Frascati Physics Series Vol. XLVIII (2009), pp. 73-78
YOUNG RESEARCHERS WORKSHOP: *"Physics Challenges in the LHC Era"*
Frascati, May 11 and 14, 2009

A MICROCALORIMETER MEASUREMENT OF THE NEUTRINO MASS, STUDYING ^{187}Re SINGLE β DECAY AND ^{163}Ho ELECTRON-CAPTURE DECAY

Daniela Bagliani
University and INFN of Genoa, Italy

Abstract

The neutrino mass scale is a relevant parameter of the theoretical framework beyond the Standard Model of particle physics, and therefore a crucial challenge of future experimental efforts. In this paper I will make an overview of the proposals for the direct searches of the absolute neutrino mass by means of ^{187}Re single β decay and ^{163}Ho electron-capture decay. The sensitivity, needed to constrain m_ν, is achieved thanks to the high responsivity of superconducting microcalorimeters and their low intrinsic noise.

1 Introduction

In the Standard Model framework neutrino mass scale represent an open problem whose solution could provide crucial informations in Cosmology, Particle and Astroparticle Physics. Because neutrino are massive, single β

decay and neutrinoless double-β-decay could set the absolute scale and nature, Dirac or Majorana.
Presently, the lower limits on electron neutrino mass (2.2 eV) have come from tritium β-decay experiments. The aim of these experiments is the analysis of the events near the endpoint energy, where the spectral shape is affected by the modifications of the phase-space factor induced by a finite neutrino mass. Calorimetric techniques have been developed in the past few years with the aim to achieve higher sensitivity and lower systematics than in well-established β-impulse spectroscopy.

2 Calorimetric measurement of ^{187}Re single β decay and ^{163}Ho electron-capture decay

The measurement of the neutrino mass via single β and electron capture (EC) decays is done by searching the deficit at the end-point of energy spectrum. The deficit amplitude in both cases scales as the third power of the neutrino mass. The required high sensitivity in the 0.1 eV/c^2 region makes ^{187}Re and ^{163}Ho decays favourite candidates for calorimetric spectroscopy, due to their low endpoints: 2.5 keV for ^{187}Re, and 2.5 $\div$ 2.8 keV for ^{163}Ho.

2.1 ^{187}Re single β decay

Natural metallic rhenium is composed by ^{187}Re for its 63%. ^{187}Re decays in ^{187}Os, and the whole energy released can be measured detecting the temperature rise following the absorption of the emitted electron by the rhenium crystal itself cooled at 0.1 K [1)].
This is the principle of operation of the calorimetric spectroscopy for rhenium β decay, that offers several advantages. The decay energy spectrum can directly be measured, without model dependent corrections for atomic and molecular final states. Nuclear recoil energy and electron energy losses don't affect the spectrum shape. Unfortunately rhenium decay is first forbidden unique: the ^{187}Re half life is 4.5×10^{10} years, thereby the specific count rate is very low. The expected activity of 1 mg is 1 Bq.

2.2 ^{163}Ho electron-capture decay

Holmium EC decay is a promising alternative tool respect to the study of rhenium [2]. The first advantage is the holmium half life: 4.5×10^3 years. The EC energy spectrum has a shape for finite m_ν very similar to the rhenium decay at the endpoint, but the half life seven order shorter can significantly improve the statistics. Moreover the EC spectrum presents lines corresponding to the inner orbitals M and N involved in the process, consequently the source can be even employed for self calibration of the microcalorimeter, monitoring its linearity during the measurements.
Despite all, the study of ^{163}Ho require a technological effort in assembling the source. ^{163}Ho in metallic state must be produced in laboratories and embedded into an adequate absorber. The modern techniques of producing beams of heavy ions allow to obtain ^{163}Ho by fragmentation or spallation of atoms in a target hit by protons, as in the ISOLDE facility at the CERN laboratories. The beam of resulting products could implant ^{163}Ho in a layer less than 1 μm thick. Much care must be taken for the purification process from isobars, which could contaminate the source with excess radioactivity.

3 The superconducting microcalorimeters

In the last two decades thermal detectors have developed reaching the highest sensitivity available at keV energies. Here we consider a specific kind of detectors, the transition edge sensor (TES) microcalorimeters. These cryogenic detectors have been employed to study electromagnetic radiation from X-rays to the far infrared in many different physics domains, reporting an energy resolution up to two order of magnitude better than most performing solid state detectors off the shelf.
In first approximation we can describe the microcalorimeter in three fundamentals elements: an absorber of heat capacity C strongly thermally coupled to a sensor, the sensor itself and a weak thermal link of conductance G coupled to an heat sink. At each radiation absorption the detector response is a temperature transient $\Delta T = E_R/C$, where E_R is the energy absorbed. The initial temperature is restored fastly by the help of the electrothermal feedback (ETF) with a time scale $\tau = C/(G - G_{ETF})$.
To take the advantage of fast pulses produced by ETF, TES are made of

a superconducting thin film biased with a constant voltage and it is cooled at a working temperature corresponding to an electrical resistance of a few percents of the normal value. The whole sensitivity of these detectors is related to the steepness of the phase transition. If the film is patterned and has an inner structure with low impurities, the transition width can be as narrow as 0.3 mK, giving very high temperature responsivity. Thermal fluctuations due to Brownian motion of phonons in the film represent the intrinsic energy resolution of the TES. Their root mean square amplitude can be estimated as $\Delta U_{rms} = \sqrt{k_B T^2 C}$. The resulting achievable energy resolution is $\Delta E_{FWHM} = \zeta\sqrt{k_B T^2 C}$, that in a typical case is less than 1 eV. The parameter ζ contains the dependence from the ETF, G and the steepness of the transition. For further details on TES thermal and electrical models see ref. [3].

