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A scintillating bolometer for experiments on double beta decay

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Abstract

The scintillation yields of CaF_2 crystals with different doping concentration of Europium have been measured at low temperatures and their bolometric behavior has been investigated. After these studies we have constructed the first ''scintillating bolometer'' where the heat and scintillation pulses produced by charged particles are simultaneously recorded. With this method a strong suppression of the background from α-particles in the energy region of interest for searches on double beta decay of ^{48}Ca can be achieved. © 1998 Elsevier Science B.V.

1. Introduction

One of the main problems in low energy experiments on rare events is the reduction of the background of spurious counts which could cover the expected signal. Cosmic rays are strongly suppressed by operating the set- up underground, while suitable shields reduce heavily the effect of environmental radiation. More difficult is the suppression of the intrinsic background coming from radioactive contamination in the materials facing the detector or in the detector itself. It is therefore very important to discriminate the signals produced by the searched particle from those of this background. This has been recently accomplished in scintillators [1] and in semiconductor detectors [1,2] by pulse shape discrimination.

A different approach has been recently implemented in the new field of low temperature thermal detectors, which are progressively being applied to searches in non accelerator physics [4,5]. These ''bolometers'' consist of a crystal of dielectric and diamagnetic material kept at low temperature and in thermal contact with a suitable thermometer. Their heat capacity can become very small, being proportional to the cube of the ratio between the operating and Debye temperatures. As a consequence even the tiny energy deposited in the crystal in form of heat by a particle can be revealed and measured from the consequent increase of temperature.

A so-called ''hybrid'' technique, based on these bolometers, has been recently implemented for

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searches on direct interactions of WIMPS. The nuclear recoils produced by these particles would totally deliver their energy in form of heat: their detection efficiency with a thermal detector would therefore be near to one [5,6]. These recoils are on the contrary poorly ionizing particles, unlike electrons and γ-rays which constitute the most relevant part of the background. As a consequence detectors have been constructed where the heat produced in the absorber, which is a semiconductor, is measured simultaneously to its ionization [7,8]. An analysis of the relative pulse height in the thermal and electronic channel allows to select the poorly ionizing recoils from the background of strongly ionizing electrons and γ-rays.

A similar approach can be applied to the simultaneous measurement of scintillation and heat [9,10]. The analysis of the relative pulse height in the thermal and scintillation channel would also allow to eliminate the background electrons and γ-rays with respect to the poorly scintillating nuclear recoils. An equivalent pulse height analysis could allow to reject poorly scintillating background events in experiments like those on double beta decay [11]. This rare process [12,13] consists of the simultaneous emission of two electrons from a nucleus (A,Z). Double beta decay where two antineutrinos are emitted together with the two electrons is allowed by the Standard Model and has been so far found or at least indicated for ten nuclei. Neutrinoless double beta decay where no neutrino is emitted would indicate non conservation of the lepton number as suggested by the Grand Unified or Supersymmetric theories. The expected sum spectrum of the two electron energies would display in this case a peak corresponding to the transition energy. Other lepton number violating double beta processes like those involving the emission of a Majoron will not be considered here.

Double beta decay candidates with large transition energy are particularly attractive due to their correspondingly large available phase space. The interest in double beta decay of ^{48}Ca, which is the candidate with the largest transition energy (4272 keV), is also connected to the possibility to calculate its rate with good precision in the shell model [13]. The difficulties of the various experiments carried out on this nucleus are related to its very low isotopic abundance (0.187%). Enrichment in this isotope, which cannot be performed with ultracentrifuges, is very expensive and can lead to a considerable radioactive contamination. With a large amount (32 kilograms) of natural CaF2 scintillators [14] operated underground the Beijing group has obtained lower limits of 9.5×10^{21} and 3.6×10^{19} years for neutrinoless and two neutrino double decay, respectively. A more recent experiment carried out with two samples of enriched Calcium in the Irvine TPC [15] has provided evidence for two neutrino double beta decay of ^{48}Ca with a lifetime of $(4.3^{+2.4}_{-1.1}$ [stat] ±1.4 [syst] $)\times10^{19}$ years.

The background problems for the few double beta decay candidates with very large transition energy, and in particular for ^{48}Ca, are different than those where this energy is lower. The expected peak for neutrinoless decay is definitely above the energy range of the background due to β and γ-rays from naturally occurring radioactivity [16]. More relevant in this energy region is on the contrary the background due to α-decays occurring inside the detector or in the regions immediately surrounding it. In the case of ^{48}Ca the neutrinoless peak is dangerously close to a peak at 4269 keV from and internal contamination of ^{238}U due to sum of the 4197 keV energy of the α-particle and the 72 keV energy of the corresponding nuclear recoil [17]. Another contribution to the background could come from α-particles of higher energies generated in regions immediately close to the detector whose energy could be degraded. Since the scintillation yield of α-particles in CaF_2 is however much lower than the corresponding yield for the two electrons, relative pulse height analysis of the simultaneous scintillation and heat signals would substantially reduce the background in the region of neutrinoless double beta decay.

