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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Large calorimetric devices for double beta decay and dark matter

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The use of cryogenic thermal particle detectors permits the realization of detectors of various compositions, various sizes and very good energy resolution. In particular these characteristics are very promising for the realization of double beta decay and dark matter search experiments. Our group is mainly interested in the study of double beta decay of ^{130}Te and ^{116}Cd. For tellurium we have realized various detectors using TeO_2 crystals, the final one with a mass of 334 g For cadmium a $CdWO_4$ crystal of 58 g has been used in various tests. The double beta decay measurement has been performed in the Gran Sasso Underground Laboratory. Measurements on the 334 g TeO_2 crystal have been performed for 3000 h. Detector resolution is around 10 keV FWHM and the internal contamination of ^{238}U and ^{232}Th in the crystal is of the order of 10^{-13} g/g. A lower limit on the half-life of neutrinoless double beta decay for ^{130}Te of 8.2×10^{21} yr (90% CL) is measured. The test measurements of $CdWO_4$ reach an energy resolution of about 5 keV FWHM with a very high efficiency to gamma ray detection. A limit on the neutrinoless channel of 7×10^{19} yr (90% CL) is evaluated in 340 h. In this test an end point energy of $318.8 \pm 1.4 \pm 5$ keV and a half-life of $(9.3 \pm 0.5 \pm 1) \times 10^{15}$ yr for the beta decay of ^{113}Cd are also measured. The last part of the paper is dedicated to a brief discussion of our proposal for the solar neutrino flux measurement and for the search of dark matter using cryogenic detectors.

1. Introduction

The realization of cryogenic thermal detectors was proposed in 1984 by different authors [1,2]. The new idea is very simple and at the same time permits the study and realization of a new kind of detector. In fact when a particle interacts with a solid state material, it releases most of its energy as heat. Starting from this point it is clear that a detector that is able to measure the heat produced by a particle interaction can reach very good performance in energy resolution. In particular a thermal detector measures the energy carried by thermal phonons produced by the particle energy deposited inside the material.

For a good energy resolution it is necessary to evaluate the amount of energy necessary to create an elementary energy carrier event. In the case of germanium detectors the energy needed to generate a hole–electron pair is about 3 eV. The energy of the thermal phonons inside a crystal is proportional to kT (where k is the Boltzmann constant and T is the temperature). In order to have a minimum value of energy per phonon generation it is necessary to put the detectors at very low temperature. Normally the cryogenic thermal detectors are operated at a temperature around 10 mK, where kT is few tenth of μeV.

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The theoretical energy resolution of this type of detectors is defined by the thermodinamical relation $\Delta E = \xi (kT^2C)^{1/2}$, where C is the thermal capacity of the detector and ξ is a parameter connected to the type of thermal sensor used. The thermal capacitance for a dielectric and diamagnetic crystal is described with the Debye law:

$$C = 1944 \frac{m}{m_M} \left(\frac{T_D}{T} \right)^3,$$

where m is the mass of the crystal, m_M is the molecular weight and T_D is the Debye temperature. From this formula it is clear that the heat capacity decreases with the third power of temperature and it is directly proportional to the mass. For these reasons it is more simple to reach very high resolution using a very small detector than using a large mass detector. The best result with a thermal detector was obtained with a very small silicon crystal by the NASA–Winsconsin collaboration. This device presents a resolution of 7.3 eV exposed to X-rays of ^{55}Fe [3]. Typically the small silicon detector has been realized in a monolithic structure.

The situation of the large device is quite different because, in general, the realization of the detector needs the connection between the absorber (the part of the detector in which the interacting particle releases its energy) and the sensor (the part that converts

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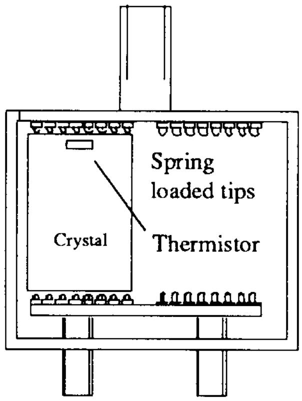

Fig. 1. Crystal mount realized using an OFHC copper frame.

