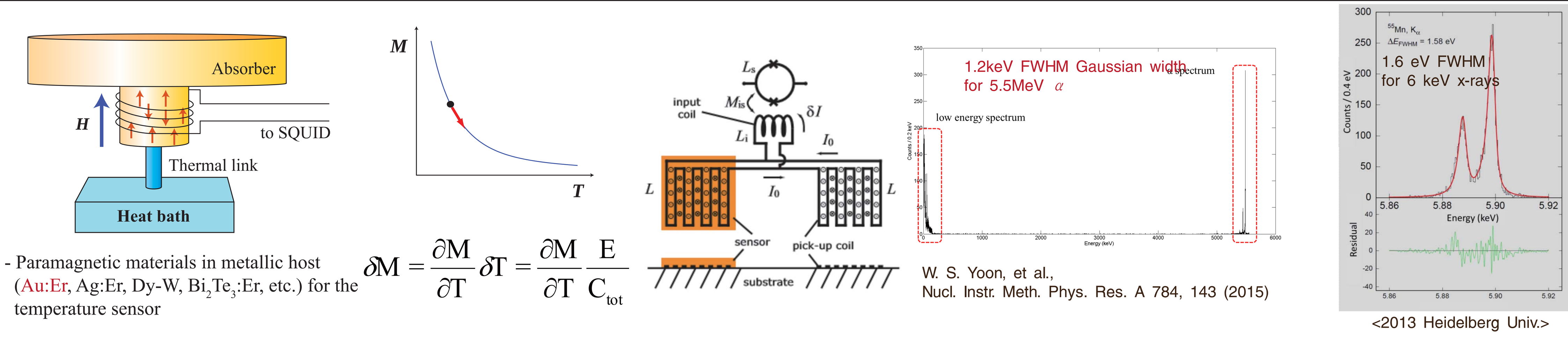
Metallic Magnetic Calorimeter (MMC) is a highly sensitive temperature sensor that uses the paramagnetic nature of erbium in gold host and superconducting electronics composed of a planner niobium coil and a current sensing Superconducting Quantum Interference Device (SQUID). It can operates at cryogenic temperature with a scintillating crystal that is a target material for rare-event search experiments. A small increase in temperature change of the crystal induced by particle absorption is measured with an MMC-based phonon sensor which is in strong thermal contact to the crystal. The phonon sensor is also weakly coupled to the copper holder which serves as a thermal reservoir to maintain its low temperature. The amount of scintillation can also be measured with an additional MMC, using crystalline semiconductor wafer such as Germanium or Silicon as light absorber. MMC sensor is employed to read out the temperature increase of the wafer when absorbing the scintillation light. Its high energy resolution obtained by using a low-noise SQUID and low heat capacity of material at cryogenic temperature makes the calorimeter a suitable sensor for rare-event search experiment such as direct detection of dark matter and search for neutrino-less double beta decay. We present the measurement principle of the simultaneous detection of phonon and scintillation signals together with astroparticle physics applications.

Cryogenic Detectors

Heat capacity of metal, given as a function of temperature $C = \gamma T + AT^3$, decreases radically at cryogenic temperature. This means a small energy input to a metallic absorber results in a great temperature change of the absorber. The metallic absorber at cryogenic temperature can then be used as a highly precise energy sensor which can be applied to measuring the energy of radiation-induced events with extremely high resoultion.

