CUORE: low temperature techniques for neutrino physics

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Abstract

Neutrino physics represents today a hot topic in elementary particle physics, due to the observations of flavour oscillations both in the atmospheric and in the solar sector. This proves the existence of finite neutrino masses. In order to fix their absolute values, sensitive experiments on Neutrinoless Double Beta Decay (a rare nuclear process) must be carried on. The experiment here described, named CUORE (Cryogenics Underground Observatory for Rare Events), can extend the neutrino mass sensitivity down to 30 meV. CUORE will consist of a large, closely-packed, high-granularity array of 1000 tellurite (TeO_2) low temperature calorimeters, operated at 10 mK and with a total mass of 800 Kg. The final structure of the detector and the preliminary tests are presented and discussed.

Key words: neutrino physics; bolometric detectors; low-temperature calorimeters

1. Neutrino Physics and Double Beta Decay

In the Standard Model of Particle Physics neutrinos are strictly massless, although there is no theoretical reason for such a prejudice. On the experimental side, there exists now undoubtful evidence from the atmospheric [1] and solar [2] neutrino data to conclude that neutrinos oscillate among different flavours, implying that they are massive particles. Unfortunately, neutrino flavour oscillations can only fix differences between squared neutrino masses, whereas they cannot determine the absolute values of these crucial parameters. Moreover, neutrinos and antineutrinos are supposed to be different particles in the Standard Model, but no experimental proof has been provided so far.

Neutrinoless Double Beta Decay (0ν-DBD) [3] is a

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rare nuclear process described by the following equation

$$(A, Z) \rightarrow (A, Z+2) + 2e^-, \qquad (1)$$

in which, unlike standard electroweak process, no neutrino is present in the final state. In reaction (1) in fact, neutrino does not appear explicitely but it is hidden as a virtual particle joining two electroweek vertices. This role can be played if and only if neutrino is a self-conjugated "Majorana" particle and if at least one neutrino eigenstate has a non-zero mass. Search for 0ν-DBD is presently the only viable experiment which can reveal the Majorana nature of neutrino. The connection between the lifetime τ of process (1) and neutrino mass is quantitatively expressed by

$$\frac{1}{\tau} = G_{0\nu} |M^{0\nu}|^2 \left(\frac{\langle \mathrm{m}_\nu \rangle}{\mathrm{m_e}} \right)^2 \qquad (2)$$

(assuming the dominance of the so-called mass mechanism) where $G_{0\nu}$ is a phase-space factor growing steeply with the Q-value of process (1), $|M^{0\nu}|$ (the "nuclear matrix element") includes all the nuclear physics of the decay, and $\langle \mathrm{m}_\nu \rangle$, sometimes defined "effective Majorana mass", is a linear combination of the three neutrino physical masses. The coefficients of this linear combination are connected to the neutrino mass matrix, and represent therefore the bridge between flavor oscillations and 0ν-DBD [4]. Present experimental limits on $\langle \mathrm{m}_\nu \rangle$ are of the order of ~ 1 eV, with a large systematics originated by the difficult computation of $|M^{0\nu}|$. Values of $\langle \mathrm{m}_\nu \rangle$ in the range of a few tens of meV are compatible with present results on oscillation in some plausible scenarios. Therefore, new generation 0ν-DBD experiments (like CUORE) aiming at this sensitivity have now a strong scientific motivation.

2. The bolometric technique and ^{130}Te

A very sensitive approach for the study of 0ν-DBD consists in developing a device which is at the same time source and detector of the phenomenon. In this method, the detector containing the candidate nuclides must be massive (at least of the order of 10 kg, better if of the order of 100-1000 kg for new generation experiments). Furthermore, it must exhibit high energy resolution and low radioactive background. Bolometric detection of particles [5] is not only able to provide all these features, but it looks like the only technique capable to ensure them at the ton scale with reasonable costs.