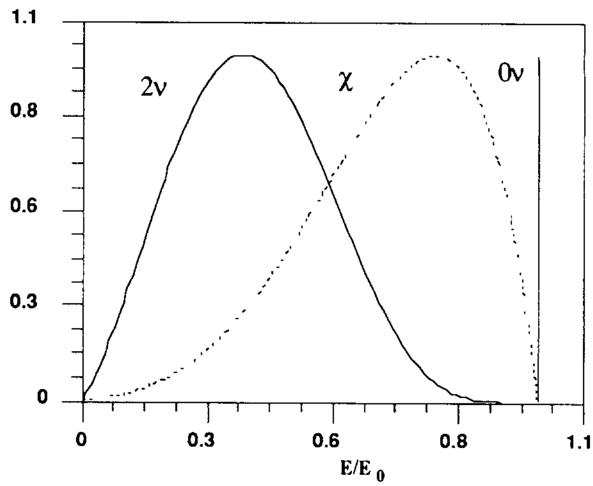

Fig. 2. Electron sum energy spectra for the three type of double beta decay transitions.

the variation of temperature in a variation of another measurable quantity, typically a voltage or a current). Another important thing is the crystal mount; for a small detector the connecting wires can hold the crystal in the correct position, while for a detector mass greater than 1 g this is practically impossible. In this case a more complicated structure is necessary, of which a typical example is represented in Fig. 1; the realization of that is very crucial for obtaining the minimum base temperature and the best signal to noise ratio.

2. Double beta decay experiment on ^{130}Te

The double beta decay transition is a spontaneous radioactive process that involves the transformation of a nucleus (A, Z) into the isobar $(A, Z+2)$ with the emission of two electrons [4]. The theoretical channels in which the decay can evolve are: (a) the decay with the emission of two electrons and two electron antineutrinos, that is allowed by the electroweak standard model; (b) the neutrinoless decay, where only the two electrons are emitted; this process implies the violation of the lepton number conservation and indicates that the neutrino is a Majorana particle; (c) the decay with the emission of two electrons and a massless Goldstone boson (Majoron) representing another lepton number violating process. These three types of decay channels present different signatures in the electron energy spectra (Fig. 2).

In our experiment we are especially interested in the study of the double beta decay of ^{130}Te. The characteristics of this nucleus are very interesting: the natural abundance is around 33% and the transition energy of the decay is 2528.8 keV. The decay for this nucleus was proven by the evidences obtained in the geochemical experiments [5-7], which however cannot distinguish between the different decay modes. Chemical separation from the parent nuclei of the daughters brings no information on the decay mode. Moreover, data reported by different experiments are not in complete agreement with each other. It is therefore crucial to investigate the decay of this nucleus with a different technique.

The cryogenic thermal detector permits the realization of a fully calorimetric approach to the experiments. In particular we have chosen a crystal of TeO_2 for the realization of the absorber. After the tests with a crystal with a mass less than 100 g, the last measurement (still running now) was realized using a single crystal of 334 g of TeO_2. The crystal is maintained in the correct position inside a dilution refrigerator using an OFHC copper frame. The crystal mount is realized by the use of tips loaded by springs in order to compensate the different contractions between the crystal and the frame with temperature. An NTD doped ger-