In the Genoa Laboratories we produce TES of thin Ir/Au bilayers, with Al electrical contacts. Iridium films are grown on a Si_xN_y membrane by pulsed laser deposition. Gold is evaporated by electron gun on an Ir sticking layer a few angstroms thick, which provide strong film adhesion to the substrate. Finally the Ir film is deposited on the top of the gold layer. The Ir/Au bilayer is fabricated in ultra high vacuum chambers connected between them. Typical thicknesses are from 50 to 100 nm for Ir films, and 20 to 50 nm for Au layers. Thin films patterning is performed by microlithography in a clean room and dc sputtering. Typical final geometry of the TES is a rectangular shape of $100 \times 120\ \mu m^2$. The characterization measurements of our films have shown transition temperatures between 100 and 120 mK at constant currents between 50 nA and 1 μA. The transition width is of fractions of millikelvin and normal state resistance is of some tenths of Ohm.

The absorber preparation consist of two different processes for rhenium and holmium. In the first case a pure Re crystal of cubic shape is cut and optically lapped in order to obtain an homogeneous superconductivity state at the working temperature. Re become superconductive at 1.7 K and according to the BCS theory its thermal capacitance is strongly suppressed in the superconducting state; thereby single crystal fabrication is a crucial phase of the calorimeter fabrication, being the Re the bigger contribute to the total sensor capacitance and consequently its energy resolution. The crystal is then fixed on the TES with epoxy glue.

Holmium absorber must be composed of two parts: a superconducting absorber

layer (i.e. Bi, Sn) where the Ho atoms are implanted, and a thicker layer covering the implanted area for the absorption of the secondary products of EC decay (emission of X-rays and Auger electrons, Coster-Kronig transitions). For a full absorption of the whole decay energy and for stopping efficiently the implantation beam the absorber should be a few microns thick. In figure 1 we describe the rhenium and holmium microcalorimeters.

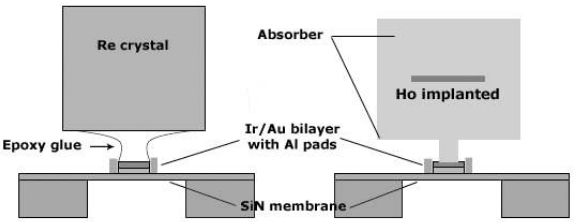

Figure 1: *Scheme of the two microcalorimeters; the second one has an absorber grown on the sensor with an inner layer containing atoms of* ^{163}Ho *homogeneously implanted.*

4 SQUID amplifier for TES arrays

The sensitivity that we foresees to achieve is $0.1 \div 0.3$ eV/c^2 with a statistics of $10^{12} \div 10^{14}$. The energy resolution of one microcalorimeter with 1 mg of Re at keV energies can be of few eV, but the quest of such high statistics makes necessary to fabricate arrays of several elements in order to have 5 years data taking. The purpose of the MARE collaboration (Microcalorimeters Array for Rhenium Experiments) is to assemble arrays for a total of 50000 detectors, and a final sensitivity of 0.2 eV. Being TES low impedance devices, the readout should be a frequency multiplexed SQUID amplifier [4]. A simple example of the cryogenic stage of the readout is reported in the figure 2. The scheme is composed by a set of resonating circuits associated to each TES. Each sensor is biased at different frequencies. the signals of a row of TES are summed in a single channel and can be read by a single SQUID. By this way a row can contain tens of detectors.

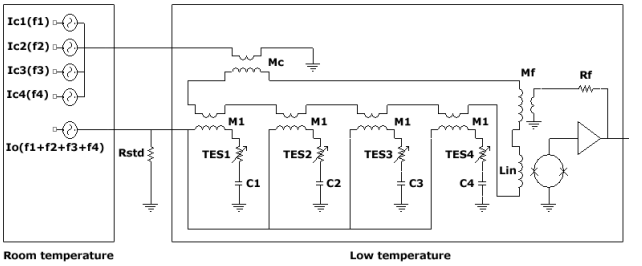

Figure 2: *The readout circuit is composed by a room temperature stage and another one cooled at the working temperature, typically below* 0.1 *mK.*

5 Conclusions

A calorimetric measurements of the neutrino mass with a sensitivity of 0.2 eV should be possible, thanks to the high sensitivity of TES microcalorimetry. A prototype of cryogenic electronics is under study in our laboratories and we foresee to test a first array of Re microcalorimeters in the next runs.

References

1. F. Gatti *et al*, Nucl. Instr. and Meth. in Phis. Res. A **315**, 260 (1992).

2. F. Gatti *et al*, J. Low. Temp. Phys. **151**, 603 (2008).

3. K.D. Irwin and G.C. Hilton, *Cryogenic Particle detection* edited by Springer **99**, 63 (2005)

4. R. Vaccarone, J. Low. Temp. Phys. **151**, 915 (2008).