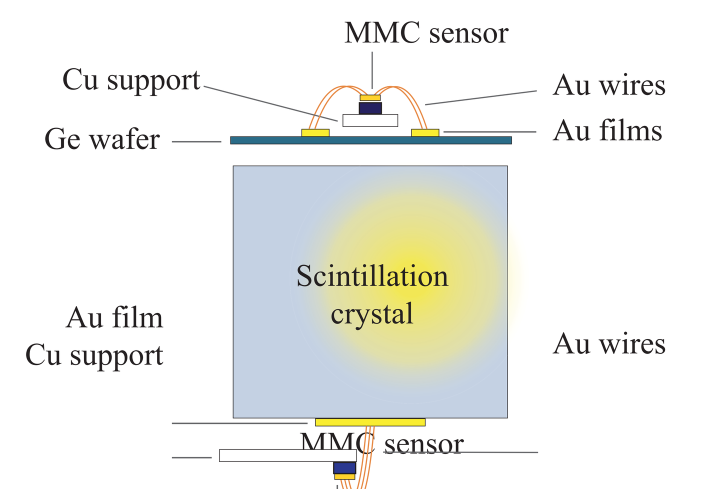


Metallic Magnetic Calorimeter



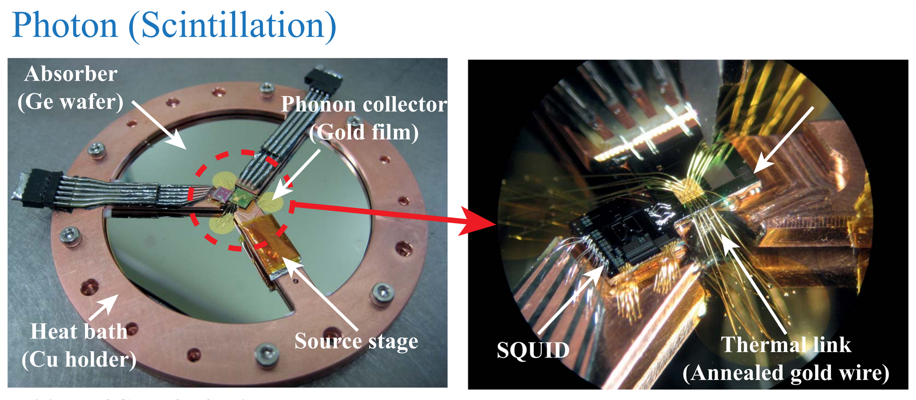
Phonon-Scintillation detection

Detector concept



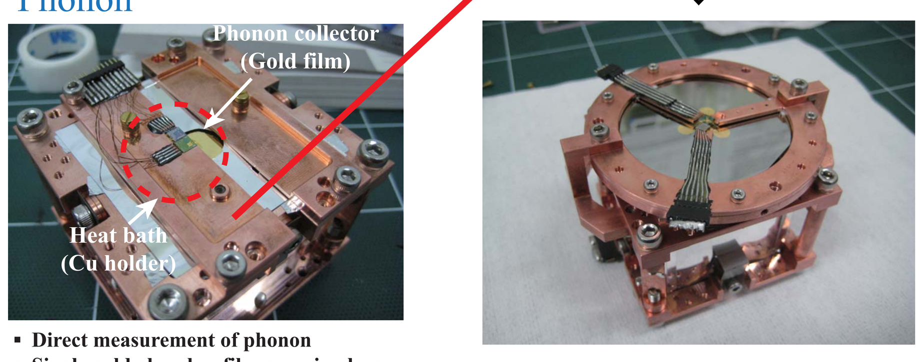
- Patchable design: MMC devices can be tested with a SQUID separately in a storage dewar.
- Regular batch of MMC fabrication procesure can be applied for 100 working devices.
- The setup can be assembled with a wafer absorber at the final stage of assembling procedure.

Photon (Scintillation)



- 2 inch of Ge wafer for light collector.
- Three circular gold patterns (ø5 mm ×320 nm) for phonon collector.
- Annealed gold wires for thermal link to the bath.

Phonon



- Direct measurement of phonon
- Single gold absorber film covering large area
- Annealed gold wires for thermal link to the bath.

Full information on both the energy absorption by crystal and the scintillation light output

Advanced Mo-based Rare Process Experiment (AMoRE)

AMoRE (Advanced Mo-based Rare process Experiment) is an international project searching for the 0νββ of ^{100}Mo. It utilizes up to 200 kg of $^{40}Ca^{100}MoO_4$ crystals by the end of planned three phases: AMoRE-pilot, AMoRE-I and AMoRE-II. Located at underground laboratory in South Korea, AMoRE-II will fulfill 1×10^{-4} counts/keV/kg/year background rate. The extreme precision of MMC detector in this zero background condition will allow the search for the 0νββ decay mode of ^{100}Mo with 1.1×10^{27} sensitivity for half life that corresponds to 12-22 meV Majorana neutrino mass.