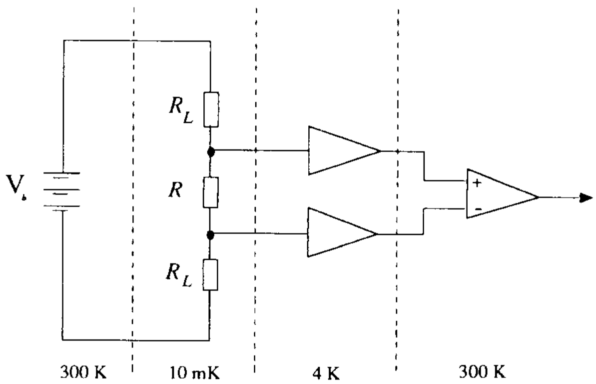

Fig. 3. Differential readout configuration for cryogenic thermal detectors with the front-end electronics realized using a GaAs technology and placed in the 4 K region.

manium sensor was glued on the crystal by means of non-conductive glue (two component epoxy). The read-out of the signal from the sensor is performed by two gold wires bonded on the thermistor. The bias of the thermistor is realized by a battery and two load resistances in order to polarize the sensor with a constant current. In this manner the variation of temperature produced by the impinging particle in the absorber is transduced in a variation of voltage across the thermistor. Each voltage pulse is read out by a differential preamplifier (Fig. 3). The front end is placed in the 4 K region in order to minimize the stray capacitance between the sensor and the preamplifier. In this way it is also possible to reduce the electromagnetic and microphonic interferences in the electronic chain. The differential configuration permits one to minimize the