2. Scintillation and thermal yield of CaF_2 crystals at low temperatures

CaF_2 crystals are good scintillators, but they have been operated as such only at temperatures above 100 K, and their scintillation yield is expected to decrease strongly with temperature, especially for intrinsic crystals. On the other side CaF_2 is normally doped with Europium, which is paramagnetic and whose contribution to the heat capacity of the absorber is therefore expected to increase at low temperatures [18]. We have therefore performed systematic measurements of the scintillating and thermal properties of CaF_2 crystals with different doping densities from room temperature to about ten milli-Kelvin.

The crystals used in this study are cylinders whose diameter and height are of about 10 mm, doped with Europium with concentrations ranging from 0 to 0.07%. They have been provided to us by the Moscow Engineering Physical Institute. The use of photomultipliers in a cryogenic environment implies obvious problems. We have therefore adopted PIN silicon photodiodes in tight contact with the CaF_2 crystal, which could be cooled together with it. Photodiodes are well suited for this application because their intrinsic radioactivity is low and the heat capacity of Silicon is small, since its Debye temperature is of about 640 K. The photodiode can be left in contact with the bolometer without the need of a thermal insulating light guide. Some deterioration in energy resolution is expected due to fluctuation of the heat generated by the migration of photoelectrons in the bias electric field. This effect should however be limited in typical conditions to few keV for signals of about 10^4 electrons.

The scintillator is exposed to α-particles from an ^{241}Am source through a small hole on one side of the crystal, which was coated with a PTFE reflector. The pulses from the photodiode, glued on the opposite surfaces of the crystal, were recorded through a GaAs charge-sensitive amplifier operated at the same temperature as the diode above 10 K. At lower temperatures the amplifier was kept at 4 K. Its intrinsic risetime was of 30 ns and its rms noise level 55e and 100e for capacitance of 0 and 100 pF, respectively. A small ^{4}He circulation cryostat and a dilution refrigerator were used for temperatures above and below 10 K, respectively. The response as a function of the temperature of a CaF_2 crystal with a 0.03% doping concentration is shown by the upper curve in Fig. 1. The lower curve shows the response to the 60 keV γ-rays, also produced by the source, which interact directly with the photodiode. This allows to renormalise the light yields of the CaF_2 crystal with respect to the variation of the response of the photodiode with temperature. The behavior for the scintillation yield shown in the figure agrees well for temperatures above 100 K with the preceding result of Rodnyi [19]. The response of the CaF2 scintillator drops rapidly from room temperature to 30 Kelvin, but remains practically constant below this value. The light yield for various doping concentrations is shown as a function of the temperature in Fig. 2. It drops to very low values below 100 K for undoped crystals which cannot therefore be used for this application. The doping concentration which maximizes the light yield is 0.03%.

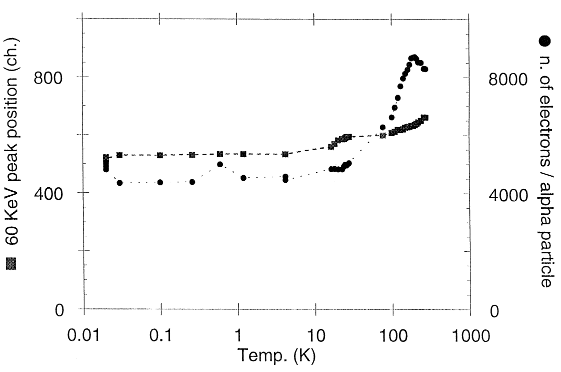

Fig. 1. Scintillation yield as a function of the temperature for 5.5 MeV α-particles and 60 keV γ-rays.

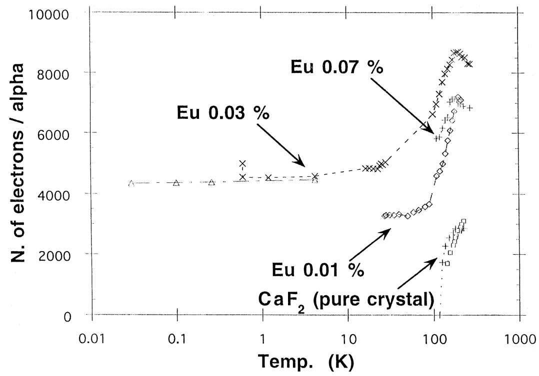

Fig. 2. Scintillation yield as a function of the temperature for 5.5 MeV α-particles at various doping concentrations.