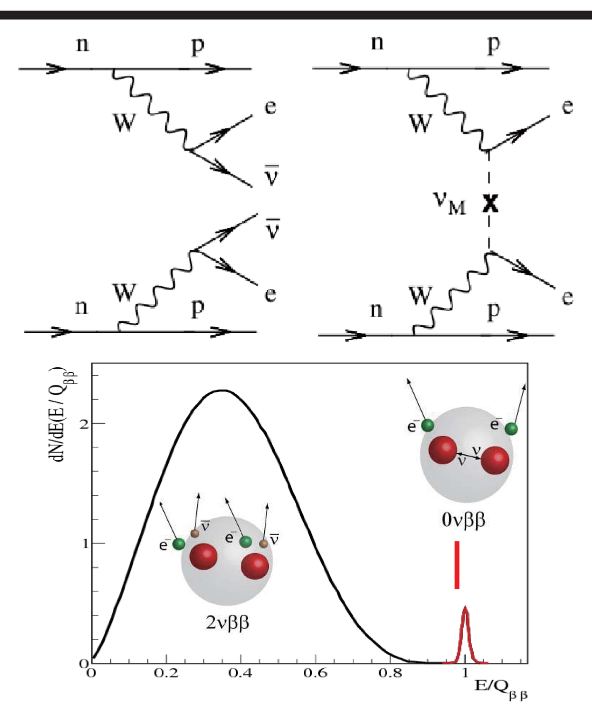
Sizeable background case

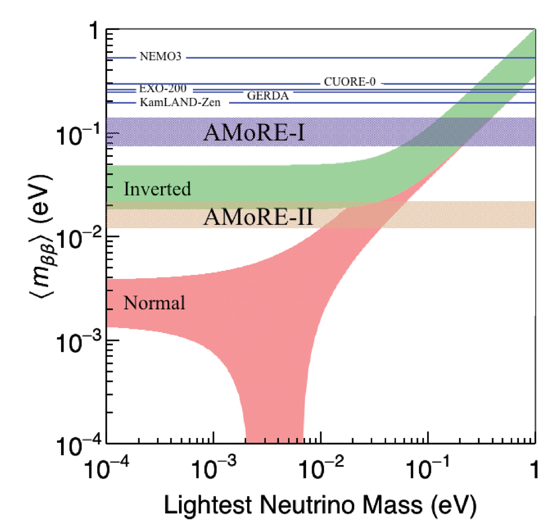
$$\lim T^{0\nu}_{1/2}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{Mt}{b\Delta E}}$$

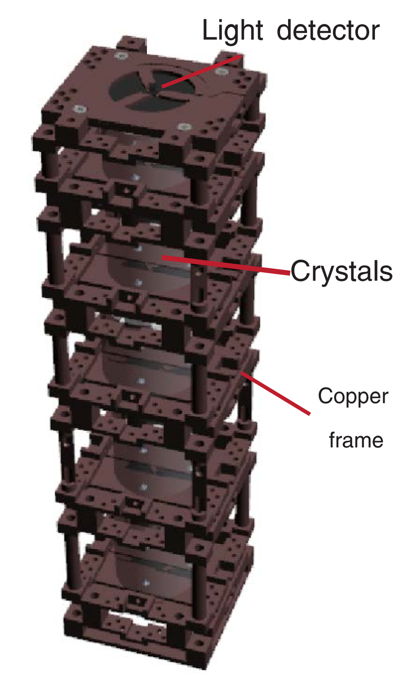
Sensitivity to life of 0νββ; Isotopic Abundance; Detection Efficiency; Detector Mass; Measurement time; Energy Resolution; Background rate; Atomic mass

"Zero" background case

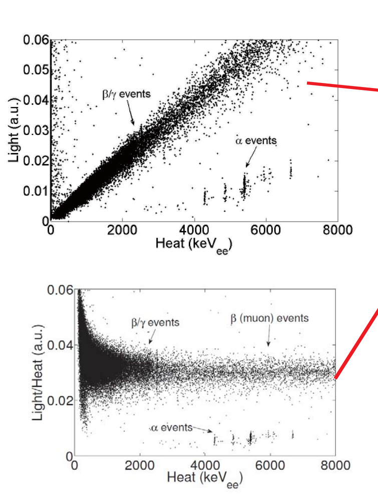
$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon Mt$$