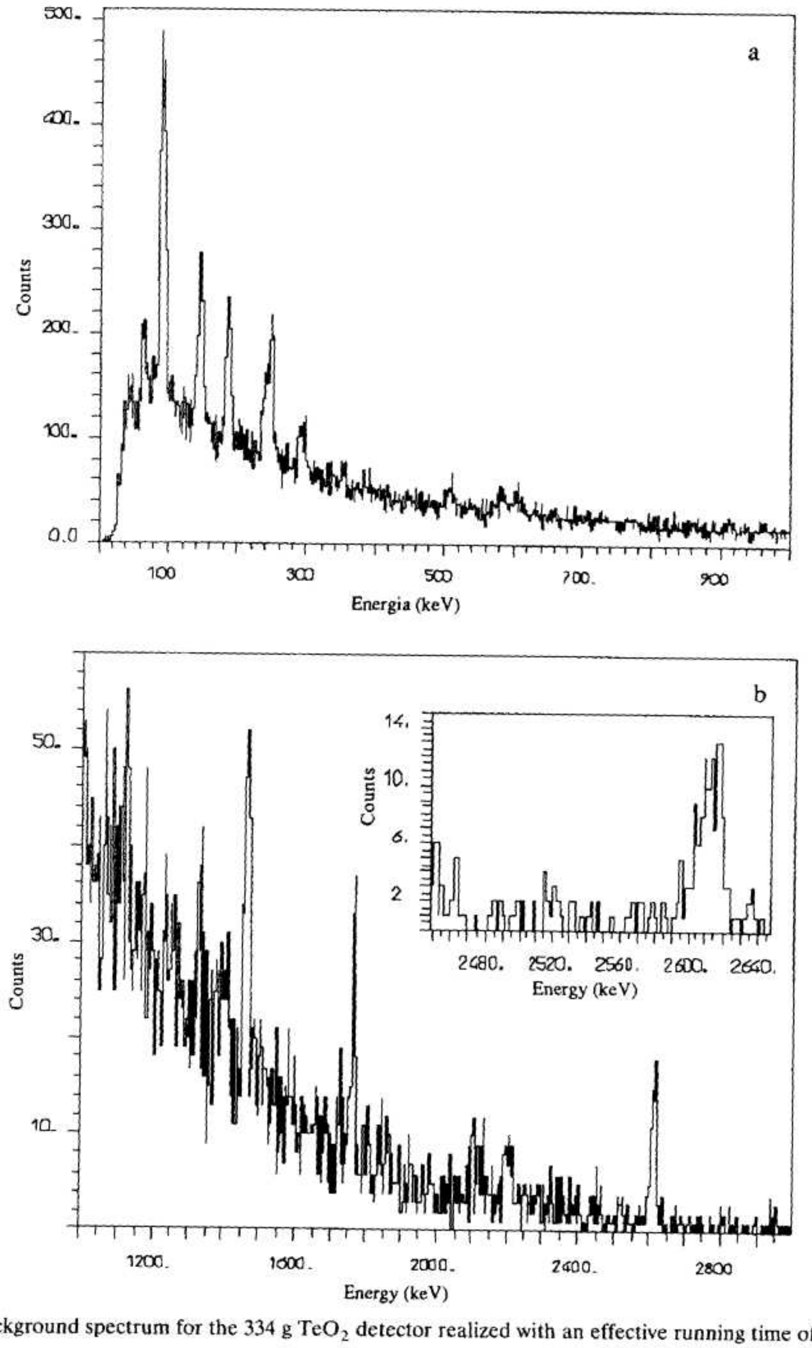

Fig. 4. Background spectrum for the 334 g TeO_2 detector realized with an effective running time of 3011.4 h.

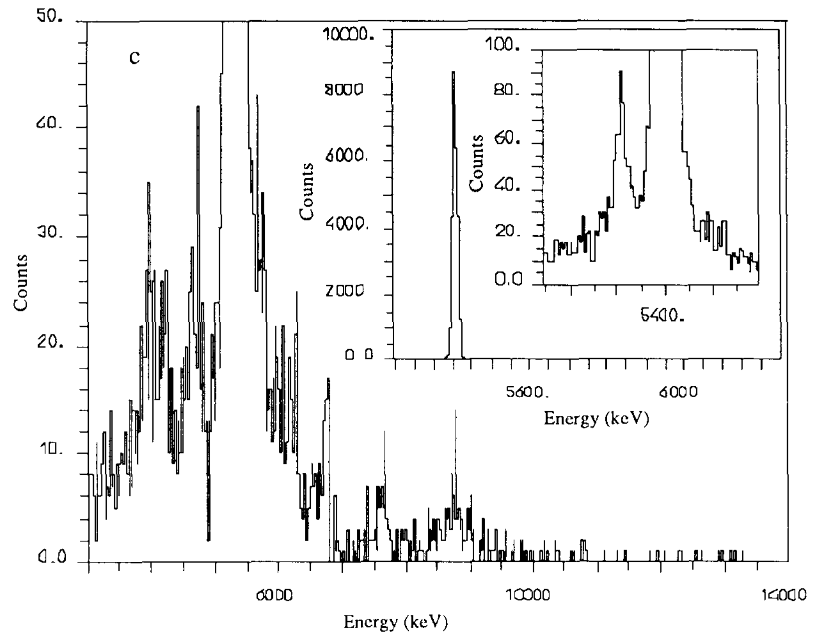

Fig. 4. (continued).

common mode noise coming from the electromagnetic and microphonic interference [8].

The dilution refrigerator, whose power is 1 mW at 100 mK, is placed in the Gran Sasso Laboratory at a depth of 3500 m.w.e., where the background of the cosmic rays and fast neutrons is reduced by 6 and 4 orders of magnitude respectively. The material used in the construction of dilution refrigerator is specifically selected for low intrinsic radioactivity. The base temperature reached is equal to 5.5 mK. The cryostat is shielded against local radioactivity by means of 10 cm thick lead externally and with 3 cm thick low activity lead just around the detector. A Faraday cage was built in order to minimize the presence of electromagnetic interferences.

The pulse coming from the preamplifier is converted with a fast digitizer and the data is stored. Off-line analysis is made in order to compensate the fluctuation of different parameters during the measurement. The optimum filter algorithm permits one to maximize the signal to noise ratio.