In bolometers, the energy deposited in the detector by a nuclear event is measured by recording the temperature increase of the detector as a whole ("calorimetric detection"). In order to make this temperature increase appreciable and to reduce all the intrinsic noise sources, the detector must be operated at very low temperatures, of the order of 10 mK for large masses. Energy resolution is a crucial parameter in searching for 0ν-DBD, since the signal is a peak in the energy spectrum of the detector positioned exactly at the Q-value of reaction (1). This peak must be discriminated over the background and therefore is to be narrow. Bolometric technique can provide energy resolutions comparable to or better than those achievable with conventional devices in the MeV range [6].

Since the only characteristic required to the detector material is to have a low specific heat at low temperatures, many choices are possible. In particular, when planning for a double beta decay experiment with bolometers one should find a compromise between the thermal properties of a compound and its content of the candidate nucleus. Several interesting bolometric candidates were proposed and tested by the Milano group [7]. The choice has fallen on natural TeO_2 (tellurite) that has reasonable mechanical and thermal properties together with a very large (27% in mass) content of the 2β-candidate ^{130}Te, which makes the request of enrichment not compulsory, as it is for other interesting isotopes. Moreover, the transition energy ($Q_{2\beta} = 2528.8 \pm 1.3$ keV) is located in the valley between the peak and the Compton edge of the 2615 keV γ-line of ^{208}Tl, at the very end of the γ natural background spectrum, making it easier to look for the signal. In comparison to other 2β-emitters, phase-space and nuclear matrix elements (even if still not well known) are quite favourable. To give an idea of the difficulty of the experiment, eq. (2) predicts for ^{130}Te a lifetime of the order of 10^{26} y for $\langle \mathrm{m}_\nu \rangle \sim 1$ eV.

The typical bolometer developed by the Milano group to search for 0ν-DBD consists therefore of a single tellurite crystal, with a mass of the order of a few hundreds of grams, thermally coupled to a Neutron Transmutation Doped Ge thermistor which operates as a temperature-to-voltage transducer. The crystal is weekly coupled to a heat sink kept at ~ 5 mK by a high power dilution refrigerator. Technical details on this device and its operation parameters can be found in [9].

3. The MIBETA experiment and the CUORICINO project

Following the approach outlined in the previous section, an experiment using crystalline tellurite (TeO_2) and studying ^{130}Te (MIBETA experiment) has been developed by the Milano group [8], allowing to reach one of the highest sensitivities in the world. The MI-

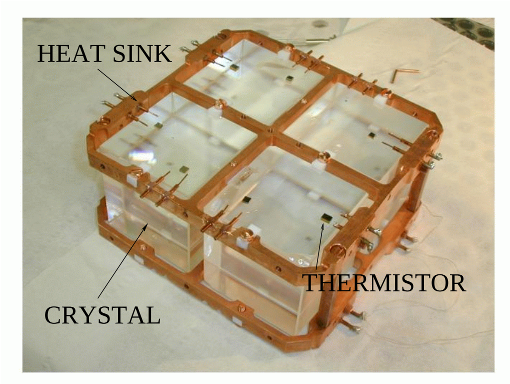

Fig. 1. Photograph of a 4 element CUORE/CUORICINO test module.

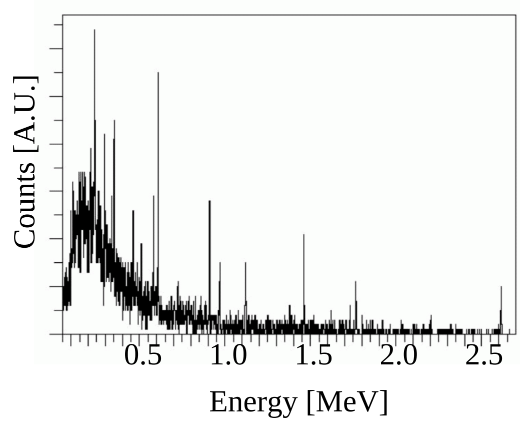

Fig. 2. Spectrum of a ^{232}Th source collected with a CUORE test element. Several narrow lines are visible up to the 2615 keV ^{208}Tl line.