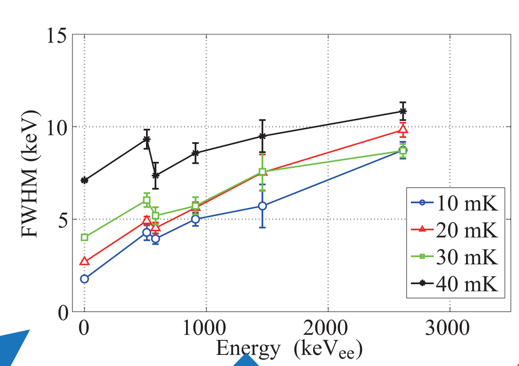




Experiment and results

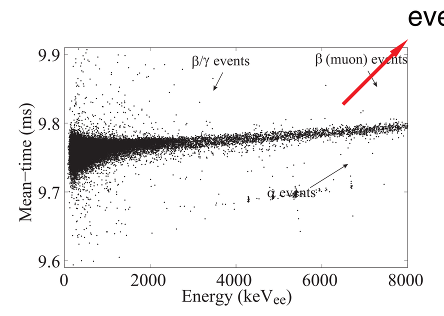


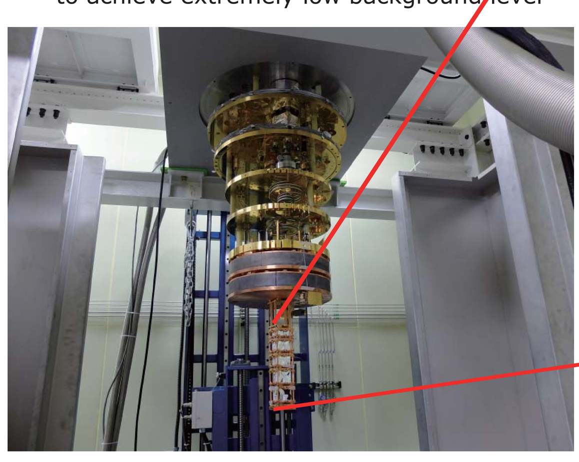
Extreme separation power due to photon-phonon simultaneous measurement technique

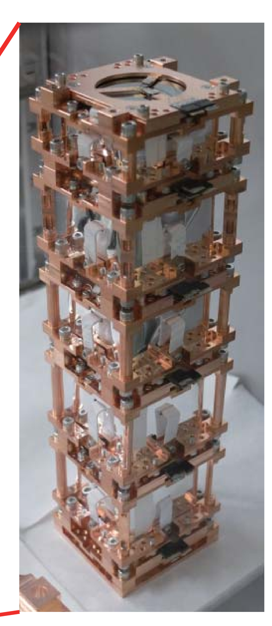


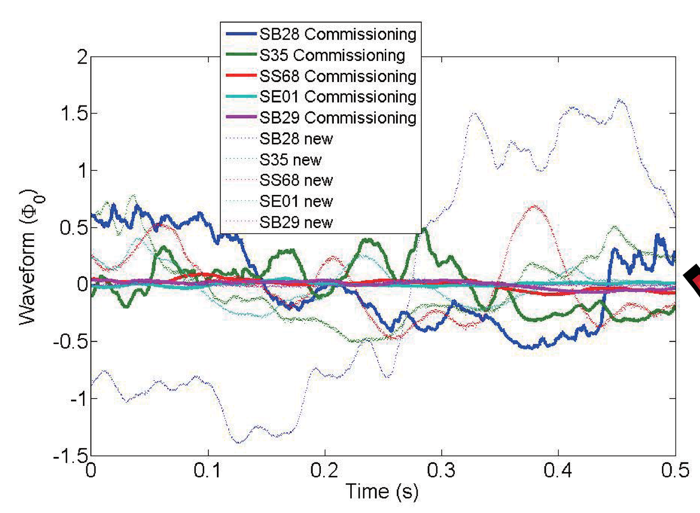
Experiment in the underground laboratory to achieve extremely low background level

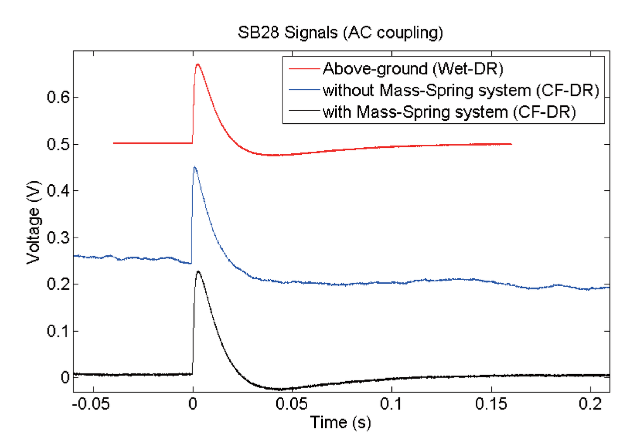
Pulse shape discrimination enables further separation between alpha and gamma events











Use of Mass-Spring damping system to cancel out vibrational noise will enable the high-resolution measurement in the underground laboratory;

With the scintillation-phonon simultaneous measurement technique using cryogenic MMC sensors, AMoRE will achieve zero-background measurement of neutrino-less double beta decay process

Crystal	AMoRE Pilot run-1	AMoRE Pilot run-2	AMoRE Pilot run-4 (current)
SB28	36.8 keV	25.0 keV	[redacted]
S35	N/A	16.3 keV	[redacted]
SS68	52.6 keV	24.2 keV	BETTER?
SE01	39.7 keV	24.6 keV	[redacted]
SB29	42.6 keV	N/A	[redacted]

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