The 334 g TeO_2 detector worked in the present measurement at a base temperature of 8.7 mK that rises to 10.5 mK when it is biased with 6.2 mV through a 5 GΩ load resistor. The working thermistor resistance is equal to 191 MΩ. The long term stability of the detector is controlled by a ^{60}Co and ^{232}Th source periodically. The energy resolution of this detector is around 10 keV FWHM over the total energy spectrum. The background spectrum of an effective running time of 3011.4 h is shown in Fig. 4.

The analysis of the peak in the spectrum shows that the α lines are due to external contamination with respect to the crystal except for the 5.4 MeV line that corresponds to an internal contamination of ^{210}Po, an isotope usually present in the tellurium compounds. The ^{210}Po signal corresponds to the full energy deposited inside the crystal because the cryogenic detector presents a very high efficiency in the measurement of low ionizing events like nuclear recoils. This hypothesis is confirmed by the presence of a much weaker peak at 5313 keV corresponding to the energy of the α particle probably due to the contamination of the surface. The distance between the two signals is evaluated to be 95 ± 10 keV, which is in excellent agreement with the value of 103 keV calculated for the nuclear recoil. In addition the analysis of the activity of the peak is in good agreement with the lifetime of ^{210}Po. The presence of the ^{210}Po internal contamination permits the correction of the fluctuation of gain (less than few percent) during the measurement using the α decay peak as reference.

A delayed coincidence analysis was performed in order to evaluate the presence of a further contamination. For the natural chain of ^{238}U and ^{232}Th a sequence of α–α emissions has been considered, but in the analysis no signal has been found. In this condition it is possible to give a limit on the internal contamination of the TeO_2 crystal of about 2.3×10^{-13} g/g for the ^{232}Th chain and 1.1×10^{-13} g/g for the ^{238}U chain.

The presence of the ^{208}Tl peak at 2615 keV indicates the presence of a residual radioactive background due to the ^{232}Th chain. There is at the moment no precise indication of the source of this background that is very critical for the study of neutrinoless double beta decay of ^{130}Te. The ^{208}Tl peak shows a slight asymmetry. We are investigating if this is due to border effects or to other reasons (insufficient statistics, thermal instability, etc.).

The background counting rate in the neutrinoless double beta decay region (about 80 keV below the ^{208}Tl peak) is equal to 9×10^{-4} counts/(keV h kg). A small enhancement corresponding to 8.5 ± 4.7 counts appears at an energy of 2523 ± 4.3 keV. We attribute no statistical significance to this enhancement. If however, increasing the statistics, it should be confirmed, it is essential to improve the determination of its energy with a detailed study of the 2615 keV line. The possible different efficiency of our detector for an event with the emission of two electrons and for an absorption of a high energy gamma ray, which occours mainly (90%) by multiple Compton interactions, should also be considered.

Applying the maximum likelihood analysis at the spectrum in the double beta decay region we evaluate a lower limit on neutrinoless double beta decay of 1.3×10^{22} yr and 8.2×10^{21} yr at 68% and 90% confidence level respectively for the half-life of the process. These limits are more stringent than the geochemical results, thus indicating that the double beta decay measured by geochemical measurements is dominated by the two neutrino decay process.

3. Double beta decay experiment on ^{116}Cd

^{116}Cd is a very promising candidate for the study of the double beta decay process. First of all this process presents a very high transition energy (2802 ± 4 keV), around 200 keV above the end point of natural γ radioactivity. Second the natural abundance of ^{116}Cd is 7.49%, which permits the use of natural cadmium in the experiments.

We have chosen to study a thermal detector realized with a crystal of $CdWO_4$ that presents a relatively high Debye temperature, and it is commercially available. Moreover, it represents a good candidate for the realization of a high Z thermal detector with high γ ray efficiency. The crystal is normally used in the realization of scintillators; therefore it could be possible to obtain a simultaneous measurement of heat and light for a possible reduction of the background contribution.