BETA detector was a segmented device consisting of 20 elements of 340 g each. Their good reproducibility can be appreciated considering that the sum spectra obtained during calibrations show energy resolutions of $\sim$ 8 keV FWHM at 2.6 MeV (near the ^{130}Te Q-value). With a total active mass of 6.8 kg this detector has been up to now by far the largest thermal detector ever operated. The array was held in a copper tower-like frame, mounted inside a dilution refrigerator in Hall A at the Gran Sasso National Laboratories. Details on the detector, the shieldings, the read-out, the data acquisition and the detector performances have been reported elsewhere [8]. The MIBETA array has been operated, in two different configurations, for 3.55 kg $\times$ year of effective running time. No evidence of the 2528.8 keV line due to ^{130}Te neutrinoless decay to the 0^+ ground state of ^{130}Xe has been found in the background spectrum, leading to a limit on the half-life of ^{130}Te neutrinoless decay to the 0^+ ground state of ^{130}Xe of 2.08 $\times$ 10^{23} years at 90% C.L. (including in the statistics also previous lower mass experiments). We would like to note that our limit on the lepton non conserving channel is the most stringent in the literature after those obtained in double beta decay experiments with ^{76}Ge. Our limit on lifetime restricts the upper bound of $\langle m_\nu \rangle$ to values ranging from 1 to 2 eV, according to most theoretical calculations.

Proposed as an intermediate step to demonstrate the feasibility of a large mass high sensitivity cryogenic experiment to search for rare events (CUORE), CUORICINO is actually a true experiment. The CUORICINO set-up will be installed within the end of 2002 in Hall A at the Gran Sasso National Laboratories (in the same dilution refrigerator housing the MIBETA array) and will consist of an array of 44 5-cm-side cubic crystals and of 18 $3 \times 3 \times 6$ cm crystals of natural TeO_2, with a total active mass of about 41 kg. In analogy with the

MIBETA set-up, a final design consisting in a tower structure was planned. The main advantage of such a structure is that each plane of the tower can be considered as an elementary module (of 4 crystals) and can be optimised and tested independently. A typical module is depicted in fig. 1.

After the approval of the CUORICINO experiment by the Gran Sasso Scientific Committee and by the funding authorities, an intense activity of preparation has started. Our efforts have been addressed both to the improvement of the detector performances (noise reduction, time stability, energy resolution, etc.) and to the reduction of the background. The 4-detector module is the only CUORE/CUORICINO part that was up to now realised and tested in the Gran Sasso lab. However, it is self-consistent: its bolometric optimization represents therefore an important step in the optimisation of all CUORE elements. The tests performed in Gran Sasso on this structure and on a similar structure with smaller ($3 \times 3 \times 6$ cm^3) crystals have allowed to get important achievements, which definitely show that CUORE is a viable project from the point of view of the detector properties. Main improvements were obtained in thermistor choice and mounting, in microphonic noise through the use of cold electronics and mechanical suspension of the module [10], in response stabilisation of the detector using a calibrated pulser (in fact a simple heater) on the crystal itself [11]. As a result we reached, despite the much larger mass (790 vs 340 grams), energy resolutions similar or even better than those obtained with the MIBETA detectors. In particular, an energy resolution of 1 keV for the 46.5 keV γ line of ^{210}Pb and of 3.2 keV FWHM on the ^{210}Po α-line, together with an energy threshold of about 5 keV were obtained in our test measurements. At the ^{130}Te Q-value the energy resolution, monitored with a γ source, is around 4 keV FWHM. A calibration γ-spectrum is shown in fig.2. We would like to stress that the obtained energy resolutions for α particles are three times better that those ever obtained with any other type of detector.