A crystal of 2.1 grams with the above quoted 0.03% doping concentration has been used to measure the thermal response at low temperatures. It was framed to the mixing chamber of the dilution refrigerator by means of spring loaded tips and connected to a NTD (Neutron Transmutation Doped) thermistor. The read-out configuration is similar to the ones usually adopted by us in our experiments with cryogenic detectors [20]. Even if this mounting is only a preliminary one from the thermal point of view, the measured heat capacity at the optimum operating temperature (60 mK) is of 0.6 nJ/K. The signal amplitude is about four times less than expected value from a evaluation based on the theoretically extrapolated heat capacity of a pure CaF_2 crystal. We would like however to note that signal losses of this order normally occur in bolometers [4,5], possibly due to losses through the thermal couplings among the various thermal stages of the detector. Simultaneous measurements of scintillation and heat are therefore shown to be possible with CaF_2(Eu) crystals.

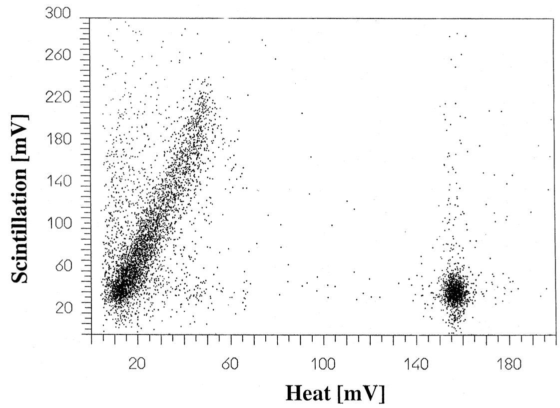

Fig. 4. Scatter plot of the thermal (horizontal) versus the scintillation pulses.

3. The scintillating bolometer

A schematic drawing of our scintillating bolometer (the first in the literature) is shown in Fig. 3. Two photodiodes are glued on the opposite sides of a CaF_2 of 2.1 g mass and 0.03% doping concentration. The remaining surface of the cylinder is covered by a layer of evaporated Aluminum of about one micron thickness which acts as light reflector. Due to the negligible mass and to the fact that it is operated quite below its 1.2 K normal-superconducting transition temperature the contribution from this reflector to the heat capacity of the entire bolometer is negligible. This is also true for the contribution from the two silicon photodiodes, whose mass is of 0.3 g only. The thermistor and the read-out system for both scintillation and heat pulses are similar to those described before.

The detector has been operated at a temperature of 18 mK and both thermal and scintillation pulses were recorded. We would like to point out that in this case the apparent heat capacity is about one order of magnitude larger than expected. This could be due to the complicated structure of the mechanical support and to the presence of the light read-out system, which in this preliminary test is not yet optimized from the thermal point of view. In particular the back of the two photodiodes was covered with a Nichrome coating of 100 mm^2 and 250 μm thick whose contribution to the heat capacity could be relevant.

The scatter plot of Fig. 4 has been obtained by exposing the detector to a mixed source of ^{241}Am

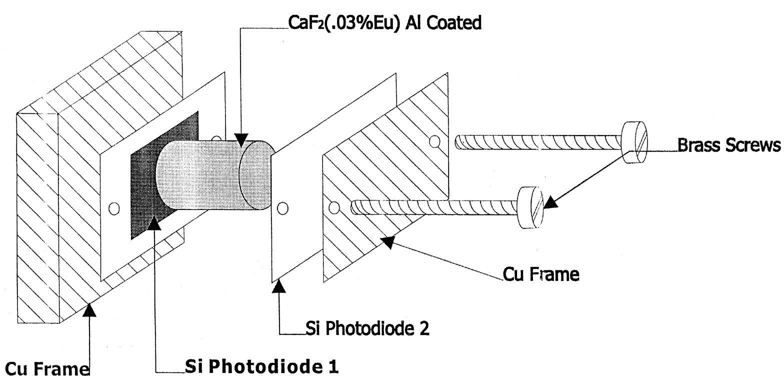

Fig. 3. Schematic drawing of the scintillating bolometer.

and ^{232}Th and recording simultaneously the heat and scintillation pulses. The energy scales for the horizontal (heat) and vertical (scintillation) axes are of about forty and ten keV/mV, respectively. The much faster scintillating signal is used for trigger. The efficient separation of the signals due to γ-rays from those of the poorly scintillating α-particles can be noted.

4. Conclusions

The preliminary tests reported in this paper and the performance of this first scintillating bolometer prove that heat and light produced by a charged particle in a composite detector can be simultaneously recorded and measured. This allows to efficiently separate the strongly scintillating particles, like the electrons emitted in double beta decay, from the poorly scintillating α-particles. Operation of a detector with the two pulses in coincidence should therefore improve strongly the ratio between the signal due to double beta decay (especially in the neutrinoless mode) and the background due to α-particles and more in general by nuclei. We believe that this approach will become essential for searches on double beta decay of ^{48}Ca when large quantities of this isotope will become available.

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