The test is performed using a crystal with a mass of 58 g. The mounting structure is very similar to that described for the TeO_2 crystal. The crystal was mounted inside our second dilution refrigerator in the Gran Sasso Laboratory to test the performances and the background. This new cryostat is similar to the old one but less powerful (100 μW at 100 mK). The base temperature reached by the crystal is equal to 19.5 mK, and applying a bias of 7.7 mV through a load resistance of 1.55 GΩ leads to an operating condition of 25.3 mK of temperature and 4.4 MΩ of the thermistor resistance.

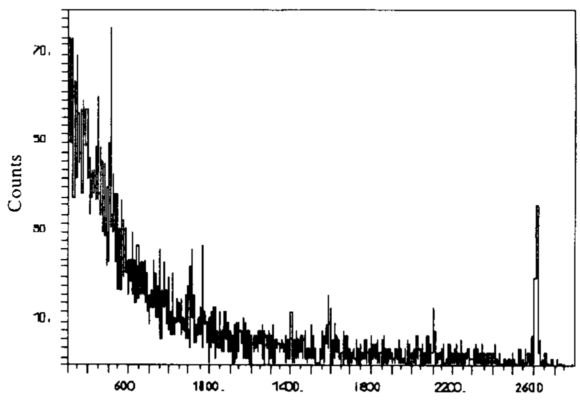

Fig. 5. Calibration spectrum of $CdWO_4$ detector with a ^{232}Th source; resolution is around 5 keV FWHM.

A calibration measurement with the ^{232}Th and ^{60}Co source was performed. The spectrum of the ^{232}Th source is shown in Fig. 5 and it presents an energy resolution of about 5 keV FWHM. This characteristic gives us a detector with very high efficiency and very high energy resolution.

A 340 h of effective running time measurement was carried out. The background spectrum is shown in Fig. 6. In the high energy region no indication of background contamination is present. In the low energy part of the spectrum it is clearly beta spectrum. This is

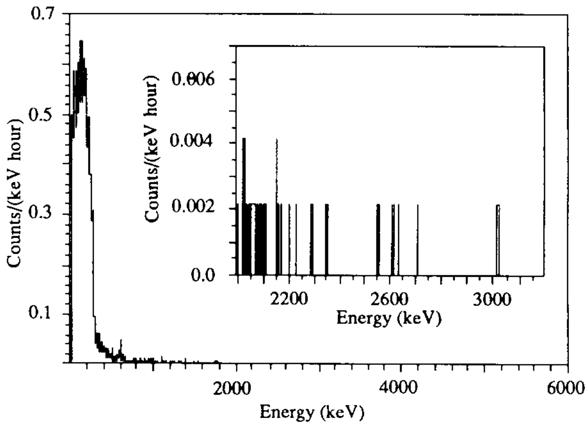

Fig. 6. Background spectrum for the 58 g $CdWO_4$ detector.

the beta decay of ^{113}Cd that is present in the natural cadmium with an abundance of 12%. A preliminary fit of data was carried out for this beta transition (fourth forbidden, non-unique). In this way a precise value of the transition energy (318 ± 1.4(stat) ± 5(syst) keV) and of the lifetime (9.3 ± 0.5(stat) ± 1(syst) × 10^{15} yr) has been evaluated.

The analysis of the spectrum in the region of the neutrinoless double beta decay of ^{116}Cd gives us a preliminary lower limit for the half-life of 7×10^{19} yr at 90% confidence level.

4. Solar neutrino flux measurement using ^{81}Br

One of the most important scientific goals in physic is the correct measurement and the complete comprehension of the solar neutrino flux. The fraction of this flux coming from the ^{7}Be electronic capture is particularly important for the implication on the solar model and on the neutrino properties [9].