4. CUORE: structure and sensitivity

As for CUORICINO, CUORE will be based on an elementary module of 4 crystals. Groups of ten modules will be stacked together so as to form a 10-plane tower. The CUORE array will consist of 25 of these towers, in a 5×5 structure, forming a cubical configuration with 10 crystals per side, with a total active mass of 790 kg. Each tower will be completely equivalent to the tower that will be tested in CUORICINO, both from the mechanical and thermal point of view, and substantially independent of the nearby towers. The close packing and the high granularity will help in background identification and rejection. The array will be housed in a specially-made high-power dilution refrigerator (fig. 3) and operated underground at a temperature of 10-15 mK. More details on CUORE design can be found in [12]. The time estimated for CUORE construction is of the order of three years.

One of the main goals of CUORE is to reach an extremely low background level in the range of 0.001-0.01 events/(keV kg y) in the energy region of interest for 0ν-DBD of ^{130}Te. This means an improvement by a factor 100-10 with respect to the MIBETA result. In order to assess if this is indeed achievable, we started a detailed program of Monte Carlo simulations of all the relevant background sources, introducing reasonable radiopurity levels of the most relevant materials. The sensitivity of CUORE is evaluated on the predicted values of 5 keV FWHM resolution at 2.5 MeV. The background rate at the same energy is assumed to be 0.001 counts/(keV kg y), as predicted by the Monte Carlo. To be on the safe side we consider also the possibility that the background be higher by a factor of 10. In the optimistic case, the sensitivity to lifetime will be $\sim 3.6 \times 10^{26} \sqrt{\mathrm{t}}$ y (where t is the live time measured in years) assuming an energy resolution of 5 keV FWHM. This will imply that in one year of statistics CUORE will provide $\langle m_\nu \rangle$ upper bounds smaller than 0.03 eV (with the appropriate nuclear matrix elements). These predictions could be admittedly optimistic since other sources of background, not taken into account by the Monte Carlo, could be present. Under the more conservative hypothesis of a background of 0.01 counts/(keV kg y) the upper limit on $\langle m_\nu \rangle$ would be 0.05 eV. In conclusion the ultimate sensitivity of CUORE for 0ν-DBD searches stagnates at ~ 0.04 eV for the upper bound of $\langle m_\nu \rangle$, with a very soft dependence with live time ($\mathrm{t}^{-1/4}$). This sensitivity level starts to attack the neutrino mass range suggested by the oscillation results.

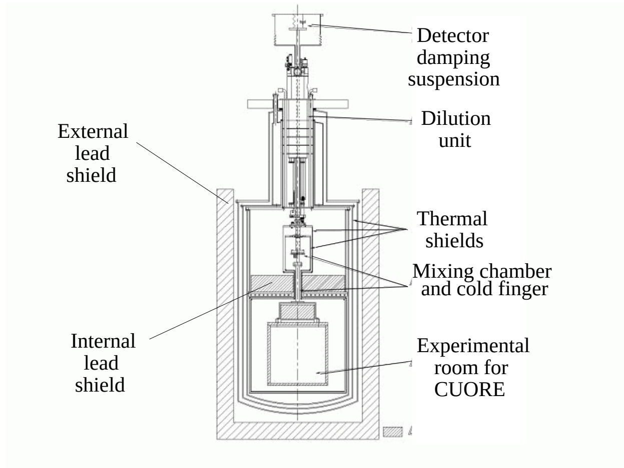

Fig. 3. Schematic structure of the CUORE cryostat. The experimental space allows to host a 70 cm side cube.

The CUORE set-up will enable not only an improved search for 0ν-DBD, but also a sensitive experiment on direct interactions of WIMPs (particle candidates to the composition of Dark Matter), via the seasonal variation of their interaction rate. We also plan to investigate the possible subdiurnal modulation of the signal induced in this detector by electromagnetic interactions of axions coming from the Sun.

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