Our group has proposed a new kind of solar neutrino experiments using a thermal detector approach with a ^{81}Br nucleus as a target. The basic idea is related to the process ^{81}Br $(\nu_e, e^-)^{81}$Kr* [10]. The excited state of ^{81}Kr presents an energy of 190 keV and decays with an half-life of 13 s. In this way the detection of the solar neutrino coming from a ^{7}Be source is indicated by a pulse of 390 keV followed, within around 1 min, by a signal of 190 keV. This sequence gives us a precise signature of the event that permits a very strong reduction of the background. In this way we can realize a "neutrino spectroscopy".

We have planned an experiment with NaBr crystals, where the total mass of the detector must be of the order of 100 ton divided in 10^5 channels. The background evaluation considering a contamination of the material equal to 10^{-12} g/g in ^{238}U and ^{232}Th gives us a signal to background ratio equal to 10^3.

It is clear that this experiment is a very complicated technical challenge. It is difficult, at 10 mK, to cool down a large mass of material and it is not simple to realize a readout for 10^5 channel inside a cryogenic environment. Preliminary considerations on the cryogenic system allow one to evaluate the dilution refrigerator for this application. This is only four times more powerful with respect to our old machine in Gran Sasso. The readout problem will be further analyzed in order to optimize the technical approach at the problem.

In order to test the feasibility of the experiment, a small NaBr crystal placed at few tens of mK was exposed to a ^{232}Th source. Preliminary results are shown in Fig. 7, the energy resolution obtained is of the order of 50 keV FWHM, a much worse resolution compared to TeO_2 and $CdWO_4$ crystals; investigations are in progress.

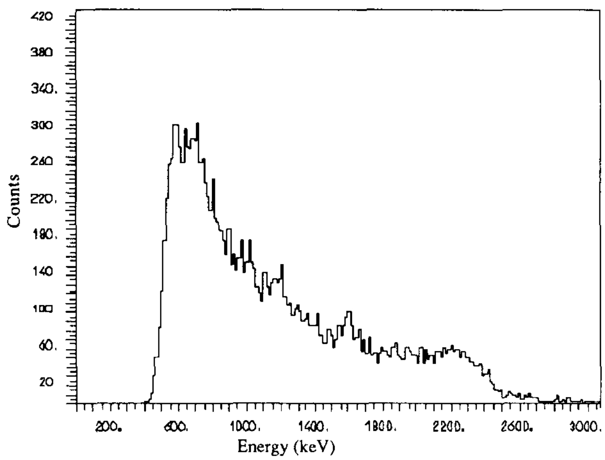

Fig. 7. Test measurement for a small NaBr crystal exposed to a ^{232}Th source.

The realization of this experiment is also interesting for dark matter search. In fact the cryogenic detector presents a very high efficiency to the nuclear recoil events (demonstrated in our TeO_2 experiment); this type of signal is the main signature of the possible interaction of the dark matter particle. In particular with the NaBr crystal we have a low Z nucleus (Na) with non-zero spin that can be used to investigate not only the coherent scattering but also the spin interaction with the dark matter.

5. Conclusion

The introduction of cryogenic thermal detectors in particle physics open the way to the study and realize new types of experiments with a high energy resolution device.

A double beta decay experiment based on ^{130}Te and ^{116}Cd can be realized using this new technique. The preliminary results from the ^{130}Te experiment exclude, at 10%, with a 90% confidence level, that the decay rate measured by the geochemical experiment is due to the neutrinoless channel. The tests on $CdWO_4$ crystal give us very promising data for a future experiment on ^{116}Cd.

For the double beta decay experiments our group plans to realize in the near future an array of detectors in order to reach a mass for the experiment of the order of few kg. In particular for the ^{130}Te experiment we want to measure two different samples: one isotopically enriched in ^{130}Te and another enriched in ^{128}Te in order to investigate the two neutrino double beta decay.

The new idea on solar neutrino spectroscopy is now under study. Our goal is to have a NaBr detector with a mass of the order of 100 g with a good energy resolution. When this goal will be reached, we plan to study the realization of a prototype in order to investigate the real possibility of the construction of the experiment.

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